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Community ecology

Establishing rates of carbon sequestration in mangroves from an earthquake uplift event

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We assessed the carbon stocks (CS) in mangroves that developed after a magnitude 7.1 earthquake in Silonay, Oriental Mindoro, south Luzon, The Philippines in November 1994. The earthquake resulted in a 50 cm uplift of sediment that provided new habitat within the upper intertidal zone which mangroves colonized (from less than 2 ha pre-earthquake to the current 45 ha, 23 years post-earthquake). The site provided an opportunity for a novel assessment of the rate of carbon sequestration in recently established mangroves. The carbon stock was measured in above-ground, below-ground and sediment compartments over a seaward to landward transect. Results showed a mean carbon stock of 549 ± 30 Mg C ha^{-1} (of which 13% was from the above-ground biomass, 5% from the below-ground biomass and 82% from the sediments). There was high carbon sequestration at a 40 cm depth that can be inferred attributable to the developed mangroves. The calculated rate of C sequestration (over 23 years post-earthquake) was 10.2 ± 0.7 Mg C ha^{-1} yr^{-1} and is comparable to rates reported from mangroves recovering from forest clearing. The rates we present here from newly developed mangroves contributes to calibrating estimates of total CS from restored mangroves (of different developmental stages) and in mangroves that are affected by disturbances.

1. Introduction

Mangroves are considered among the most important ecosystems that can be managed for adaptation and mitigation strategies against the impacts of climate change [1]. They are considered as 'Blue Carbon systems' because of their capacity to store a large amount of organic carbon (OC) over long periods [2]. They have been widely degraded over their distribution [3], particularly in The Philippines [4]. Thus, efforts to restore mangroves to reinstate ecosystem services such as carbon sequestration have been increasing. But, there are few studies within tropical latitudes that document rates of OC accumulation after mangroves have been re-established.

In the Silonay Mangrove Conservation Ecopark (located in south Luzon, The Philippines), an earthquake in 1994 resulted in the uplift of sediment into the intertidal zone, which was then colonized by mangroves. This provides a novel location in which to assess rates of OC accumulation in mangroves. However, the mangrove-colonized stands may have varying rates of C accumulation depending on the vegetation structure (e.g. tree height and diameter), sediment properties and the position in the intertidal zone. For example, landward (LW) sites that are located at relatively high elevations are less exposed to tidal action, and hence may retain more carbon. By contrast, mangroves located in seaward (SW) sites are more exposed to waves and tides, and hence may

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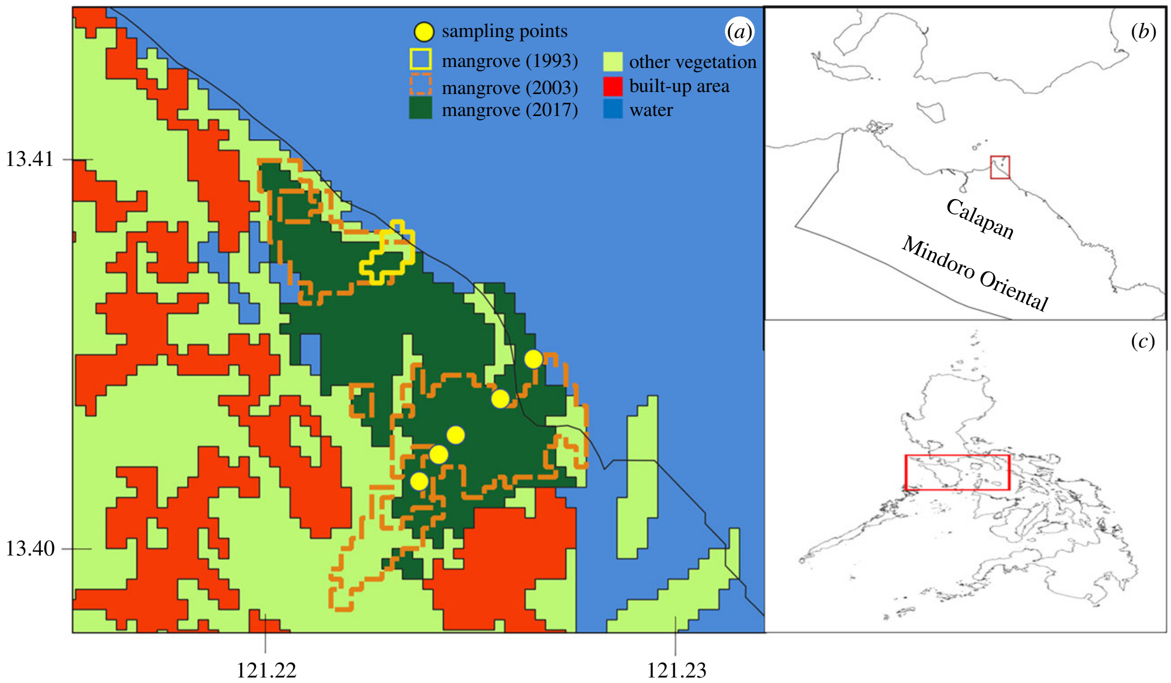

Figure 1. Location of the sampling points and the development of mangroves in Silonay Mangrove Conservation Ecopark before ((*a*), 1993, dashed yellow polygon) and after the magnitude 7.1 earthquake (2003, dashed orange polygon, and 2017, green polygon). The site is located in the municipality of Calapan in the province of Oriental Mindoro (*b*) in southern Luzon, The Philippines (*c*).

have a lower capacity to store carbon. In this study, we measured OC stocks (CS) over the intertidal zone in the uplifted area. Through the assessment of post-earthquake CS, we provide novel estimates of C sequestration in newly developed mangroves.

2. Material and methods

(a) Site information

On 15 November 1994, a magnitude 7.1 earthquake struck the Mindoro Island. The epicentre was located in Verde Island Passage, a strait separating mainland Luzon and the province of Mindoro [5]. The earthquake resulted in a fault slip from the offshore epicentre that extended into the inner Mindoro with 2–3 m horizontal and vertical displacements and which generated 3–4 m tsunami wave heights [6,7]. In Silonay, the local community observed at least 50 cm of uplifted sediments. Prior to the earthquake (1993), the mangrove cover in the area was only less than 2 ha but it is now estimated at 45 ha (figure 1). The depth of tidal waters ranges 0.8–1.9 m.

(b) Experimental design and sampling

Five sites were designated based on elevation above mean tidal levels and distance perpendicular from the shoreline (figure 1), referred to as: SW, middle (MW), landward 1 (LW1), landward 2 (LW2) and landward 3 (LW3), with corresponding distances of 20, 250, 400, 500 and 550 m from the shoreline, respectively. In each site, three representative vegetation plots (of 5 m radii with approx. 20 m distance between plots) were randomly selected. In each plot, the diameter and height of all trees were measured, including the seedling density, sapling density and canopy cover. From each plot, sediment properties were assessed from the porewater (such as conductivity, pH, redox, salinity, temperature and total dissolved solids) in triplicate using a portable water quality monitoring instrument. A 20 cm sediment core sample was collected from each plot. The vegetation and sediment assessment were conducted over multiple field campaigns in February, June and September 2017. To measure total soil carbon (SC), one 100 cm sediment core was collected once from one of the plots in each site to assess down-core variation in carbon and bulk density (BD) over sediment depths.

(c) Data analyses

Tree biomass (above-ground and below-ground biomass) was computed using species-specific allometric equations (see [8]). The biomass values were multiplied by 0.5 to calculate the CS (from biomass) based on the assumption that the biomass is made up of 50% C [2]. The biomass C stocks were calculated per plot (in Mg ha^{-1}). Each 100 cm core was sectioned at every 1 cm over 0–10 cm depth, every 2 cm over 10–20 cm depth and every 5 cm from 20 to 100 cm depth. All samples were analysed for soil dry BD and organic matter (OM) content. The OM was measured using the loss on ignition (LOI) method at 450°C for 4 h and was converted into OC using the equation, $\%OC = 0.415 \times \%OM + 2.89$ [2]. The SC stock was computed per subsampling depth by multiplying the OC with BD and sample thickness. It was then summed for the entire 100 cm sample to obtain the total SC. The total carbon stocks (TCS) were computed as the sums of the above-ground carbon (AGC), below-ground carbon (BGC) and SC. Using a stock-change approach (cf. [9]), the rate of C accumulation (in Mg C ha^{-1} yr^{-1}) was computed by dividing the TCS by 23 years. We calculated the contribution of the mangrove to the SC by subtracting SC that was present before the earthquake, which we assumed to be similar to the SC at 40–100 cm depth. Thus, SC stock that accumulated after the earthquake was assumed equal to the stocks (summed over the entire 100 cm slices) obtained by subtracting the mean SC density at 40–100 cm extrapolated over the entire 100 cm core.

The differences in TCS over sites were assessed using one-way ANOVA and Tukey's tests. The datasets from three samplings were also subjected to Principal Component Analysis (PCA) to determine the relationship among vegetation and sediment variables and with sites (electronic supplementary material, table S1). All statistical tests were implemented in R Statistical Software [10].

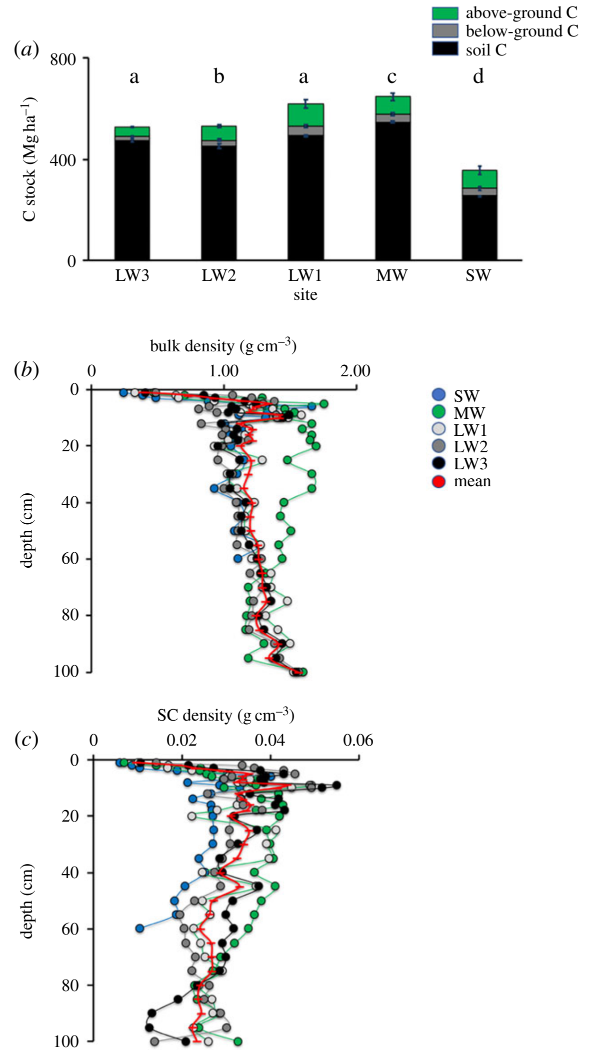

Figure 2. Variation in carbon stocks (*a*), bulk density (*b*) and carbon density (*c*) relative to distance from the shoreline: seaward (SW) to middle (MW) and landward (LW). Different letters above the bars indicate a significant difference in carbon stocks between sites ($p < 0.001$) based on ANOVA and Tukey's tests.

3. Results

The total CS ranged from 354 to 667 Mg C ha^{-1} and were highest in the MW and lowest on the seaward edge. All sites were significantly different from each other except LW1 and LW3 (d.f. = 4, error d.f. = 10, $F = 682$, $p < 0.001$; figure 2*a*). There was no linear SW to LW trend. The SW has 42–52% lower CS compared with the other sites.

The change in CS over the 23 years since the earthquake was 549 ± 30 Mg C ha^{-1} (figure 2*a*). We therefore calculated a C sequestration rate of 24 ± 1 Mg C ha^{-1} yr^{-1}, of which 13% was from the above-ground biomass, 5% from the below-ground biomass and 82% in the soils. The soil BD was low (less than 1.0 g cm^{-3}) in the surface soils (0–5 cm), abruptly increased at 5–20 cm depth (1–1.15 g cm^{-3}), was relatively stable at 20–40 cm depth, then gradually increased with depth (figure 2*b*). The SC density showed differentiation among sites, where the SW sites had lower values than the group of MW, LW1, LW2 and LW3 (figure 2*c*). High SC was evident across sites and gradually increased from 0 to 40 cm depth, then gradually decreased with depth. Based on the PCA values, the SW site was clearly different from the other sites while the MW site was similar to the group of LW1, LW2 and LW3 (electronic supplementary material, figure S1).

4. Discussion

The occurrence of a magnitude 7.1 earthquake in November 1994 resulted in the uplift of coastal sediments in Silonay that provided new habitat in the upper intertidal zone where mangrove seedlings colonized, grew and eventually developed as a mature forest. Mangrove age (e.g. through chronosequence, cf. [11]) influences the CS in both biomass and soil compartments. This provided a novel setting to assess rates of C sequestration in mangroves of the region.

The observed total C stocks in this study (354–667 Mg C ha^{-1}) are comparable to the local reports of forest C stocks in the central Philippines (441 Mg C ha^{-1}; [12]) and in Bangladesh (566 Mg C ha^{-1}; [13]), but are 40–60% lower than values from Southeast Asia (911–1267 Mg C ha^{-1}; [13–15]). The variation in sequestered C among sites since the earthquake is due to a range of factors. The SW sites (with 50–80% lower stocks and rates) have less developed vegetation than the LW sites (electronic supplementary material, figure S1). They are more exposed to coastal currents and tidal inundation than LW sites, and therefore may export more C through export of sediment, litter or dissolved C fractions [3]. By contrast, the MW to LW sites have more developed mangroves than those in SW locations and are hydrologically isolated, which may favour higher levels of C accumulation (electronic supplementary material, figure S1). The lower C stocks in Silonay as compared with other tropical locations may reflect the age of the forest as well as other environmental factors. The site is frequently affected by typhoons [7], which could contribute to the relatively shorter heights and lower biomass compared with the tropical mangroves of Indonesia. Severe typhoons in The Philippines are known to result in 60–80% reduction in biomass [16] compared to mangroves which are less exposed to typhoons. Aside from age [11], the ecosystem health and conditions of mangroves also contribute to localized differences in C stocks.

Our results show that after 23 years the uplifted sediments have been influenced by the growth and development of mangrove vegetation. The increase in sediment C was similar to that reported through sediment accretion in mangroves in Indonesia [17] and to that observed in subtropical Moreton Bay [18]. Mangroves in French Guiana that are less than 40 years had homogeneous C density to soil depths of 100 cm [11]. In Silonay, however, high C density was pronounced in the surface soils to 40 cm depth (inferred from figure 2*b*,*c*), indicating recent accumulation after the uplift event, compared with C density of sediments lower in the core. From the uplifted sediments, we assumed that the new mangroves contributed to the gradual accumulation of C in approximately the top 40 cm as the forest matured. Other studies have noted mangroves influence C accumulation to similar soil depths (approx. 45 cm; for example, in French Guiana [19]). The mean cumulative soil CS to 100 cm depth were computed at 19 Mg C ha^{-1} yr^{-1}. By subtracting possible C before the earthquake (assumed to be similar to sediment C observed at 40–100 cm depth), the mean rate of sediment C accumulation was computed at 8 Mg C ha^{-1} yr^{-1}. We acknowledge the uncertainty of such assumptions due to the absence of data on accretion.

The computed mean C sequestration within both biomass and soils (up to 40 cm depth) was 10.2 ± 0.7 Mg C ha^{-1} yr^{-1} but was highly variable between sites. This rate is at least 50% higher than the published reports (mean: 1.9 Mg C ha^{-1} yr^{-1}; [20–22]) in intact natural mangroves. But, our computed rate is similar to the rate reported in restored mangroves (18-year-old stands in the northern Philippines; [4]) and in Malaysian mangroves that recovered from forest clearing (9.5 Mg C ha^{-1} yr^{-1}; [23]). It is possible, however, that such high rates will eventually decline and become stable as the forest reaches maturity (cf. [23,24]) and sediment accretion slows.

Ethics. There are no ethical concerns in this study. All fieldwork was carried out with permission from the local government and community.

Data accessibility. Raw data are available as electronic supplementary material and in Dryad [25].

Authors' contributions. S.G.S. and V.M. conceived and designed the experiment, and collected data. V.M. did all laboratory analyses. V.M., M.C.A.G. and S.G.S. analysed the data. H.M.P. did the spatio-temporal analysis of mangrove maps. S.G.S. wrote the initial draft of the manuscript. All authors contributed to the editing and finalization of the manuscript. All authors approved the final version of the manuscript, and agree to be held accountable for the content therein.

Competing interests. We have no competing interests.

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