Aboveground Dynamics and Productivity of Major Mangrove Communities on Pohnpei Island, Federated States of Micronesia

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Abstract

The aboveground dynamics, biomass, productivity and carbon storage rate of major mangrove communities on Pohnpei Island, Federated States of Micronesia, were estimated using census data obtained from two 1-hectare permanent plots during about two decades. The aboveground biomass increased from 526 t ha^{-1} in 1994 to 572 t ha^{-1} in 2010 for the plot situated in a coral reef-type habitat, referred to as PC1, and from 637 t ha^{-1} in 1994 to 744 t ha^{-1} in 2011 for the plot situated in an estuary-type habitat, referred to as PE1. Both were higher than any other estimates for mangrove forests throughout the world, though the tree density decreased from 1,558 trees ha^{-1} to 1,074 trees ha^{-1} in PC1 and from 651 trees ha^{-1} to 473 trees ha^{-1} in PE1. The ratio of trees cut by local residents to all deceased trees was higher in PC1 (35%) than PE1 (15%) because of different accessibility. The potential rates of aboveground carbon storage were estimated at 1.66 t C ha^{-1} yr^{-1} for PC1 and 2.79 t C ha^{-1} yr^{-1} for PE1. The difference was considered to have resulted from different stages of succession and site environments, such as soil water EC, ground elevation and frequency of submergence by tides.

Key words: aboveground biomass, carbon storage, forest dynamics, forest productivity, mangrove

1. Introduction

Micronesian mangrove forests situated in the mid-tropics are expected potentially to have the highest productivity among the earth's mangrove forests because of optimal climatic conditions for the growth of mangrove trees. Studies of tree biomass and productivity contribute to the creation of a sustainable forest management system and evaluation of the ability of forests to absorb carbon dioxide. Komiyama *et al.* (2008) investigated the tree biomass and productivity of mangrove forests by reviewing 23 and 11 papers, respectively, on these topics, published since the 1960s, which constituted almost all of studies published in the field as of that time. The biomass study areas were distributed worldwide in tropic-subtropical regions, though Micronesian mangrove forests were not included. The productivity study areas, however, were limited to South to Southeast Asia, Central America and Florida.

The USDA Forest Service conducted forest inventories of Micronesian mangrove forests between 1985 and 1996 (*e.g.*, MacLean *et al.*, 1986, 1988; Devoe, 1992; Devoe & Cole, 1998; Ewel *et al.*, 1998). The inventories established 65 permanent plots that were randomly located in >12,500 ha of mangrove forests in the Federated States of Micronesia and Palau (Cole *et al.*, 1999). Cole *et al.* (1999) estimated tree volumes and diameter growth rates of major mangrove species on Micronesian islands using these data. The biomass and productivity of the main mangrove communities, however, were not calculated.

We established two 1-hectare permanent plots in the major mangrove communities of Pohnpei Island in the Federated States of Micronesia in 1994 to observe the forest dynamics and productivity (Fujimoto *et al.*, 1995). This paper describes the forest dynamics, estimates aboveground productivity, and discusses the carbon sequestration ability of these forests.

2. Regional Settings

Pohnpei is a high oceanic island of about 35,500 ha consisting of Tertiary volcanic rocks and is surrounded by barrier reefs (Fig. 1b). The average annual rainfall is 4,745 mm with no apparent dry season, and the annual mean temperature is 27.1°C with less than 1°C of annual variation (Western Regional Climate Center, 2012). The mean tidal range at Pohnpei Harbor is about 70 cm, and the diurnal tidal range is approximately 104 cm (NOAA, 2010).

Mangrove habitats have developed mainly on the reef flats fringing the island, although some of them are situated in estuaries (Fig. 1b). The former habitat is referred to as the coral reef type and the latter as the estuary type (Fujimoto *et al*., 1995). The substrata of these mangrove habitats mainly consist of peat (Miyagi & Fujimoto, 1989; Fujimoto & Miyagi, 1993; Fujimoto *et al*., 1995, 1999). The mangrove forests on Pohnpei Island have not significantly suffered from human impact; therefore a clear zonation of mangrove communities can be found.

Based on the phytosociological method, the mangrove forests in Pohnpei have been classified into three community types, along with six subcommunities and five subunits, by Mochida *et al*. (2006). The community types are as follows:

I. the *Rhizophora stylosa* community, with three subcommunities:
   (1) the typical subcommunity,
   (2) the *Enhalus acoroides* subcommunity, and
   (3) the *Bruguiera gymnorrhiza* subcommunity.
II. the *Sonneratia alba* community, and
III. the *Rhizophora apiculata – B. gymnorrhiza* community, with three subcommunities:
   (1) the typical subcommunity,
   (2) the *S. alba* subcommunity, with three subunits:
       a) the typical subunit, b) the *Xylocarpus granatum* subunit, and c) the *Lumnitzera littorea* subunit, and
   (3) the *X. granatum – Heritiera littoraris* subcommunity, with two subunits:
       a) the typical subunit and b) *Barringtonia racemosa* subunit.

Communities I and II develop along the seaward edge of coral reef-type habitat. Communities III(1) and III(2)a develop in coral reef-type habitat with a mangrove peat layer less than 1 m thick, and community III(2)b, which occupies the widest area of the mangrove forests in Pohnpei, develops in coral reef-type habitat with a mangrove peat layer more than 1 m thick, usually around 2 m, and estuary-type habitats with a deep mangrove peat layer, usually 3 to 5 m. Communities III(2)c and III(3) are usually found in landward and relatively high elevation areas (Fujimoto *et al*., 2006).
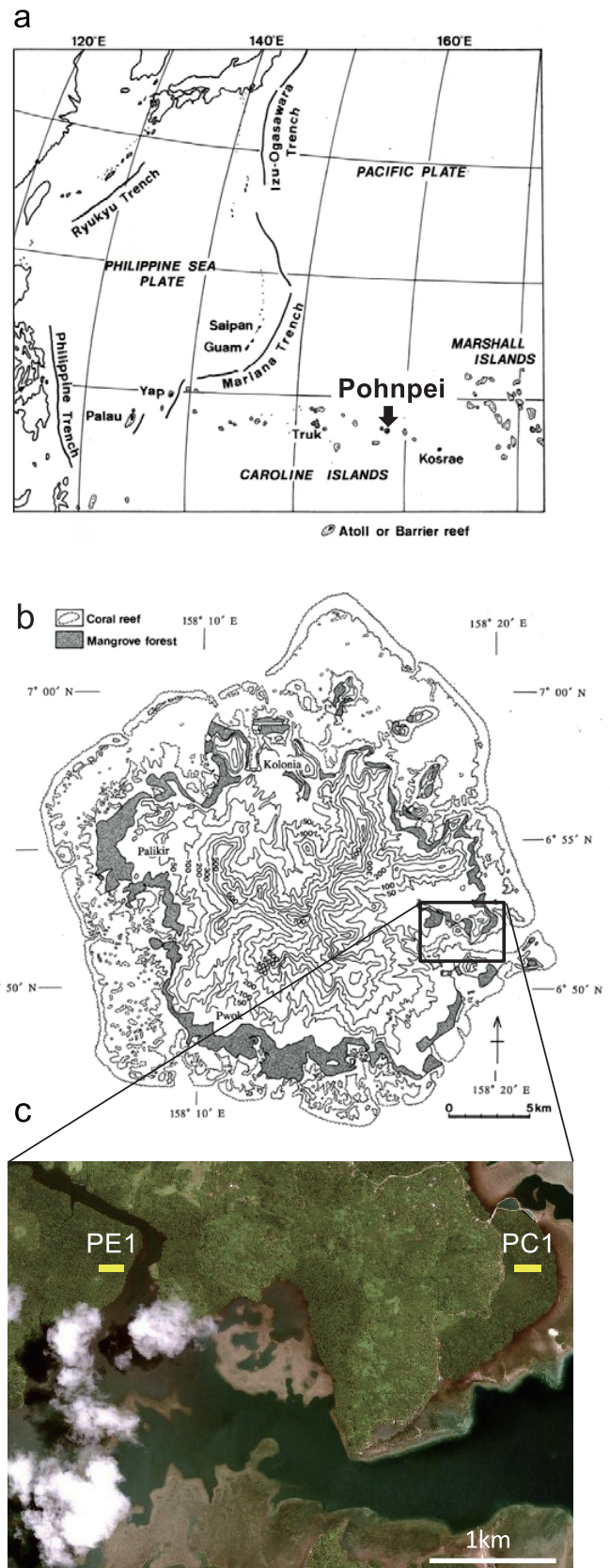
Fig. 1 Map showing the location of Pohnpei Island (a), landform of Pohnpei Island and distribution of mangrove habitats (b; after Fujimoto *et al*., 1995) and the location of the permanent plots (c; satelite photo taken by QuickBird on Aug. 15, 2003).
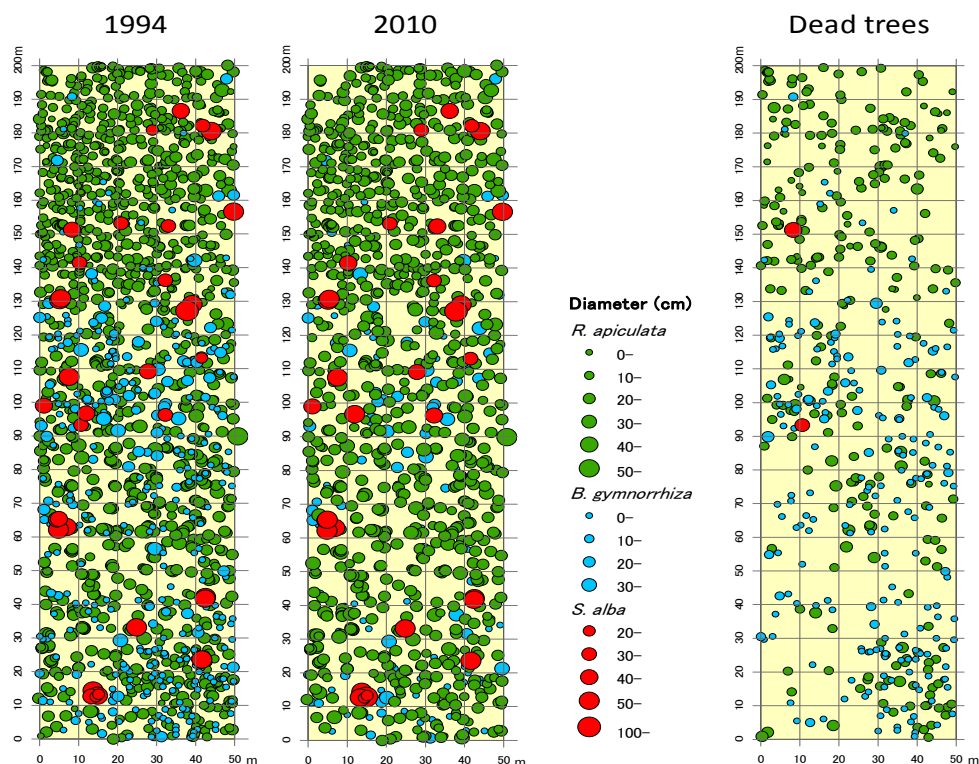
Fig. 2 Distribution of living trees by species and diameter in 1994 and 2010 and locations of trees that died or were harvested between 1994 and 2010 in PC1. The 0 m line of the vertical axis is situated in the direction of the sea.

3. Methods

Two permanent plots 50 m wide and 200 m long were set up in a III(2)a community in a coral reef-type habitat at right angles to the coast line and a III(2)b community in an estuary-type habitat at right angles to the river channel, located in the eastern part of Pohnpei Island, and were named PC1 and PE1, respectively (Fig. 1c).

Tree censuses were carried out in February 1994, March 1997, December 1999, and September 2002, 2004 and 2010 for PC1 and in February 1994, March 1997, December 1999, August 2003, and September 2005 and 2011 for PE1. All trees taller than 1.3 m were numbered, and their position, species and stem diameter, at 30 cm above the root collar for *R. apiculata* and DBH for the other species, were recorded. Tree height was calculated using equations created from the relationship between diameter and height of sample trees for each species (Tabuchi *et al.*, 2006). Tree biomass was estimated using allometric relationship equations from Komiyama *et al.* (1988).

4. Results

4.1 Forest dynamics

In PC1, three mangrove species, *i.e., R. apiculata, B. gymnorrhiza* and *S. alba*, were found (Fig. 2). Tree density decreased from 1,558 trees ha^{-1} in 1994 to 1,074 trees ha^{-1} in 2010 (*R. apiculata*: from 1,173 to 896 trees ha^{-1}, *B. gymnorrhiza*: from 351 to 146 trees ha^{-1}, *S. alba:* from 34 to 32 trees ha^{-1}). In particular, *B. gymnorrhiza* smaller than 10 cm in diameter and *R. apiculata* smaller than
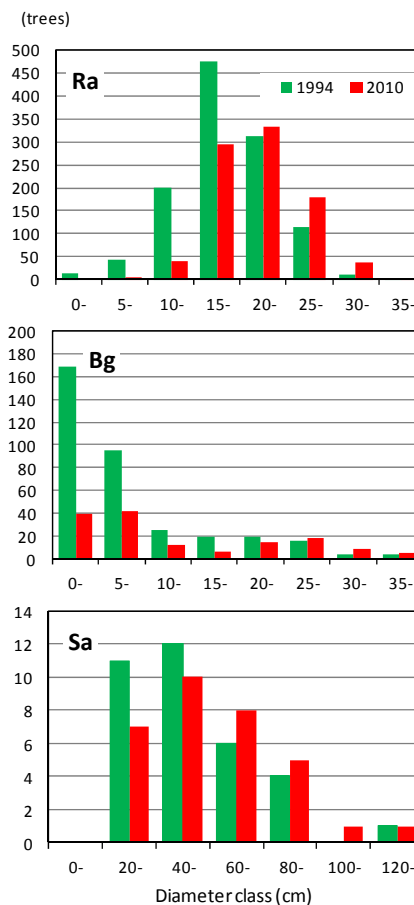
Fig. 3 Frequency distribution of diameter classes of respective species in PC1 in 1994 and 2010. Ra: *R. apiculata*, Bg: *B. gymnorrhiza*, Sa: *S. alba*.

15 cm in diameter dramatically declined from 264 to 81 trees ha^{-1} and from 256 to 46 trees ha^{-1}, respectively (Fig. 3). The average tree diameters of each species increased from 18.6 to 22.0 cm for *R. apiculata*, from 8.6 to 13.7 cm for *B. gymnorrhiza* and from 53.9 to 60.1 cm for *S. alba* during the period.

Sixty-five percent of the dead trees had been killed by natural factors such as dieback and windfall, while 35% of them had been cut by local residents. Looking at the causes of death by species and diameter class, natural deaths of *B. gymnorrhiza* (hereafter referred to as Dead
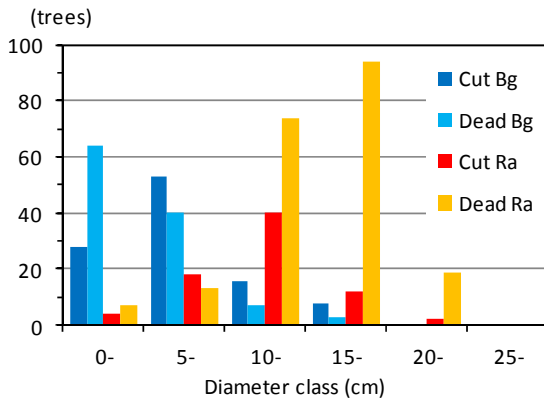
Bg) and *R. apiculata* (hereafter referred to as Dead Ra) occurred most frequently for trees of less than 10 cm in diameter and between 10 and 20 cm in diameter, respectively. Harvested *B. gymnorrhiza* (hereafter referred to as Cut Bg) and *R. apiculata* (hereafter referred to as Cut Ra) were most frequently less than 10 cm in diameter and around 10 cm in diameter, respectively (Fig. 4). The average diameters of Dead Bg, Dead Ra, Cut Bg and Cut Ra were 5.5 ± 3.5 cm, 14.9 ± 4.1 cm, 7.6 ± 3.9 cm and 11.9 ± 4.0 cm, respectively. Significant differences in diameter were found between Dead Bg and Dead Ra (p<0.001, Welch's *t*-test), Dead Bg and Cut Bg, Cut Bg and Cut Ra, and Dead Ra and Cut Ra (p<0.001, Student's *t*-test).

In PE1, four mangrove species, *i.e.*, *R. apiculata*, *B. gymnorrhiza*, *S. alba* and *X. granatum*, were found (Fig. 5). Tree density decreased from 651 trees ha^{-1} in 1994 to 473 trees ha^{-1} in 2011 (*R. apiculata*: from 369 to 285 trees ha^{-1}, *B. gymnorrhiza*: from 184 to 110 trees ha^{-1}, *S. alba:* from 34 to 31 trees ha^{-1}, *X. granatum*: from 64 to 47 trees ha^{-1}). Most dramatically, *B. gymnorrhiza* smaller than 10 cm in diameter declined from 81 to 29 trees ha^{-1}, *X. granatum* smaller than 15 cm in diameter declined from 16 to 4 trees ha^{-1}, and *R. apiculata* smaller than 20 cm in diameter declined from 156 to 45 trees ha^{-1} (Fig. 6). The average tree diameters of each species increased from 21.8 to 27.6 cm for *R. apiculata*, from 23.1 to 32.3 cm for *B. gymnorrhiza*, from 86.6 to 99.3 cm for *S. alba* and from 28.9 to 37.0 cm for *X. granatum* during the period.

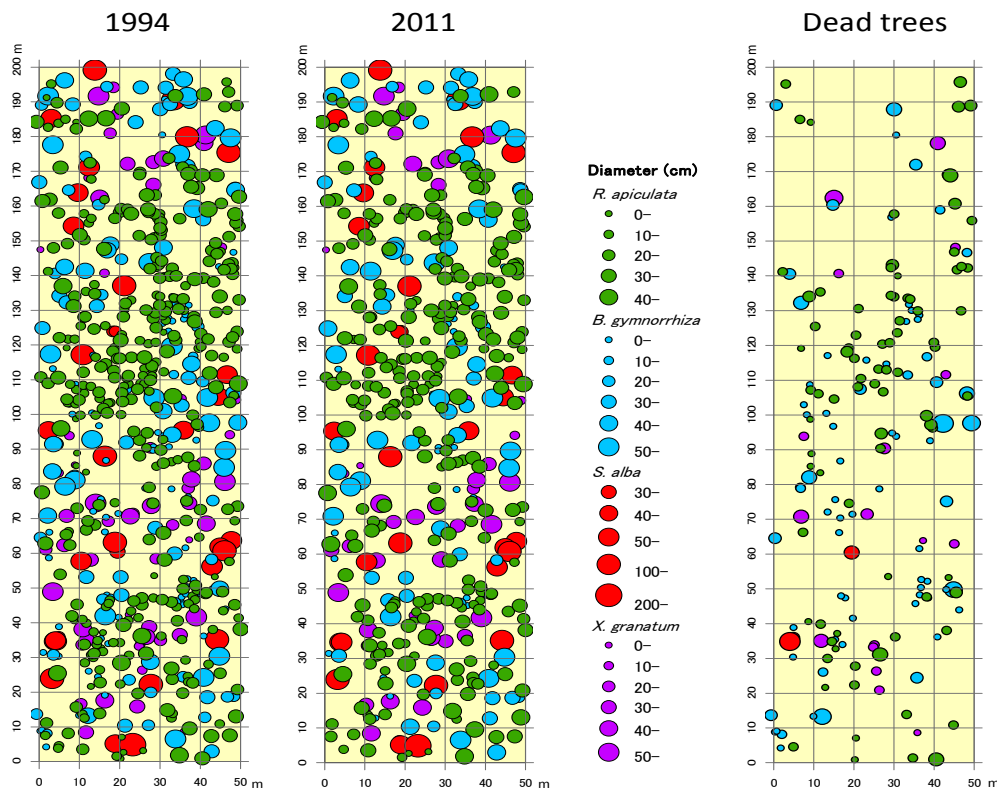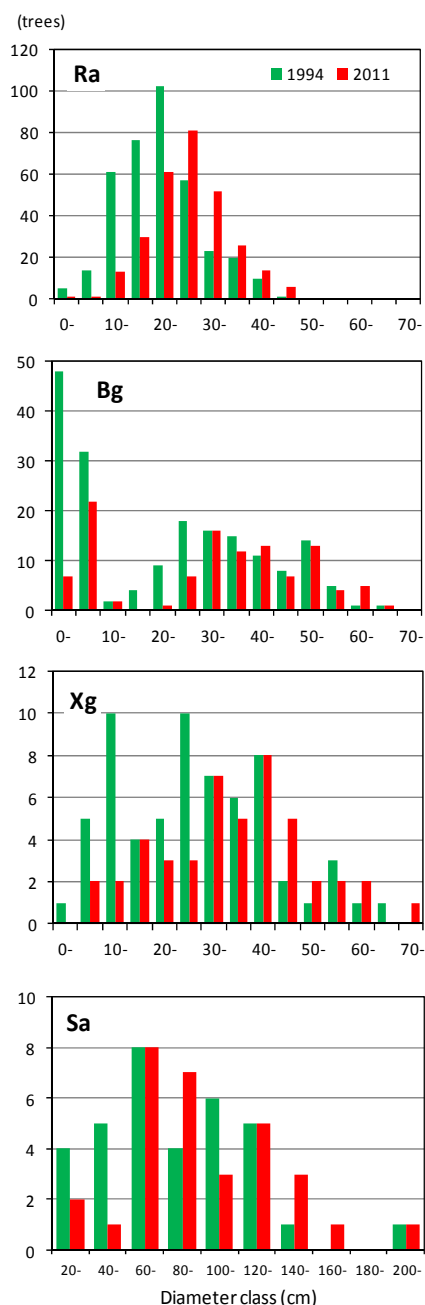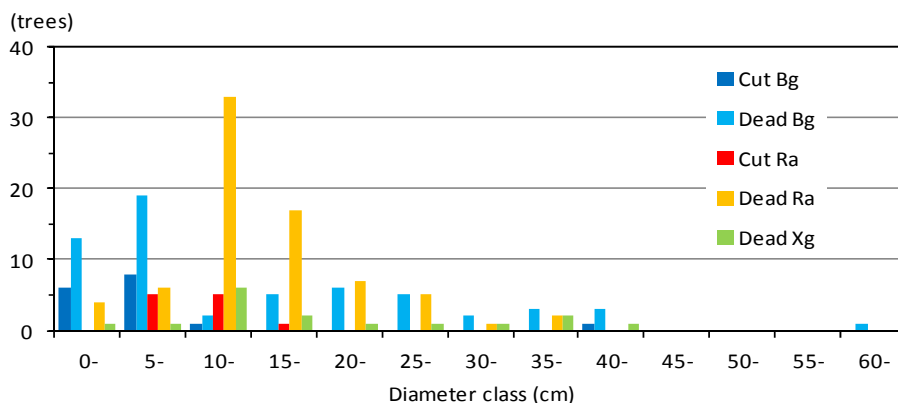Eighty-five percent of dead trees had been killed by

Fig. 4 Frequency distribution of diameter classes of deceased trees by species and causes in PC1 between 1994 and 2010. Cut Bg: harvested *B. gymnorrhiza*, Dead Bg: *B. gymnorrhiza* that died a natural death, Cut Ra: harvested *R. apiculata*, Dead Ra: *R. apiculata* that died a natural death.

Fig. 5 Distribution of living trees by species and diameter in 1994 and 2011 and locations of trees that died or were harvested between 1994 and 2011 in PE1. The 0 m line of the vertical axis is situated in the direction of the sea.

Fig. 6 Frequency distribution of diameter classes of respective species in PE1 in 1994 and 2011. Ra: *R. apiculata*, Bg: *B. gymnorrhiza*, Xg: *X. granatum*, Sa: *S. alba*.

natural factors, while 15% had been cut by local residents. Looking at the causes of death by species and diameter class, Dead Bg and Dead Ra were most frequently less than 10 cm in diameter and between 10 and 20 cm in diameter, respectively, though larger dead trees were also found, and Cut Bg and Cut Ra were most frequently less than 10 cm in diameter and between 5 and 10 cm in diameter, respectively (Fig. 7). The average diameters of Dead Bg (one at 64.8 cm was declared an outlier by Smirnov-Grubbs rejection test (P<0.01)), Dead Ra, Cut Bg (one at 40.6 cm was declared an outlier by Smirnov-Grubbs rejection test (P<0.001)) and Cut Ra were 14.6 ± 12.3 cm, 15.8 ± 6.8 cm, 5.9 ± 2.0 cm and 10.9 ± 2.3 cm, respectively. Significant differences in the average diameter were found between Dead Bg and Cut Bg (p<0.001, Welch's *t*-test), Cut Bg and Cut Ra (p<0.001, Student's *t*-test), and Dead Ra and Cut Ra (p<0.001, Welch's *t*-test).

4.2 Aboveground productivity

In PC1, the total aboveground biomass increased from 526 t ha^{-1} in 1994 to 572 t ha^{-1} in 2010 (*R. apiculata*: from 396.5 to 425.4 t ha^{-1}, *B. gymnorrhiza*: from 26.6 to 26.9 t ha^{-1}, *S. alba*: from 102.7 to 120.1 t ha^{-1}) (Fig. 8). The average annual increment rate between 1994 and 2010 was calculated to be 2.81 t ha^{-1} yr^{-1}. On the other hand, the aboveground necromass arose at a rate of 3.67 t ha^{-1} yr^{-1} during the period, including the harvested necromass, which arose at a rate of 0.88 t ha^{-1} yr^{-1} (Fig. 9a). Dead Ra accounted for 69% of total annual necromass emergence.

In PE1, the total aboveground biomass increased from 637 t ha^{-1} in 1994 to 744 t ha^{-1} in 2011 (*R. apiculata*: from 195.8 to 238.2 t ha^{-1}, *B. gymnorrhiza*: from 109.3 to 121.9 t ha^{-1}, *S. alba:* from 287.9 to 331.7 t ha^{-1}, *X. granatum*: from 44.1 to 51.9 t ha^{-1}) (Fig. 8). The average annual increment rate between 1994 and 2011 was calculated to be 6.06 t ha^{-1} yr^{-1}. The aboveground necromass arose at a rate of 3.34 t ha^{-1} yr^{-1} during the period, including harvested necromass, which arose at a rate of 0.13 t ha^{-1} yr^{-1} (Fig. 9b). The ratios of Dead Ra, Dead Bg and Dead Sa to total annual necromass emergence were 35%, 27% and 26%, respectively.
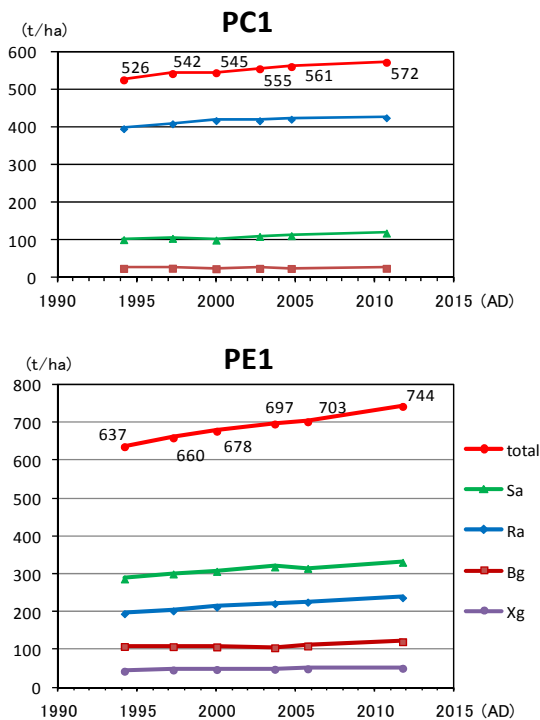

Fig. 7 Frequency distribution of diameter classes of deceased trees by species and causes in PE1 between 1994 and 2011. Cut Bg: harvested *B. gymnorrhiza*, Dead Bg: *B. gymnorrhiza* that died a natural death, Cut Ra: harvested *R. apiculata*, Dead Ra: *R. apiculata* that died a natural death, Dead Xg: *X. granatum* that died a natural death.

Fig. 8 Changes in aboveground biomass in PC1 and PE1. Ra: *R. apiculata*, Bg: *B. gymnorrhiza*, Sa: *S. alba*, Xg: *X. granatum*.
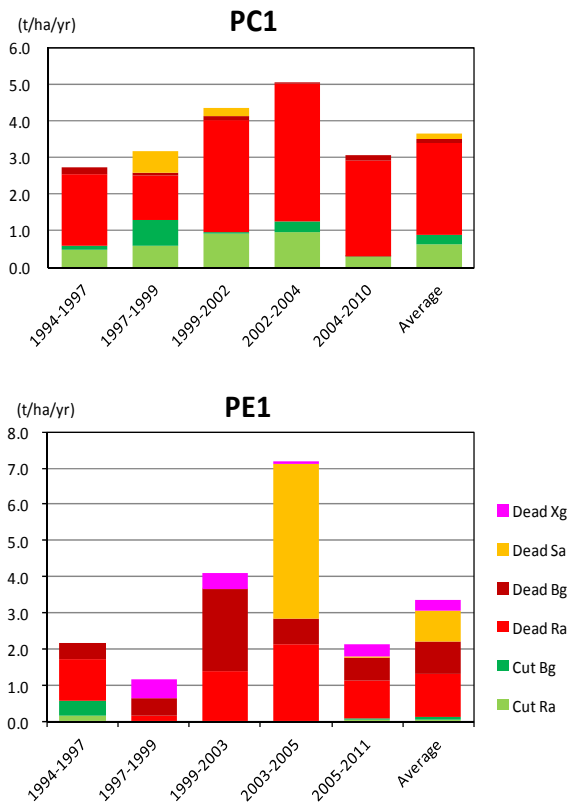
Fig. 9 Aboveground necromass occurrence rate between censuses and the average. Cut Bg: harvested *B. gymnorrhiza*, Dead Bg: *B. gymnorrhiza* that died a natural death, Cut Ra: harvested *R. apiculata*, Dead Ra: *R. apiculata* that died a natural death, Dead Xg: *X. granatum* that died a natural death.

5. Discussion

5.1 Differences in forest structure, dynamics and productivity between different community types

PC1, which is situated in a III(2)a community, has a mangrove peat layer less than 1 m thick, while PE1 situated in a III(2)b community has a mangrove peat layer more than 2 m thick (Fujimoto *et al.*, 1995). The radiocarbon ages obtained from the mangrove peat of PE1 indicate that the habitat is older than 2000 years (Fujimoto *et al.*, 1999), while that of PC1 is estimated to be younger than 1,000 years (Fujimoto *et al.*, 2006). The presence or absence of *X. granatum*, which is in PE1 but is not in PC1; and differences in tree density, which is higher in PC1 than PE1, and tree size, which is smaller in PC1 than PE1, seem primarily to be due to differences in stage of primary succession associated with habitat age. Additionally, disturbance by huge typhoons, such as in 1905, may have caused secondary succession partially (Imanishi & Kira, 1944).

Human impact has also affected the forest structures. The ratio of cut trees to all deceased trees was higher in PC1 than PE1, probably because of a difference in accessibility, namely, PC1 is located in a place which is approached easily from land, while PE1 can only be approached from the sea by boat. The high density of *R. apiculata*, which is a less shade-tolerant species (Kitao *et al.*, 2003) and usually dominates at relatively lower elevations than *B. gymnorrhiza* (Mochida *et al.*, 1999), in the landward part of PC1 (Fig. 2) seems to have been caused by severe human impact such as clear cutting.

The average diameter of Dead Ra was around 15 cm in both plots, while that of Dead Bg differed between PC1, at around 5.5 cm, and PE1, at around 15 cm. The main factor in natural deaths of *R. apiculata* in both plots and *B. gymnorrhiza* in PE1 was windfall, while that of *B. gymnorrhiza* in PC1 was dieback because most of them were shrubs of small diameter (Fig. 4).

Potential aboveground productivity, which is calculated by adding the rate of harvesting to the increment rate of aboveground biomass, was estimated to be 3.69 t ha^{-1} yr^{-1} for PC1 and 6.19 t ha^{-1} yr^{-1} for PE1, excluding litter production, which was estimated to be 15 t ha^{-1} yr^{-1} for PC1 by the litter trap method (Ono *et al.*, 2006). The difference in productivity between the two plots seems to have been caused by a difference in stage of primary or secondary succession and some site environmental factors, such as soil water EC, ground elevation and submergence frequency by tides. The soil water EC at 20 cm depth in 1994 (Fujimoto *et al.*, 1995) was significantly higher in the seaward part (up to the 50 m line from the seaward edge of the plot) of PC1, 45.5 ± 1.9 mS cm^{-1}, than that of PE1, 37.4 ± 2.4 mS cm^{-1} ($p<0.01$, Student's *t*-test), while no significant difference was found in the landward part. The ground elevation in 1994 was higher in PC1 than PE1, which means that the submergence frequency was lower in PC1 than PE1 (Fujimoto *et al.*, 1995). The ground elevation in PC1, especially in the landward part, where *R. apiculata*

dominates unnaturally, is possibly too high for optimal conditions for the growth of *R. apiculata*.

5.2 Carbon sequestration ability

The aboveground biomass was estimated to be 572 t ha^{-1} in 2010 for PC1 in a middle stage of primary succession and 744 t ha^{-1} in 2011 for PE1 at almost the climax stage of succession. These values were higher than any other estimates for mangrove forests in the previous studies compiled in Komiyama *et al.* (2008). The highest estimate in the previous studies was 460 t ha^{-1} for an *R. apiculata* dominant forest in Matang, Malaysia, by Putz and Chan (1986).

Pohnpei mangrove forests also store the largest amount of carbon in sediments in the Asia-Pacific Region, reaching about 650 t C ha^{-1} up to 1 m deep (Fujimoto, 2004). These facts suggest that among the earth's mangrove forests, Pohnpei's mangrove forests store the greatest amount of carbon per unit area.

The potential rates of aboveground carbon storage are estimated to be 1.66 t C ha^{-1} yr^{-1} for PC1 and 2.79 t C ha^{-1} yr^{-1} for PE1, supposing that the carbon content of a mangrove tree is 45% of its dry weight. The below-ground carbon burial rates during the stable and rising sea-level phases in Pohnpei were estimated to be 0.6 to 0.9 t C ha^{-1} yr^{-1} using radiocarbon ages obtained from bulk samples of mangrove peat (Fujimoto, 2004). Higher-precision estimates of the formative age of mangrove peat using the AMS radiocarbon dating method for non-reworked samples such as bark, excluding roots, and clarification of the mechanism of below-ground production and decomposition are needed in order to enable evaluation of the carbon sequestration abilities of the mangrove ecosystem accurately.

The constant increment of aboveground biomass in both plots suggests that the mangrove forests of Pohnpei have been managed sustainably at least during the last two decades. However, the sea-level rise induced by global warming, which is already observed to have been +1.8 mm yr^{-1} between 1974 and 2004 and +16.9 mm yr^{-1} between 2002 and 2010 at Pohnpei, though the cause of the rapid rise in recent years is not clear (Bureau of Meteorology, Australian Government, 2010), is possibly affecting the productivity and habitat conditions. Continuous monitoring of the permanent plots is needed in order to detect the effects of sea-level rise on mangrove ecosystems.

Acknowledgments

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Ryuichi TABUCHI is a senior researcher at the Forestry and Forest Products Research Institute Japan. Since studying in Thailand under a fellowship of the Thai Government when he was a graduate school student, he has continued to be attracted by the topic of forest ecosystems in the tropics and has been involved in several forest ecological studies in Southeast Asia and Pacific islands. His major interest is in swamp forests, particularly mangroves, which involve human activity as an important component and sustain the livelihood of local residents.

Yasumasa HIRATA

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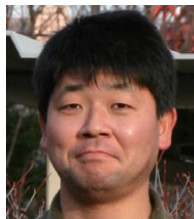
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