

Perspective

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Effects of sea-level rise on blue carbon stocks of mangrove ecosystems: insights from Pohnpei Island, Federated States of Micronesia

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Abstract

Carbon storage processes in mangrove ecosystems are summarized and future research directions are discussed based on findings from our long-term monitoring studies on Pohnpei Island in the Federated States of Micronesia. On Pohnpei, where coral reef-type mangrove forests dominate, *Rhizophora* communities maintain their habitat by accumulating mangrove peat at over 5 mm year⁻¹ in response to rapid sea-level rise, but surface erosion is progressing in communities where the tree density of *Rhizophora* spp. has declined through succession. However, high-resolution aerial photographs taken by drones have identified trees with reduced vigor even in *Rhizophora* forests, and if sea-level rise occurs at a rate close to the IPCC's maximum prediction, then *Rhizophora* forests, which are valuable carbon storage sites due to mangrove peat accumulation, are likely to disappear. The impact of relative sea-level rise is determined by the sum of the rate of ground-level change by the external sediment budget and the rate of ground-level rise with mangrove peat accumulation. In the future, each region will need to conduct its own quantitative evaluation.

Keywords: Mangrove ecosystem, carbon sequestration, sea-level rise, mangrove peat, sediment budget



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INTRODUCTION

Since a UNEP (United Nations Environment Programme) report in 2009^[1] named the carbon absorbed and stored by coastal ecosystems, including mangrove forests, as “blue carbon”, the carbon sequestration abilities of mangrove ecosystems have attracted much attention, and the number of related research and review papers have been increasing rapidly^[2-5].

On the other hand, since mangrove forests are ecosystems that develop in the upper part of the intertidal zone^[6], sea-level rise induced by global warming is thought to have a great impact on their survival^[7-9]. The sea-level rise that threatens the survival of mangrove ecosystems can have a significant impact on their carbon sequestration abilities. On Pohnpei Island, Federated States of Micronesia (FSM), where the sea level has risen faster than the global average in recent years, the effects of sea-level rise are already visible in the form of surface erosion^[10].

In this paper, we summarize the carbon stock process in mangrove ecosystems and discuss the direction of future research on the impact of sea-level rise on mangrove blue carbon based on the effects of sea-level rise on Pohnpei Island, FSM, where we have conducted long-term monitoring surveys.

OVERVIEW OF PREVIOUS STUDIES ON CARBON STORAGE ABILITIES

To understand blue carbon capacity of the mangrove ecosystem, it is necessary to clarify aboveground biomass (AGB), aboveground productivity (AGP), belowground biomass (BGB), belowground productivity (BGP), soil organic carbon (SOC) and accumulation processes of SOC. The accumulation processes of SOC must be clarified in terms of not only autochthonous biological processes but also the allochthonous sediment budget associated with surface runoff and coastal processes and inflow/outflow of associated organic matter. Research on the carbon sequestration abilities of mangrove ecosystems has been compiled in several reviews^[3,5,11-14]. Here, we provide an outline of related issues in this field.

Estimation of above- and belowground biomass and productivity

The biomass in mangrove forests has often been studied from a forestry perspective. Therefore, research up to the 1980s focused on estimating stem volume and its growth rate^[15,16]. To estimate the total AGB, it is necessary to conduct a survey in which multiple trees of different sizes are felled and the full weight is weighed for each part, and then an allometric equation is created based on these data^[17-21]. Although such surveys are possible in managed forests, it is difficult to conduct them in protected natural forests. Therefore, there have been few reports of new allometric equations for natural mangrove forests in recent years. The studies prior to the use of the term “blue carbon” were summarized by Komiyama *et al.* (2008)^[13].

To estimate AGP, it is essential to conduct periodic tree census at a fixed plot^[10]. However, if lightning strikes or strong winds cause fallen trees in the plot, the AGB will decrease significantly. Therefore, to estimate the average AGP, it is necessary to conduct monitoring surveys over the longest possible period in a fixed plot with a certain size, rather than simply surveying the AGB at two points in time.

In recent years, methods for estimating AGB from light detection and ranging (LiDAR) and RGB (Red/Green/Blue) images using airborne or unmanned aerial vehicles (UAVs) have been developed^[22,23]. However, while these methods can estimate AGB with some accuracy, it is difficult to estimate AGP, which requires litterfall data plus detection of a diameter growth rate of a few mm per year. On the other hand, tree shape and height measurement techniques using 3D laser scanners equipped with LiDAR and SLAM (simultaneous localization and mapping) have been developed for forests^[24,25], but they have not yet reached the stage where data can be acquired with the accuracy required.

To measure BGB, it is necessary to excavate the root system. For this purpose, the high-pressure water injection method^[20] and the trench method^[26,27] can be used. However, these are destructive methods and require a great amount of time and effort, so examples of such studies are extremely limited.

BGP, i.e., root productivity, has been estimated primarily by the ingrowth core method^[28-32] or sequential soil core method^[33]. The primary production of roots cannot be estimated using the ingrowth core method alone because the amount of roots decomposed during the experiment is unknown, but it can be estimated using the litter bag method in conjunction with the ingrowth core method^[31]. However, the values obtained with the ingrowth core method indicate that the amount of roots, including dead roots, accumulated in two years was clearly more than twice the amount accumulated in the first year^[31,32], which points to the fact that it takes a certain period of time for the roots to stably invade. Based on our experimental results, the duration was estimated to be up to 58 days for *Bruguiera gymnorrhiza* and 215 days for *Rhizophora stylosa*^[31]. Therefore, in order to estimate root production using the ingrowth core method without underestimation, cores should be collected twice after installation, the first time at least six months later and the second time one year after that. The sequential core method may result in variations in data from different sampling locations because roots are not homogeneously distributed^[26,27]. Therefore, to obtain an average, a sufficiently large amount of data must be collected to account for tree location and root distribution. This is also the case for the ingrowth core method.

Estimation of accumulated carbon in soil

Twilley *et al.* wrote the first paper reviewing mangrove ecosystems from the perspective of carbon sinks^[11]. They determined AGB and BGB for each latitudinal zone and converted them into carbon stocks, although the data on BGB were particularly limited. They also evaluated AGP from the perspective of wood production, although they did not mention belowground BGP. For SOC, they only conducted very general estimates, as no studies had actually measured it at that time.

In the mid-1990s, the authors began a survey of soil carbon storage in mangrove forests in the Asia-Pacific region. In mangrove forests, inorganic sediments are mainly deposited in areas affected by rivers, whereas mangrove peat is deposited in areas with little sediment inflow^[34-38]. In the Asia-Pacific region, the habitats of *Rhizophora* spp. consist of mangrove peat, whereas the habitats of other mangrove species mainly consist of inorganic deposits^[39-41]. On the other hand, in the Caribbean and the Americas, mangrove peat has been reported to be distributed not only in *Rhizophora* communities but also in *Avicennia germinans* communities^[42,43]. The thickness of the mangrove peat layer generally reaches approximately 2 m on the islands of the Philippines and Micronesia, but in some cases, it reaches 4 m or more in estuaries at the mouths of small rivers with minimal sediment supply^[2,9,44-46]. The main parent material of mangrove peat is dead fine roots^[47]. The SOC of the coral reef-type mangrove habitat of Pohnpei Island in Micronesia, where fibrous peat with almost no inorganic matter is deposited, reaches 650 Mg C ha⁻¹ at up to 1 m deep and over 2,000 Mg C ha⁻¹ at up to 3.5 m deep in the estuary-type habitat^[46]. This was the first paper to report SOC from a continuous undisturbed core taken to a depth of up to 3.5 m, although SOC at the surface layer of 50 cm was reported in 1998 as a case study of an Australian mangrove forest^[48].

After that time, especially after the term “blue carbon” started to be used, the number of reports on SOC increased in various regions^[2,43,49,50], and the mangrove ecosystem became recognized as a valuable ecosystem that accumulates a large amount of carbon, especially belowground^[2,3,5].

However, it should be noted that the amount of accumulated SOC varies greatly among communities. [Figure 1](#) compares the values up to 1 m deep obtained from the Asia-Pacific region by the authors^[46,51-55] to

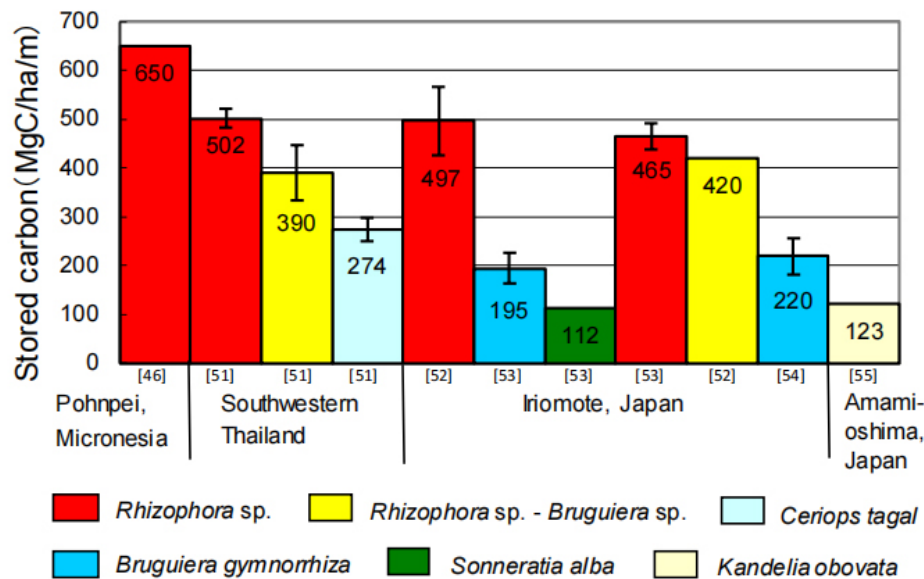


Figure 1. Soil organic carbon by community up to 1 m deep in the Asia-Pacific region. Numbers in square brackets at the bottom of each columnar diagram indicate the literature number of the data source.

compare the amount of carbon stock in the soil for each community. From this information, it can be seen that only *Rhizophora* communities have remarkably high soil carbon stocks of 500 Mg C ha⁻¹ or more, reaching up to a depth of 1 m, while communities dominated by other species have only one-half to one-fourth of that amount. Similarly, in southern China, SOC varies by community, with the highest SOC reported in *R. stylosa* forests^[49]. In the Atlantic, *Laguncularia racemosa* has been reported to accumulate large amounts of carbon in the soil, along with *Rhizophora* communities^[5,56]. Kauffman *et al.* reported no significant differences among communities except for significantly lower values of *Avicennia*^[5], but the data used there included values obtained from riverine mangrove forests^[50], which may contain a certain amount of allochthonous carbon.

It is worth noting that the SOC of the *Rhizophora* community on Iriomote Island in the subtropics has accumulated as much carbon as the tropical Pohnpei Island and southwestern Thailand [Figure 1]. This finding means that even in the subtropics where tree size is smaller than in the tropics and productivity is lower, if enough time passes, then the systems have the ability to accumulate similar amounts of SOC as in the tropics.

Sources of soil organic carbon

Sources of SOC can be divided into autochthonous carbon originating from within the mangrove ecosystem represented by root dynamics and allochthonous carbon derived from other habitats including adjacent catchment areas, seagrasses, phytoplankton and offshore POC (Particulate Organic Carbon). Mackenzie *et al.* summarized the biological, biogeochemical, and geomorphological factors that affect the SOC of mangrove sediments^[57].

The ability to accumulate SOC is determined by the balance between the supply rate of organic matter and the decomposition rate by soil animals and microorganisms^[57,58]. The process of supplying organic matter is also affected by the supply of litter due to the dying and shedding of aboveground biomass, such as leaf litter and fallen trees. However, the litter decomposition rate on the forest floor is high, and tidal runoff also

occurs; thus, aboveground litter does not always have a significant effect on SOC accumulation^[59]. Belowground fine roots have a greater influence than litter supplied from aboveground biomass. This scenario is based on the fact that mangroves have a very high fine root accumulation rate and fine root production rate^[30-32] and that dead roots are the main parent material of mangrove peat, based on the results of radiocarbon dating^[47]. In particular, it is thought that fine roots greatly contribute to soil carbon accumulation.

The percentage of allochthonous carbon is higher in deltaic environments than in other environments. Soil carbon content is high in the surface layer of coral reef-type (oceanic type) habitats and begins decreasing rapidly from approximately 1 m depth, whereas in estuarine type (riverine type) habitats, there is little change from the surface to approximately 2 m depth^[2]. This finding suggests that the origin of SOC in estuarine-type habitats may be mostly allochthonous carbon.

Research identifying that the supply of allochthonous carbon is associated with sediment transport in mangrove ecosystems began by elucidating the process of sediment flux related to tides and waves^[60,61]. In riverine-type (R-type) mangals facing tidal creeks, suspended sediment transport is predominant. Specifically, suspended sediment in the rising tide intrudes from the mouth of the river and creeks and inundates the forest floor, which has a high hydrodynamic drag force, reducing the flow speed and causing the suspended sediment to settle and accumulate on the floor. During ebb tide, the flow velocity in the forest is further slowed, and the tide drains for a long period of time, resulting in a phenomenon of high velocity in the creek where such drainage accumulates in different phases. Numerical models have confirmed that this phenomenon is caused by flow asymmetry during flood and ebb tides and that the asymmetry is controlled by the ratio of forest floor area to channel area, the tree density in the forest, and the slope of the forest floor^[62-64]. Numerical models of flow in mangrove forests are dominated by the modeling of drag forces by the aboveground root system and sediment transport mechanisms^[65-68]. Although it is difficult for such numerical models to predict topographic changes and vegetation changes caused by long-term flow-sediment interactions, attempts to determine this information have been implemented in recent years^[69].

Because these flows rarely exceed 1 m s^{-1} and are on the order of 0.1 m s^{-1} on the forest floor, sediment transport in the forest has been evaluated by vertically integrated, barotropic depth-averaged flow^[70]. However, this is not exactly the scenario during wave interaction. For example, when large wave action and complex root systems occur, such as during approaching typhoons, the vertical distribution of water particle movements becomes dominant^[71]. Some studies have calculated the aspect of rapid energy dissipation in forests from analytical solutions incorporated with vertical particle velocity distribution due to waves by using the potential connection method and separately calculated Reynolds-number-dependent expressions for the drag coefficient^[72]. Resuspension by flow has also been modeled, suggesting that the three-dimensional structure of the root system effectively reduces erosion on the forest floor^[73]. Comparisons with tidal flats have also shown that mangrove forests have almost 10 times higher wave attenuation rates^[74]. Thus, it can be inferred that resuspension and erosion due to direct wave action are negligible or minor in mangrove forests. Nevertheless, waves in the front area of a forest can have an indirect effect on sediment transport by increasing suspended sediment in the inundated water.

EARLY STUDIES ON PREDICTING THE IMPACTS OF SEA-LEVEL RISE

The ability of a mangrove forest to survive in the face of sea-level rise depends on the relative relationship between the possible accretion rate and the relative sea-level rise rate at a given location. The possible accretion rate at a site is determined by the sum of the deposition rate due to external sediment supply from

rivers and other sources and the accumulation rate of mangrove peat^[75-77]. Thus, if there is little or no sediment supply from the river, only the accumulation rate of the mangrove peat will determine the possible accretion rate at the site.

Therefore, earlier studies predicting sea-level rise impacts often used geomorphological and geological methods to estimate the extent to which a site could sustain its location in response to past sea-level rise based on the spatial distribution and depositional age of mangrove peat and other mangrove forest floor sediments^[79,78-81]. Most of these studies concluded that mangrove peat deposition could only catch up to sea-level rise from approximately 1 mm to less than 5 mm year⁻¹, except for one case study^[9] [Table 1]. Thus, pessimistic predictions stated that mangrove forests, which are supported by peat accumulation, would have difficulty maintaining their habitat if sea-level rise progressed at a rate faster than the moderate sea-level rise rate projected by the IPCC.

ACTUAL IMPACTS OF SEA-LEVEL RISE

According to the IPCC's latest sixth assessment report^[82], the global mean rate of sea-level rise was 1.73 mm year⁻¹ from 1901-2018, but it was 2.33 mm year⁻¹ between 1971 and 2018, 3.25 mm year⁻¹ between 1993 and 2018 and 3.69 mm year⁻¹ for 2006-2018, indicating an accelerating trend in recent years. The fifth assessment report^[83] reported that sea level rose at a rate exceeding 10 mm year⁻¹ during 1993-2010 in the low latitudes of the northwestern Pacific Ocean from the Philippines to Micronesia.

On Pohnpei Island, Federated States of Micronesia, the sea-level rise was measured at a rate of 1.9 mm year⁻¹ from 1974 to 2004 but 5.4 mm year⁻¹ from 2002 to 2020, which was faster than the global mean in recent years^[10]. Furthermore, rapid sea-level rise of 8.3 mm year⁻¹ during 1993-2010 and 16.0 mm year⁻¹ during the short period of time from 2002-2010 have been observed, as noted by the IPCC^[83], and levels even exceeding these have been measured^[10].

Therefore, some mangrove communities on Pohnpei Island have already experienced significant surface erosion, while in the *Rhizophora* communities, the ground level is rising due to the accumulation of mangrove peat^[10]. The communities that showed surface erosion were the *Sonneratia alba* community located on the seaward front and the *B. gymnorrhiza* community, where vegetation succession has reduced the tree density of *Rhizophora* species. According to observations of changes in the height above the ground surface of piles inserted until they reach the base rock, surface erosion rates ranged from 0.4 to 2.8 mm year⁻¹ in the *S. alba* community and 4.2 mm year⁻¹ in the *B. gymnorrhiza* community. On the other hand, ground elevation increased from 2.8 to 7.6 mm year⁻¹ in the *R. stylosa* community and from 2.3 to 3.4 mm year⁻¹ in the *Rhizophora apiculata* community^[10]. The *B. gymnorrhiza* community, where surface erosion was observed, is located behind the *R. stylosa* community, a seaward frontal edge community approximately 40 m wide [Figure 2]. The ground surface is covered with exposed knee roots of *B. gymnorrhiza*, creating a landscape that is distinctly different from the typical habitat [Figure 3]. A fixed plot 20 m wide and 130 m long (plot code: PK) was established in 2017 within the *B. gymnorrhiza* community, perpendicular to the shoreline; for all trees above breast height (1.3 m) in the plot, tree species, stand position, and diameter (30 cm above the highest prop root for *R. apiculata* and 1.3 m above the ground surface for other tree species) were determined, and a detailed level survey was conducted to map the topography and vegetation distribution [Figure 4]. Elevation was calculated using the tide table for Madolenihmw, located in the southeastern part of the island, and the specific elevation from the tide level at the time of the survey.

Table 1. Possible rate of mangrove peat accumulation estimated by geomorphological and geological methods

Related papers	Method	Estimated upper limit of mangrove peat accumulation rate (mm year ⁻¹)	Region
Ellison and Stoddart (1991) ^[77]	¹⁴ C	0.8-1.2	Florida, Australia and Pacific islands
Parkinson et al. (1994) ^[78]	¹⁴ C	1	Caribbean region
	¹³⁷ Ce ²¹⁰ Pb	3.7	
Macintyre et al. (1995) ^[79]	¹⁴ C	4.3	Belize
Miyagi et al. (1995) ^[80]	¹⁴ C	2 or more and less than 5	Philippines and Micronesia
Fujimoto et al. (1996) ^[9]	¹⁴ C	2 or more and less than 10	Kosrae Island, Micronesia
Mckee et al. (2007) ^[81]	¹⁴ C	3.5 or more and less than 5	Belize



Figure 2. Satellite image around the *Bruguiera gymnorrhiza* dominant community plot (PK) undergoing surface erosion on Pohnpei Island, FSM, taken by WorldView-3 on March 3, 2020. Source: ©NTT DATA, Included ©Maxar Technologies, Inc. The dark green zone on the seaward (right) side of the plot is a *Rhizophora stylosa* community. White dots indicate the point where the root gap height of *B. gymnorrhiza* was measured, shown in Figure 6.

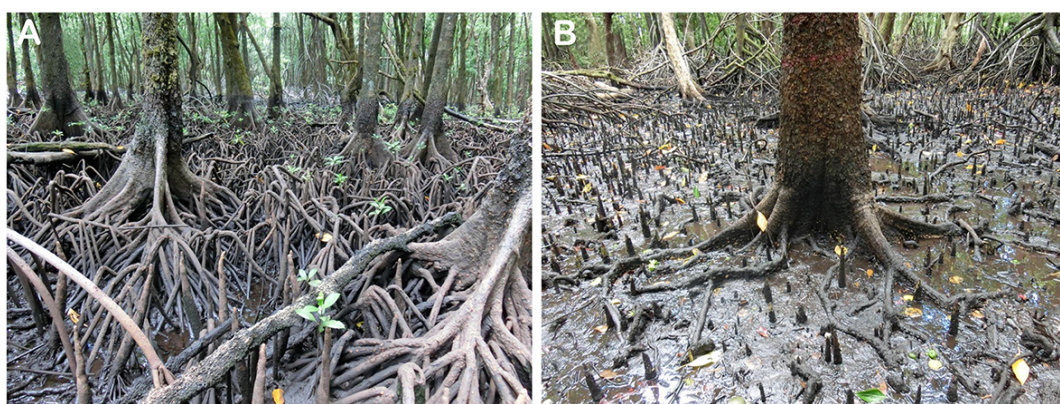


Figure 3. (A) *Bruguiera gymnorrhiza* community undergoing surface erosion on Pohnpei Island, where the knee roots of *B. gymnorrhiza* are exposed (after Fujimoto et al., 2023^[10]). (B) Normal *B. gymnorrhiza* root zone on Pohnpei Island.

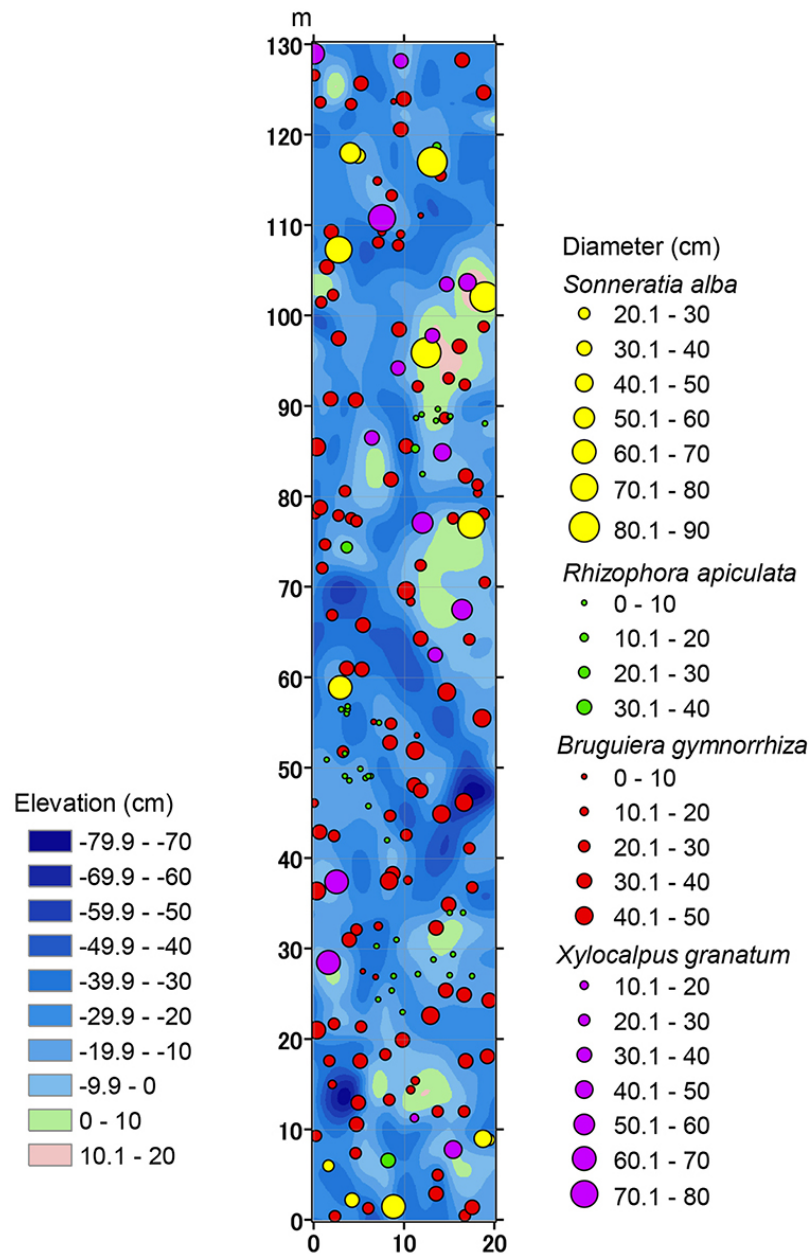


Figure 4. Ground elevation and vegetation distribution in PK, which is a fixed plot established in 2017 in a *Bruguiera gymnorrhiza*-dominated community undergoing surface erosion on Pohnpei Island, FSM.

Ground elevation in this community is mostly below the mean sea level [Figure 4]. Considering that mangrove habitats are usually established above mean sea level, it is clear that surface erosion has progressed. A 4.2 mm year^{-1} decrease in ground elevation was observed in the *B. gymnorrhiza* community^[10]. When the height of the gap at the base of the *B. gymnorrhiza* [Figure 5] was measured from seaward to inland, the gap height was more than 40 cm approximately 50 m from the forest edge, but almost no gap was detected at approximately 350 m [Figure 6], indicating that surface erosion is more pronounced on the seaward side. The fact that the amount of surface erosion is greater on the seaward side probably means that the erosive force is stronger seawards.



Figure 5. Gap at the base of *Bruguiera gymnorhiza*. As an indicator of surface erosion, the height from the top of the gap to the ground surface was measured as indicated by both arrows.

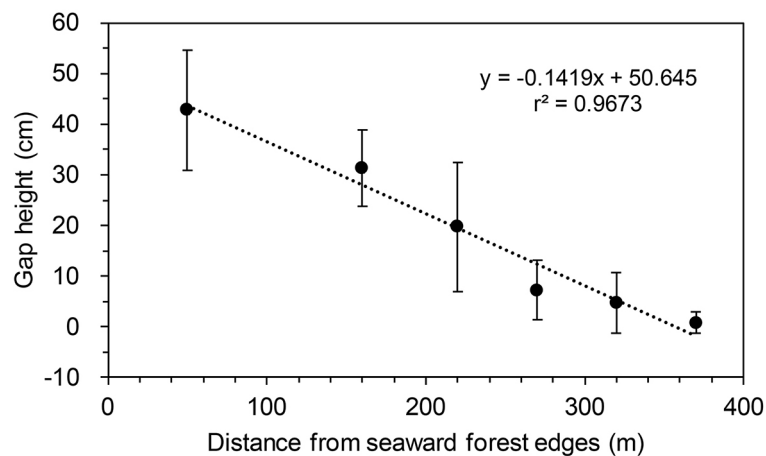


Figure 6. Relationship between the gap height at the base of *Bruguiera gymnorhiza* and the distance from the seaward forest edge. The number of samples for which the gap height was measured is 22, 12, 9, 9, 7, and 8, respectively, from the seaward side.

Trees with respiratory roots, such as *B. gymnorhiza* and *S. alba*, extend their cable roots several tens of centimeters deep belowground, and at regular intervals, they extend their respiratory roots to the surface, generating fine roots at the base of the respiratory roots. When the cable roots of *S. alba* are exposed on the ground surface at sites with advanced surface erosion [Figure 7], surface erosion progresses to the depth of the cable roots.

Observational studies of detailed ground-elevation dynamics in mangrove habitats from the Caribbean to the Pacific have also found declines in ground elevation in some communities^[81,84,85], but they attribute this primarily to the decomposition and compaction of mangrove peat and not to the effects of surface erosion.



Figure 7. Cable roots of *Sonneratia alba* exposed on the ground surface on Pohnpei Island, FSM. Yellow arrows indicate exposed cable roots.

In the Asia-Pacific region, mangrove peat is generally found only in habitats of *Rhizophora* spp.^[39-41], although it is also found in communities that have transitioned from *Rhizophora* communities to other species through vegetation succession on Pohnpei Island, and its main matrix consists of very fine roots less than 0.5 mm in diameter^[32]; in addition, fine root productivity is reported to be higher for *Rhizophora* spp. than for other mangrove species^[31,32]. On Kosrae Island in Micronesia, it has been reported that the root productivity of *S. alba* is higher than that of *R. apiculata* and *B. gymnorrhiza*^[28]. This may be due to the use of ingrowth cores with a mesh size of 1 cm, which allowed for the mixing of large roots as well as fine roots. Large roots, which are not the main parent material of mangrove peat, even in small quantities, have a significant influence on weight and can lead to overestimation of the rate of mangrove peat accumulation.

Coral reef-type mangrove forests in Micronesia generally first establish pioneer communities of *R. stylosa*, followed by a transition to *R. apiculata* communities as ground elevation increases, and then to *B. gymnorrhiza* communities^[86]. Based on the abovementioned surface erosion^[10] and differences in fine-root productivity by tree species^[32], it was concluded that mangrove peat accumulation did not keep pace with the recent rapid sea-level rise in forests where the tree density of *Rhizophora* spp. has decreased due to succession and that the peat layer above the cable roots of *B. gymnorrhiza* and *S. alba*, where fine-root production is difficult, was eroded. On the other hand, *R. stylosa* and *R. apiculata* communities appear to be able to keep pace with the 5-8 mm year⁻¹ sea-level rise by concentrating their productivity on fine roots. Ground elevation increases of 2.3-7.6 mm year⁻¹ have been measured in the *Rhizophora* communities^[10]. Thus, mangrove peat accumulation rates of < 5 mm year⁻¹ estimated by early geomorphological and geological methods^[7,78-81] were averaged over hundreds to thousands of years and did not take into account the effect of the decrease in mangrove peat accumulation rate due to vegetation succession during that period. The low mangrove peat accumulation rates estimated by earlier methods were likely also influenced by post-depositional compaction.

On the other hand, aerial drone photos show declining and defoliated trees in the *R. stylosa* forest [Figure 8]. The community has been characterized by densely developed prop roots, and as much as 60%



Figure 8. Aerial photo taken by drone (DJI Phantom4 PRO) of *Rhizophora stylosa* forest on Parempei Island in Pohnpei Lagoon, FSM, on September 8, 2017. Declining and deciduous trees are abundant, especially at the seaward forest edge.

(199 Mg ha⁻¹) of the aboveground biomass (327 Mg ha⁻¹) in 2019 was prop root biomass. In addition, 81% (4.6 Mg ha⁻¹ year⁻¹) of the average aboveground biomass accumulation rate between 2003 and 2019 (5.7 Mg ha⁻¹ year⁻¹) was prop root increase^[10]. This scenario suggests that these trees are trying to survive by concentrating their productivity on their roots and producing mangrove peat in response to the recent rapid rise in sea level. In the *R. stylosa* forest, especially at the seaward forest edge, fine root production relative to aboveground production is also extremely high compared to that in other communities^[32] [Figure 9]. The presence of trees of declining vigor suggests they are approaching the limits of their survival in response to the recent rapid rise in sea level.

On Pohnpei Island, extremely dense pneumatophores have also developed in *S. alba* communities located on the seaward front [Figure 10A]. Here, surface erosion has progressed at the seaward edge, roots less than 1 cm in diameter growing from the base of the pneumatophores have been exposed on the ground surface, and new pneumatophores have been generated in large quantities [Figure 10B]. This phenomenon may indicate that *S. alba* communities are also trying to survive by depositing mangrove peat by concentrating much of their productivity on pneumatophore production in response to sea-level rise; however, this deposition is not keeping pace with sea-level rise, resulting in surface erosion.

EFFECTS OF SEA-LEVEL RISE ON CARBON STORAGE

Surface erosion associated with sea-level rise means that the organic matter accumulated in sediments has been washed out of the system, indicating a decrease in the amount of carbon stored within mangrove ecosystems. The discharged organic matter is expected to be redeposited on the adjacent sea floor, where seagrass beds may form^[87-91].

In response to sea-level rise, mangrove forests that maintain their habitat solely through mangrove peat accumulation, as confirmed on Pohnpei Island, are thought to be attempting to survive by allocating much of their production to root production. However, since there is an upper limit to productivity, the rate of aboveground production will probably decrease during periods of sea-level rise as the amount allocated belowground increases. The fact that the aboveground biomass accumulation rate in Pohnpei (2.2-6.8 Mg ha⁻¹ year⁻¹)^[10], a humid tropical island with optimal climate conditions for the growth of mangrove forests, is not large compared to values in other tropical regions (1.4-24.1 Mg ha⁻¹ year⁻¹)^[12] is likely an indication of the effects of sea-level rise.

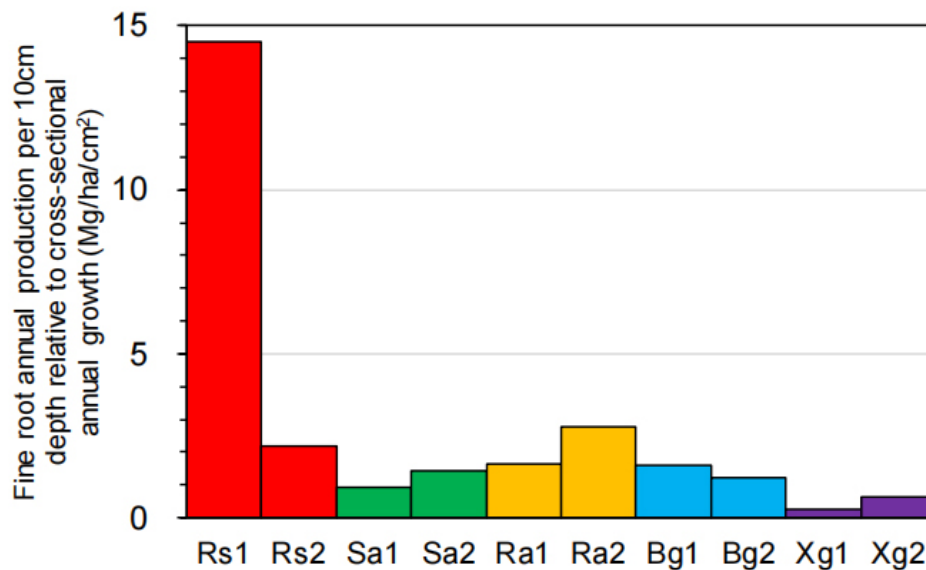


Figure 9. Fine root annual production per 10 cm in depth relative to cross-sectional annual growth among tree species on Pohnpei Island, FSM. Rs1: *Rhizophora stylosa* seaward site, Rs2: *R. stylosa* landward site, Sa1: *Sonneratia alba* seaward site, Sa2: *S. alba* landward site, Ra1: *Rhizophora apiculata* seaward site, Ra2: *R. apiculata* landward site, Bg1: *Bruguiera gymnorrhiza* seaward site, Bg2: *B. gymnorrhiza* landward site, Xg1: *Xylocarpus granatum* seaward site, and Xg2: *X. granatum* landward site. Created using data from Table 4 of Ono et al. (2022)^[32].



Figure 10. (A) Densely developed pneumatophores in a *Sonneratia alba* community on Pohnpei Island, FSM. (B) At the seaward forest edge, roots less than 1 cm in diameter at the base of the pneumatophores are exposed by surface erosion, while new pneumatophores occur in large numbers.

Mangrove forests, where belowground allocation is approaching the limits of productivity, will decline in vigor and eventually die back, as already seen in the *R. stylosa* communities on Pohnpei Island. Thus, the disappearance of coral reef-type (fringe-type) mangrove forests, which have served as valuable carbon storage sites through the accumulation of mangrove peat, will likely disappear. Based on the current status of Pohnpei Island, even if the sea-level rise continues to progress at the current global average rate, it is unlikely to immediately turn into a carbon release field, but the risk increases if it progresses above 8 mm year⁻¹, which is close to the maximum predicted by the IPCC^[82].

On the other hand, in delta-type (riverine-type) mangrove forests, where the habitat is maintained by sediment supply and root production, mangrove forests can persist as long as the rate of increase in ground

level is maintained and the sum of the two does not fall below the rate of sea-level rise. However, the belowground productivity of mangrove species growing in such habitats, such as *Sonneratia* spp, *Ceriops* spp. and *Xylocarpus* spp., is inferior to that of *Rhizophora* spp. [Figures 1 and 5]; therefore, we cannot place high expectations on belowground carbon accumulation. Nevertheless, communities with well-developed buttress roots and pneumatophores are likely to have a high capacity to capture and fix sediments containing organic matter entering from the catchment area, so although autochthonous belowground production is low, they may be able to contribute to carbon storage by fixing allochthonous carbon.

FUTURE RESEARCH DIRECTIONS

The surface erosion we have identified on Pohnpei Island and the rise in ground elevation associated with the deposition of mangrove peat in the *Rhizophora* communities may be underway in other areas of the Pacific. Surface erosion first occurs in locations with low sediment supply. Communities that have transitioned from pioneer *Rhizophora* communities in coral reef-type (fringe-type) habitats to species with relatively low fine-root productivity are at higher risk.

Thus, the effects of sea-level rise on mangrove ecosystems vary depending on the habitat conditions and community type. Therefore, to determine and predict the extent/rate of sea-level rise adverse effects such as surface erosion, a quantitative assessment at the community level based on the site environment and sediment budget, including the catchment area, is necessary. In conducting this assessment, the rate of ground-level change associated with the sediment flux by surface runoff and coastal processes and the rate of ground-level rise associated with the production/decomposition processes of the root system, and the main matrix of mangrove peat must be determined accurately and considered quantitatively in relation to the rate of sea-level rise.

Sea-level rise may affect sediment flux processes associated with tidal currents. In particular, an increase in mean water depth may increase surface erosive forces during ebb tides due to a relative decrease in drag forces from the bottom and root system. Although numerical models are already being developed to calculate such individual effects, it is assumed that, in practice, erosion will cause different scenarios for the flow structure. For example, exposure of the root system by erosion, including cable roots, will cause a three-dimensional flow structure and different drag formulas from the models. Therefore, future observational studies are needed to understand the actual condition of sediment transport in forests that are already eroding and in those that are not. In particular, it would be effective to conduct analysis from the viewpoint of hypothetical observations of predicted future changes by using the tidal cycle and changes in mean sea-level height and land water supply during wet and dry seasons.

In addition, the increase in mean water depth due to sea-level rise may reduce wave attenuation, causing increased wave sizes in adjacent areas (e.g., foreshore tidal flats and lagoons), thereby increasing sediment resuspension and erosion. Within forests, wave attenuation effects are not expected to be significant, but wave-induced resuspension in adjacent waters is expected to increase suspended sediment concentrations and increase the supply of sediment to mangrove channels and forests through advection. Because these processes are interconnected, it is important to develop a system dynamics model that integrates models of the network of water flow and sediment transport from the catchment to the coastal area [Figure 11].

A schematic diagram of such a model [Figure 11] shows that the upstream side of the watershed area is responsible for sediment supply through surface erosion caused by rainfall^[92], the coastal area is responsible for sediment supply from the ocean side through transport, sedimentation, and resuspension by tides, wind,

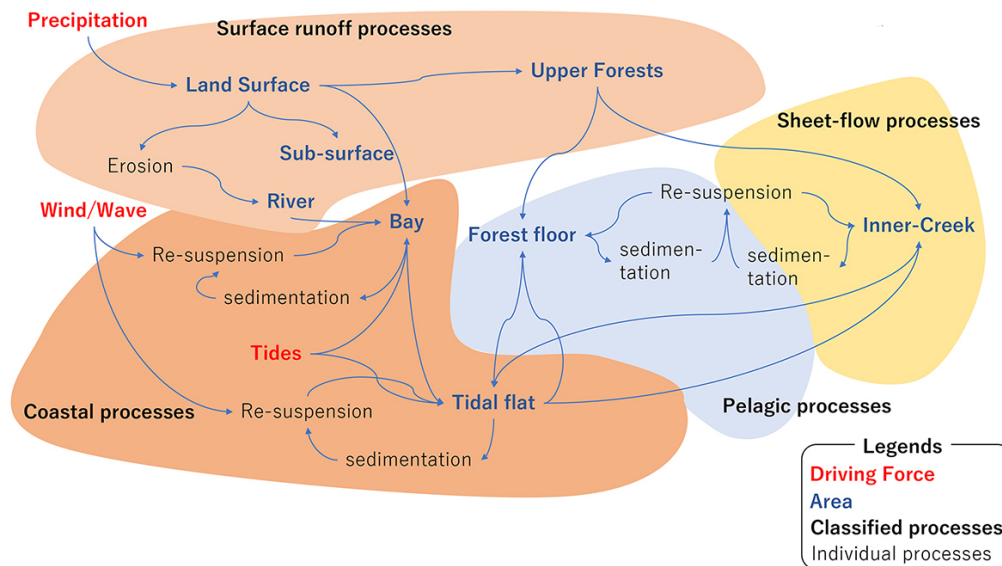


Figure 11. Schematic image of the system dynamics of the sediment transport model around estuarine-type mangrove habitats.

and waves^[93]; the mangrove forest area is sandwiched between the two areas. In mangrove forests, observations indicate the need to separately assess intensive sediment transport through secondary creeks and dispersed sediment transport over the flat forest floor (unpublished data by the authors). In order to proceed with these studies, it is necessary to accumulate further data and to construct and validate a specific model that reflects regional characteristics, which is an important issue to be addressed in the future.

For modeling and analysis of sediment transport processes, it is essential to observe the mangrove forest as an area and observe the sediment transport processes over the medium to long term (several weeks to several years) in the three-dimensional space surrounding the environment (catchment area, surface runoff area, and surrounding coasts and bay). In the future, it will be necessary to develop observation and monitoring systems that supplement the needed wide-area and long-term data from remote sensing data and meteorological data while conducting direct measurements with observation equipment and sediment traps in relevant areas.

On the other hand, to estimate the contribution of the root system to the increase in ground elevation due to production/decomposition processes, it is necessary to determine the amount of organic matter derived from roots in terms of volume rather than in terms of mass per unit volume. For this purpose, the sequential soil core method, which can determine the amount of root system-derived organic matter increase under steady-state conditions, is more effective than the ingrowth core method, which only observes the amount of newly produced roots. However, root distribution is not always uniform, so samples should be taken from a sufficiently large number of sites at intervals of several years.

Forest stands under increased stress due to sea-level rise will likely show signs of canopy vigor decline, as has been observed on Pohnpei Island. Periodic observations by drones are an effective way to identify such events quickly. In recent years, it has become possible to obtain satellite imagery with a resolution of approximately 30 cm, but it is still difficult to obtain images as clear as those obtained by drones.

On the other hand, satellite images are useful for tracking changes in mangrove distribution areas over a wide area. As sea level rises, mangrove forests will encroach inland. In areas where sediment supply is above a certain level, seaward expansion of mangrove forests will occur regardless of sea-level rise. However, we cannot identify any phenomena occurring in the forest, such as the surface erosion observed on Pohnpei Island. High-resolution satellite images can also be used to identify tree species to some extent, and when combined with LiDAR using UAV, it is possible to estimate aboveground biomass for each community based on tree height^[22,23]. However, it is difficult to determine the impact that sea-level rise has on aboveground and belowground productivity. Such an ongoing phenomenon in a forest can only be determined through long-term monitoring studies in permanent plots^[10].

The USGS, with the USDA Forest Service, developed a simulation model to predict the effects of sea-level rise on species composition and their persistence in mangrove forests on Pohnpei Island by predicting changes in ground level based on organic matter supply and decomposition from aboveground and belowground sources and inorganic matter deposition estimated from the deposition period of soil cores^[94]. However, the data on belowground production used in that model^[29] are likely an underestimate^[32]. As we have noted in this paper, although sea-level rise may affect the sediment inflow/outflow process associated with tidal currents, it has not been taken into account in the model. Furthermore, the simulations are based on the assumption that changes in relative ground elevation associated with sea-level rise will cause changes in species composition, but because other factors such as light environment also affect species succession, a decrease in relative ground elevation associated with sea-level rise may not immediately cause succession to species that prefer lower ground elevations. On Pohnpei Island, there has been no actual invasion of *R. stylosa*, which is distributed at lower ground elevations, into the *B. gymnorrhiza* community, where surface erosion has reduced ground elevation. For more reliable simulations, it is necessary to improve the current simulation model based on the above issues and further gather more reliable field data for use.

The effects of sea-level rise on mangrove ecosystems extend beyond simply reducing carbon storage sites. A mangrove ecosystem, a boundary between land and sea, is also a living place for many organisms. The loss of ecosystems as refuges for juvenile fish can lead to the degradation of not only coastal ecosystems but also marine ecosystems at a global scale. Many of the vast mangrove forests that once stretched across large deltas have already been lost, often due to the development of agricultural land and shrimp ponds. The effects of sea-level rise will first appear in locations with low sediment inflow where mangrove peat accumulates. It is important that we intensify monitoring now in such mangrove ecosystems to accurately catch the phenomena that are currently occurring and disseminate this information widely.

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Authors' contributions

Conceived and designed the study: Fujimoto K

Wrote the text: Fujimoto K, Furukawa K, Ono K

Created figures and tables: Fujimoto K, Furukawa K

Obtained drone aerial photography and conducted data analysis: Watanabe S
Conducted the field survey in Pohnpei: All authors

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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