Mangrove development and carbon storage on an isolated coral atoll

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Abstract

This study investigates the functions and vulnerability of mangroves in isolated atoll settings, by showing the mangrove development and carbon storage, based on the radiocarbon ages and detrital organic-carbon contents of cores collected on Fongafale Islet, Funafuti Atoll, Tuvalu. The mangrove peat formed a thin veneer, several tens of centimeters thick, and mangrove development was constrained by the formation of the reef flat. The initial mangrove development (389 cal yr BP) was much more recent than on other islands, possibly because the island is remote and weakly connected to other source islands. However, the mangrove forests in Tuvalu have geomorphic developmental rates and carbon burial rates similar to those in other settings. The mean carbon sequestration rate is six times that calculated previously from land use, land-use change, and forestry (LULUCF) data for Tuvalu. High vulnerability of the mangroves is suggested by the small sediment thickness and recent development of the mangrove forests, as well as by the past vertical accumulation rates potentially smaller than those of future sea-levels rise. The conservation and restoration of mangrove forests should be one of the key issues in sustaining low-lying atoll countries under climate change and increasing anthropogenic pressures.

1. Introduction

Mangrove forests are highly productive ecosystems that support both terrestrial and marine biodiversity. They fulfill many ecosystem functions, including the supply of timber and fuel, and the physical protection of coasts (Woodroffe et al. 2016). In addition to these important attributes, emerging evidence indicates that they are among the most carbon-rich forests in the tropics (Donato et al. 2011) and subsurface carbon sequestration is likely, as observed in seagrass beds and salt marshes (Nellemann et al. 2009).

The environments of mangrove forests can be classified as terrigenous and carbonate settings (Woodroffe et al. 2016). Low-lying isolated carbonate islands (atolls and reef islands) are widely distributed in the Indo-Pacific (Bryan 1953) and represent the most common type of Pacific island, constituting 36% of all Pacific islands (Nunn et al. 2016). They provide the foundations upon which mangrove forests are established (Woodroffe 1987). Mangrove forests are thought to play important roles in the geomorphic development, coastal protection, and carbon sequestration of low-lying atolls. Woodroffe (1987) stated that ‘In particular, mangrove stands of limited extent on small ‘low’ islands need to be examined. Because these are small, they are vulnerable to destruction, yet they may support resources which local inhabitants cannot find in alternative environments on these islands.’ Evaluation of the functions and vulnerability of mangroves in atoll settings is required.

Examining past developmental processes could reveal the fundamental vulnerability of mangroves in atoll settings. Atolls must have been completely drowned in the early Holocene as the sea surface rose above the level of the Last Interglacial limestones, resulting in the eradication of terrestrial vegetation, including mangroves.
(Woodroffe and Grindrod 1991, Woodroffe 1992). The re-establishment of mangroves would have depended on reef development and propagule supply from surrounding lands and/or islands, both of which are sensitive to environmental changes, including changes in sea level and surface current systems.

The vulnerability should also be discussed in relation to climate change. Climate change effects, especially sea-level rise, threaten mangrove ecosystems (Gilman et al. 2006, Lovelock et al. 2015), and their degradation may lead to losses of resources (e.g., biodiversity), coastal protection, and carbon storage, and may affect island sustainability. Because atolls are small in extent and low-lying, there is little space for the inland migration of mangroves as sea level rises. Therefore, whether current mangrove forests can keep up with rising sea levels must be investigated in terms of the developmental history of these mangroves, based on the ages of core samples. These ages, together with organic-carbon contents, allow the calculation of carbon burial rates, which are important in estimating carbon sequestration.

Despite the importance and vulnerability of the mangroves, atoll settings have been largely ignored when the developmental processes and carbon storage of mangrove forests have been examined, although global mapping (Hamilton and Casey 2016) and meta-analyses (Jardine and Siikamäki 2014, Atwood et al. 2017, Sanderman et al. 2018) are increasing rapidly. Recent studies have demonstrated the importance of considering the environmental setting of carbon storage in mangroves, and carbonate settings have shown higher carbon contents than other environmental settings (Rovai et al. 2018, Twilley et al. 2018). This encourages further examination of mangroves in various environmental settings. The purpose of this study was to investigate the functions of mangrove forests in an isolated atoll setting in terms of the geomorphic development, carbon stocks, and carbon burial rates, along with the vulnerability, based on the radiocarbon ages and organic-carbon contents of cores collected on Fongafale Islet, Funafuti Atoll, Tuvalu.

2. Field setting and methods

2.1. Study site

Tuvalu is in the tropical South Pacific (figure 1(a)), and its land comprises reef islands on atolls or table reefs. Mangrove forests contain three mangrove species (Rhizophora stylosa, Lumnitzera littorea, and Sonneratia alba) and one associated species (Pemphis acidula) (http://www.nies.go.jp/TroCEP/index.html) and are distributed in central depressions of the reef islands on the atolls and on the margins of semi-enclosed lagoons on table reefs. Among these mangrove species, R. stylosa is dominant. Woodroffe (1987) regarded this environmental setting as the ‘inland mangroves and depressions’ type in carbonate settings, which is found widely in other atoll settings. The mangrove forests of Tuvalu support biodiversity, and three new Chironomidae species have been recorded in the forests (Ueno et al. 2015).

Previous studies have estimated the areal extent of the mangroves on Tuvalu. Vegetation maps, together with landform and soil maps, were prepared in the 1980s for all the reef islands of Tuvalu (figure 1(b)) based on field surveys and the interpretation of aerial photographs (McLean and Hosking 1992). Although these studies reported the areas of mangrove forests on the different islands, no information was included on the area of mangroves on Funafuti, where mangrove forests occur in the central depression of Fongafale Islet. Therefore, we determined the area of mangroves on this island based on historical maps of Fongafale Islet (Yamano et al. 2007). According to these data, the total mangrove area of Tuvalu in the 1980s was 52.6 ha. The Food and Agriculture Organization (FAO 2007) reported 50 ha and 40 ha of mangroves in the 1980s and 2000s, respectively, whereas a recent estimate based on satellite imagery indicated 9.1 ha (Bhattarai and Giri 2011). However, the most recent studies reported no mangrove forests on Tuvalu (Hamilton and Casey 2016). Because the vegetation maps of the 1980s were based on a field survey, we consider that the most reliable estimate of the area of mangroves in the 1980s was 52.6 ha. Given that the FAO 1980s estimate was similar to that derived from vegetation maps, the area of mangroves in the 2000s could have been 40 ha, as reported by the FAO (2007).

Fongafale Islet, the capital of Tuvalu on Funafuti Atoll, has a population of ~4000, and anthropogenic pollution is a serious concern for the coastal ecosystems (Fujita et al. 2013). The island experienced extensive land modification with the construction of an airfield during World War II, and the area of mangroves decreased from 8.0 ha in 1941 to 2.9 ha in 2004, based on the historical maps of Yamano et al (2007).

2.2. Methods

Fieldwork was undertaken in October 2014 to collect cores on Fongafale Islet. Six cores were taken from a present-day mangrove forest (Fnmg-1, 2, 3, 4, 6, and 8; figure 1(c)) using a 1 m PVC pipe, following the procedure of (Adachi et al. 2010). One additional core was taken using the same procedure from a Sporobolus virginicus swamp (Fnmg-7; figure 1(c)) that had been covered by mangrove forest before the construction of the airfield (Yamano et al. 2007). The PVC pipe was hammered downward until its tip reached hard substrate. The
lengths of the cores were estimated by measuring the residual pipe length above the surface. We also measured the surface position of the core top inside the pipe and observed no compaction in any core. Because of the limited on-site facilities and capacity for transportation, only a few samples were selected, as follows, and transported to the laboratory in Japan for analysis. For age determination, we took all the charcoal flecks (mangrove bark) and corals from the cores that showed direct evidence of mangrove forest and reef-flat formation, respectively. To determine the carbon contents, each core was first divided into visually different layers based on color, and the thickness of each layer ($L_{cm}$) recorded. Three soil samples ($5cm^3$) were taken from each layer of each core with a tightly sealed sampler.

All age determinations were undertaken by Paleo Labo Co. Ltd, Saitama, Japan (Table 1). Radiocarbon age data were corrected for carbon isotopic fractionation and calibrated to calendar years BP using OxCal v. 4.3 software (Bronk Ramsey 2009) with the SHCal $^{14}C$ calibration curve and the Bomb 13SH1 2 dataset (Reimer et al 2013). In calibrated the coral samples, the marine reservoir effect at Tuvalu was assumed to be $-37 \pm 19$ yr (Petchey et al 2008). The radiometric ages discussed here are median values.

The detrital organic-carbon contents of the sediment samples from the cores were analyzed as follows. After the live roots were removed, each soil sample was dried at 80 $^\circ$C for 72 h and weighed ($W_{0 g}$). The inorganic
Table 1. Descriptions and radiocarbon age data for the charcoal and coral samples.

| Site  | Laboratory code | Sample code | Material                          | Elevation from surface (m) | 1s range of conventional age (yr BP) for pre-Bomb sample | 1s range of $^{14}$C for post-Bomb sample | 2s range of calibrated age (cal yr BP) | Calibrated age with median probability (cal yr BP) |
|-------|-----------------|-------------|-----------------------------------|-----------------------------|----------------------------------------------------------|------------------------------------------|--------------------------------------|--------------------------------------------------|
| Fnmg-1| PLD-30444       | Fnmg1-P1-24 | Charcoal fleck (*Rhizophora stylosa*) | −0.24                       | 1 ± 18                                                   | N/A                                      | 135 to 122                           | 129                                              |
| Fnmg-2| PLD-30445       | Fnmg2-P1-14 | Charcoal fleck (*Rhizophora stylosa*) | −0.14                       | N/A                                                      | 1.3800 ± 0.0027                          | −13 to −14 (25.7%)                    | −25                                               |
| Fnmg-3| PLD-30446       | Fnmg3-P1-17 | Charcoal fleck (*Rhizophora stylosa*) | −0.17                       | 327 ± 17                                                 | N/A                                      | −25 to −26 (69.7%)                    | 443 to 366 (62.3%)                       |
| Fnmg-4| PLD-30447       | Fnmg4-P1-20 | Charcoal fleck (*Rhizophora stylosa*) | −0.2                        | 126 ± 17                                                 | N/A                                      | 331 to 301 (33.1%)                    | 253 to 226 (12.9%)                       |
| Fnmg-6| PLD-30448       | Fnmg6-P1-16 | Charcoal fleck (*Rhizophora stylosa*) | −0.16                       | N/A                                                      | 1.4307 ± 0.0028                          | −13 (2.8%)                           | −23                                               |
| Fnmg-7| PLD-30449       | Fnmg7-P1-10 | Charcoal fleck (*Rhizophora stylosa*) | −0.1                        | 200 ± 18                                                 | N/A                                      | −23 to −24 (92.6%)                    | 288 to 250 (24.3%)                       |
|       | PLD-30450       | Fnmg7-P1-31c| Coral (arborescent *Acropora sp.*)  | −0.31                       | 2873 ± 21                                                | N/A                                      | 230 to 140 (66.6%)                    | 105 (1.4%)                           |
|       | PLD-30451       | Fnmg7-P1-31m| Charcoal fleck (*Pemphis acidula*)  | −0.31                       | 128 ± 17                                                 | N/A                                      | 84 to 71 (2.3%)                      | 19 to 11 (0.8%)                         |
| Fnmg-8| PLD-30452       | Fnmg8-P1-30 | Charcoal fleck (unidentified)       | −0.3                        | 168 ± 18                                                 | N/A                                      | 2753 to 2610                         | 2703                                             |
carbon present as carbonate was eliminated as gaseous carbon dioxide by adding 1 M HCl to the dried sediment, with samples being treated with HCl until no further bubbles were generated. The samples were then rinsed with deionized water, dried at 80 °C for 72 h, and re-weighed (W_f, g). A subsample of ~10 mg of dried sediment was then weighed and wrapped in tin foil, and the carbon content (C, wt%) determined with an elemental analyzer (FlashEA™ 1112, Thermo Electron Corp., USA). The detrital organic-carbon content of each sediment layer was calculated using equation (1):

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\text{Detrital organic carbon (mg C cm}^{-3}\text{)} = \frac{W_f(g) \times C (\text{wt}%) \times 10^{-2}}{5(\text{cm}^{-3})}
\]

The depth-integrated value for the top meter was calculated to allow its comparison with past studies (Rovai et al 2018), based on the thickness of the layer and the detrital organic-carbon content of each layer. Because none of the core lengths reached 1 m, we assumed that the bottom layer in each core reached a depth of 1 m from the surface when modeling the depth-integrated detrital organic-carbon contents.

The vertical accumulation rates and organic-carbon burial rates were calculated from radiocarbon ages and detrital organic-carbon contents. The surface sediment date was assumed to be 2014, when sampling was performed. To obtain the vertical accumulation rate for each core, the depth of the point at which the dated charcoal fleck was taken was divided by the difference between the fleck age and the surface age. We performed the simple procedure described above instead of using more sophisticated age–depth modeling, such as with CLAM or BACON (Blauuw 2010, Blauuw and Christen 2011) because only a single charcoal age sample was available from each core from which to calculate the accumulation rate. To obtain the organic–carbon burial rate of each core, the amount of detrital carbon from the surface to the depth of the point, where the fleck was taken, was divided by the difference between the fleck and surface ages. These rates could not be calculated for core Fnmg-7, where the surface was disturbed during the construction of the airfield (Yamano et al 2007).

3. Results and discussion

Figure 2 shows sketches of the cores with their radiocarbon ages (table 1) and organic-carbon contents. The depth-integrated carbon storage, accumulation rates, and carbon burial rates based on these values are shown in table 2. We assumed that all the cores penetrated the full sequence of mangrove peat on the reef flat, because the core tip encountered hard substrate during each coring procedure, and reef substrate materials (coral and carbonate sediment) were recovered from three (Fnmg-3, Fnmg-7, and Fnmg-8) of the seven cores (figure 2).

3.1. Development of mangrove forest

Mangrove peat formed a thin veneer, from 23 cm (Fnmg-3) to 76 cm (Fnmg-6) thick, and was typically distributed on a reef-flat substrate of coral fragments and carbonate sediment (figure 2). The lower parts of the cores contained carbonate sediments, whereas the upper parts comprised mainly mangrove peat. The oldest age of the charcoal flecks was 389 cal yr BP, and these were collected 17 cm from the surface at site Fnmg-3 (table 1). In situ fragments of arborescent Acropora, with residual surface structure, which had presumably formed the reef flat, yielded an age of 2703 cal yr BP.

The age of the coral indicates the time at which the reef flat formed. The available radiocarbon dates for Kiribati and Tuvalu (McLean and Hosking 1991) suggest that the modern sea level was attained around 4500 yr ago, the reef crest reached the sea level around 4000 yr ago, the reef flats developed continuously from that time, and the reef island then formed. These findings have been supported by (Ohde et al 2002), who showed that coral fragments from a core recovered from Fongafale Islet had ages of 2520 cal yr BP and 2550 cal yr BP at 1.2 m and 0.3 m below the island surface, respectively.

The time of mangrove development shown in this study is much more recent than that on other Pacific islands, where mangrove forests have developed since the mid Holocene (figure 1(a)). Those islands are old volcanic or Pleistocene carbonate islands, which may have allowed the development of mangrove forests on pre-existing substrate, probably in response to the Holocene rise in the relative sea level and its subsequent stability. In contrast, mangrove development on Tuvalu required the establishment of the reef flat 4000 yr ago and its later emergence above the low-water level when the sea level fell, because mangroves typically occur in intertidal settings. Yamano et al (2017) reported a late–Holocene sea-level highstand on Kiribati islands near Tuvalu, and suggested a relative sea-level fall after ~2000 cal yr BP, which could have assisted mangrove development on the reef flat.

The timing of the sea-level fall (~2000 cal yr BP) and the oldest age of our charcoal flecks (389 cal yr BP) suggest a ~1600 yr delay in mangrove development after the emergence of the reef flat. This may be attributable to the poor connections between Tuvalu and other Pacific islands that had mid–Holocene mangrove forests (figure 1(a)) and the relatively poor dispersal ability of mangrove propagules (Ellison 1991, Woodroffe and Grindrod 1991). The buoyancy of the propagules of R. stylosa, the dominant species in Tuvalu, decreases with
time, which may limit their dispersal (Kadoya and Inoue 2015). Treml et al (2008) calculated the connectivity of larval dispersal among Pacific islands based on ocean current patterns and showed that the pathway to Tuvalu extends only from Samoa. Although mangrove forests were established in Samoa at 4845 yr BP (Bloom 1980) (figure 1(a)), the time required for pelagic larvae to travel from Samoa to Tuvalu is more than 60 days, and a number of stepping-stone reefs are required to allow mangrove propagules to reach Tuvalu from Samoa (Treml et al 2008). Furthermore, among the four mangrove species in Tuvalu (R. stylosa, L. littorea, S. alba, and P. acidula), only one species (P. acidula) is distributed in Samoa (http://www.nies.go.jp/TroCEP/index.html). Collectively, these data could explain the delayed establishment of mangrove forests on Tuvalu.

The vertical accumulation rates of the mangrove facies vary from 0.4 to 3.9 mm yr$^{-1}$ (mean, 2.0 mm yr$^{-1}$) (table 2). These values are below the global mean (5.0 mm yr$^{-1}$), but are within the range of those reported for most other mangrove forests, which show a peak at 0–5 mm yr$^{-1}$ (Alongi 2012).

Figure 2. Sketches of the cores showing radiocarbon ages (table 1) and detrital organic carbon contents. The detrital organic carbon contents at Fnmg-4 could not be calculated because no soil sample was collected.
Table 2. Summary of carbon storage, accumulation rates, and carbon burial rates in this and previous studies.

| Site   | Carbon storage (mg C cm$^{-2}$) | Accumulation rate (mm yr$^{-1}$) | Carbon burial rate (g C m$^{-2}$ yr$^{-1}$) |
|--------|---------------------------------|----------------------------------|------------------------------------------|
| Fnmg-1 | 66.9                            | 1.2                              | 76.1                                      |
| Fnmg-2 | 67.6                            | 3.6                              | 188.7                                     |
| Fnmg-3 | 78.3                            | 0.4                              | 28.4                                      |
| Fnmg-4 | N/A                             | 1.4                              | N/A                                       |
| Fnmg-5 | 60.1                            | 3.9                              | 203.6                                     |
| Fnmg-6 | 86.2                            | N/A                              | N/A                                       |
| Fnmg-7 | 68.5                            | 1.7                              | 118.8                                     |

Mean of this study | 71.3 | 2.0 | 123.1 |

Global mean | 28.3–53.6 | 5.0 | 100–226 |
Mean of carbonate settings | 53.6 | 50 | N/A |

a Jardine and Siikamäki (2014), Atwood et al (2017), Rovai et al (2018), Sanderman et al (2018), Twilley (2012).
b Rovai et al (2018).
c Alongi (2012).
d Alongi (2012), Inoue (2019).

3.2. Below-ground carbon storage and carbon burial rates

The detrital carbon contents of the mangrove sediments range from 60.1 to 86.2 mg C cm$^{-2}$ (mean, 71.3 mg C cm$^{-2}$) (table 2), similar to the maximum value (71.6 mg C cm$^{-2}$) for mangrove forests in other settings and above the global mean value and the mean value of carbonate settings (Rovai et al 2018). The carbon burial rates vary from 28.4 to 203.6 g C m$^{-2}$ yr$^{-1}$ (mean, 123.1 g C m$^{-2}$ yr$^{-1}$), which are also similar to those for mangrove forests in other settings (100–226 g C m$^{-2}$ yr$^{-1}$) (Alongi 2012, Inoue 2019). These high carbon contents and burial rates may be attributable to the predominantly in situ sites of the sediments and, in particular, the unlikely export of sediments from the mangrove forest because the forest occurs in the central depression of the island (figure 1(c)). The mangrove forests on the other islands of Tuvalu could have the same storage capacities as Funafuti Atoll because they also occur in the central depressions of reef islands on atolls and at the margins of semi-enclosed lagoons of table reefs (McLean and Hosking 1992). This feature should be considered in future modeling work.

Given that the best estimate of the recent mangrove area of Tuvalu is 40 ha (FAO 2007), the carbon burial rates on Tuvalu during in situ peat formation range from 1.1 × 10$^7$ to 8.1 × 10$^7$ g C yr$^{-1}$ (mean, 4.9 × 10$^7$ g C yr$^{-1}$). The CO$_2$ emissions from Tuvalu in 2014 were 11.16 × 10$^9$ g when land use, land-use change, and forestry (LULUCF) data are included, and 11.19 × 10$^9$ g when LULUCF data are excluded (http://di.unfccc.int/detailed_data_by_party). Therefore, CO$_2$ removal by LULUCF in Tuvalu is estimated to be 0.03 × 10$^9$ g yr$^{-1}$, which is equivalent to 8.2 × 10$^9$ g C. The rate of CO$_2$ removal by mangrove forests in Tuvalu is thus 1.3–9.9 (mean, 6.0) times higher than that estimated using LULUCF data.

3.3. Importance and vulnerability of mangroves in isolated atoll settings

Despite the delayed initiation of their development and the small below-ground peat thickness that imply their fundamental vulnerability, the mangrove forests in Tuvalu function in geomorphic development, reflected in their vertical accumulation rates, which are similar to those in other settings. Their large capacity for carbon sequestration is of particular significance. These are achieved by the in situ production of sediments in central depression of the islands, with little export beyond the forests. This, in turn, means that mangrove forests in atoll settings are vulnerable because they do not receive significant input of external sediments. Further, poor connections between isolated atolls and other Pacific islands strongly suggest natural recovery of mangroves would be unlikely if they would be lost. The 10 ha area loss of mangroves in Tuvalu in the 1980s–2000s should be restored. Furthermore, conservation and restoration of mangrove forest should be considered in Tuvalu’s Intended Nationally Determined Contributions (INDC) that describe post-2020 climate actions, because there is no description of LULUCF in Tuvalu’s current INDC (Forsell et al 2016).

The vulnerability of the mangroves in Tuvalu to sea-level rise could be estimated by comparing the rates of vertical accumulation and future sea-level rise. The values overlap the rates of sea-level rise predicted under the 1.5 °C scenario of the Paris Agreement (2.6–7.7 mm yr$^{-1}$ with a 17%–84% confidence interval), but are probably below the rates under the 2.0 °C scenario (3.6–9.3 mm yr$^{-1}$) (Hoegh-Guldberg et al 2018), which means that global warming must be limited to 1.5 °C to save the mangrove forest on Tuvalu. However, caution...
should be taken regarding whether these values can be used to predict the future accumulation potential, because these accumulation rates were achieved during a possibly falling sea level in the late Holocene (Yamano et al. 2017). On-site measurements based on surface elevation tables (Lovelock et al. 2015) and process-based modeling (Morris et al. 2002) are still required.

Mangrove forests in isolated atoll settings should not be neglected, and their conservation and restoration could be a key issue in sustaining low-lying atolls during this period of rapid climate change and increasing anthropogenic pressures. We also note that past global mangrove maps (Giri et al. 2011) indicated the presence of mangrove forests in Tuvalu, but their presence (http://www.nies.go.jp/TroCEP/index.html) or absence (Hamilton and Casey 2016) is inconsistent in more recent maps. Together with further field evidence, consistent mapping will be required to examine the role and future of not only mangrove forests in atoll settings but mangrove forests worldwide.

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Data availability statement

Any data that support the findings of this study are included within the article.

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