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Blue carbon stock of aquasilviculture-based agroforestry system in Infanta, Quezon, Philippines

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Abstract Blue carbon stock of the four aquasilviculture (AQS) systems within a Community-based Mangrove Forest Management area in Infanta, Quezon was assessed. Results demonstrated that the aboveground biomass and root carbon stock of the four AQS differed significantly ($p<0.05$). AQS 4, adopted the peripheral/separate model type of AQS and dominated by *Rhizophora* sp., possessed significantly greater aboveground C stock (101.12 Mg ha^{-1}) and root C stock (48.05 Mg ha^{-1}). While the *Aegiceras* sp.-dominated AQS 3, which adopted the mixed model type, and with semi-intensive grow-out polyculture, had the highest total C sediment stock at 1,023 Mg ha^{-1}. Overall, AQS 4 had the highest total carbon stock, calculated at 1,141.47 Mg ha^{-1}. A large portion of the C stock potential of each AQS is derived from the sediment carbon pool which accounted for up to 87.5% of the total C pool, according to the results. Findings indicated that AQS contributes a substantial amount of total carbon stock comparable to that of a pure mangrove ecosystem. If valued, the blue carbon stock of the aquasilviculture systems ranged between Php 901,491.86 (USD 16,510.84) and Php 983,540.38 (USD 18,013.56). This can provide the People's Organization with additional income in addition to the income generated from their cultivation of aquatic species. Therefore, aquasilviculture system is a good climate mitigation strategy with socio-economic advantages.

Keywords: Agroforestry, Aquaculture, Community-Based Forest Management (CBFM), Mangroves

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Introduction

Mangrove forests are most important for stabilizing coastlines and their rich fish and crustacean production. Over time, these mangrove forests were being degraded and deforested. Tragically, many have been destroyed all over the tropics (Richards and Friess, 2015). For instance, in the Philippines, approximately half (51.8%) of the original mangrove area declined from 1918 to 2010 (Long *et al.*, 2014). As part of the Philippine government's Community-Based Forest Management (CBFM) program, agroforestry systems were being introduced, in conjunction with the rehabilitation process, to provide additional sources of income for the community. The type of agroforestry system introduced in the mangrove rehabilitation areas is the aquasilviculture (AQS) system.

AQS is a mangrove-friendly approach of growing fish and other aquatic organisms (Boquet, 2017), such as crabs and shrimps, enclosed with a net pen or canal under a mangrove forest without allowing the clearing of trees (Enate *et al.,* 2013; Dieta and Dieta, 2015). AQS is also a promising sustainable coastal agroforestry system that offers mangrove rehabilitation, fishery production enhancement, livelihood improvement, and coastal erosion prevention (BFAR, 2019) to help address climate change, food security, and poverty among fisherfolks (Dieta and Dieta, 2015). This system has been advocated since 2011 through the Philippine National Aquasilviculture Program (PNAP) of the Department of Agriculture – Bureau of Fisheries and Aquatic Resources (DA-BFAR) in partnership with 71 State Universities and Colleges (SUCs) and 61 provinces throughout the country (Dieta and Dieta, 2015).

Based on the PNAP status as of 2013, almost 31,000,000 mangrove propagules have been planted, covering approximately 10,000 hectares throughout the country (Dieta and Dieta, 2015). A total of 1,900 fisherfolks benefitted from the AQS techno-demo in which in the province of Bataan was able to produce a total net income of about Php 740,654.40 during the first cycle of operation (Flores *et al.,* 2016). Previous studies concentrated on the following: a) system management and improvement of the AQS system (Troell *et al*., 2009; Bosma *et al*., 2014; Flores *et al.*, 2016, Udoh, 2016; Vedra *et al*., 2017); b) process of establishing of AQS trials in various provinces of the country, i.e. Aklan (Primavera, n.d.), Bataan (Flores *et al.,* 2016), Davao del Norte (Tejada *et al.*, 2013), Misamis Oriental (Vedra *et al*., 2017), and other 56 provinces; c) socio-economic impact (Eddy *et al*., 2016; Basyuni *et al*., 2018; Kabir and Baten, 2019); and d) ecological impact, e.g. water quality (Peng *et al*., 2009; Musa *et al*., 2020), among others.

As a part of the vegetative coastal ecosystems, AQS systems also play an important sink for carbon dioxide (CO_2) (Crooks *et al*., 2017). Since AQS is comprised of mangroves and aquaculture, potential sources that contribute to the blue carbon pool are mangrove vegetation, mangrove litter, plant debris, aquatic sediments, nutrient inputs from artificial feed and fertilizers, and aquatic primary producers such as phytoplankton and aquatic plants (Nellemann *et al*., 2009; Sarkar *et al.*, 2021). The carbon stored in these ecosystems is termed blue carbon. The phrase "blue carbon" was established in 2009 to call attention to the degrading state of marine and coastal ecosystems and its needed conservation and restoration, thereby mitigating climate change and offering other ecosystem services (Lovelock and Duarte, 2019). According to The Blue Carbon Initiative (2019), coastal ecosystems sequester and store large quantities of carbon in plant and belowground sediment. Jennerjahn (2020) stated that about 50%-99% of blue carbon is stored in the soil. This led to the growing interest in quantifying the blue carbon that these systems can sequester to evaluate their CO_2 mitigation potential and to understand better this regulating service for sound management practices as well as in coastal planning (Arias-Ortiz *et al*., 2018; Kusumaningtyas *et al*., 2018).

Moreover, quantifying blue carbon stock is a valuable tool in valuing ecosystem services. It is of particular importance for Payments for Environmental Services (PES) and Reducing Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries (REDD+) schemes (Kusumaningtyas *et al*., 2018). The blue carbon in pond sediments also increases soil fertility which can invigorate the production of plankton species, benthos (deposit feeders), and mangrove plants.

This study sought to assess the blue carbon stock of aquasilviculture systems under a community-based mangrove management area in Barangay Amolongin, Infanta, Quezon.

Materials and methods

Location and site description

The study was conducted in the ongoing aquasilviculture systems inside the 17.9 hectares of CBFM area (Figure 1), being maintained by the people's organization, Binonoan Producers Cooperative (BIPCO). BIPCO-CBFM area in Barangay Amolongin is approximately at the intersection of 121°38' longitude and 14°41'10'' latitude, bounded on the north by Barangay Anibong; west by Barangay Pulo, and east by Barangay Binonoan. It is surrounded by the

Panikdikin River (north to west), Alitas River (east), and Boyobon River (south). It has a type II climate – characterized by no dry season and pronounced maximum rainfall from November to January (Uy *et al*., 2012).

The aquasilviculture site is located at a low elevation (5–21 meters above sea level) and has flat topography with a gentle to undulating slope. The study site is covered with hydrosol and has soil texture ranges from silty to silty clay to clay textural class. Hydrosol is a soil type that is saturated with water and remains wet for an extended period (2 to 3 months) or continuously wet.

Moreover, the study area was in a riverine type of mangrove forest, and the production environment is brackish water. The four AQS are in the landward zone of the CBFM area. The area is full of biodiversity, including birds, bats, insects, and amphibians. The tidal cycle of the area is semidiurnal, meaning the area is experiencing two low and high tides daily. Approximately less than one meter is the lowest low tide experienced in the area, and more than 1.25 m is the highest high tide. There were two AQS model types were observed in the study area– peripheral/separate and mixed (Susitharan and Sindhu, 2021). Mangroves are located in the boundary of the pond dike in the case of peripheral/separate type. While in the mixed type, the mangrove and aquaculture components are mixed inside the dike or pen.

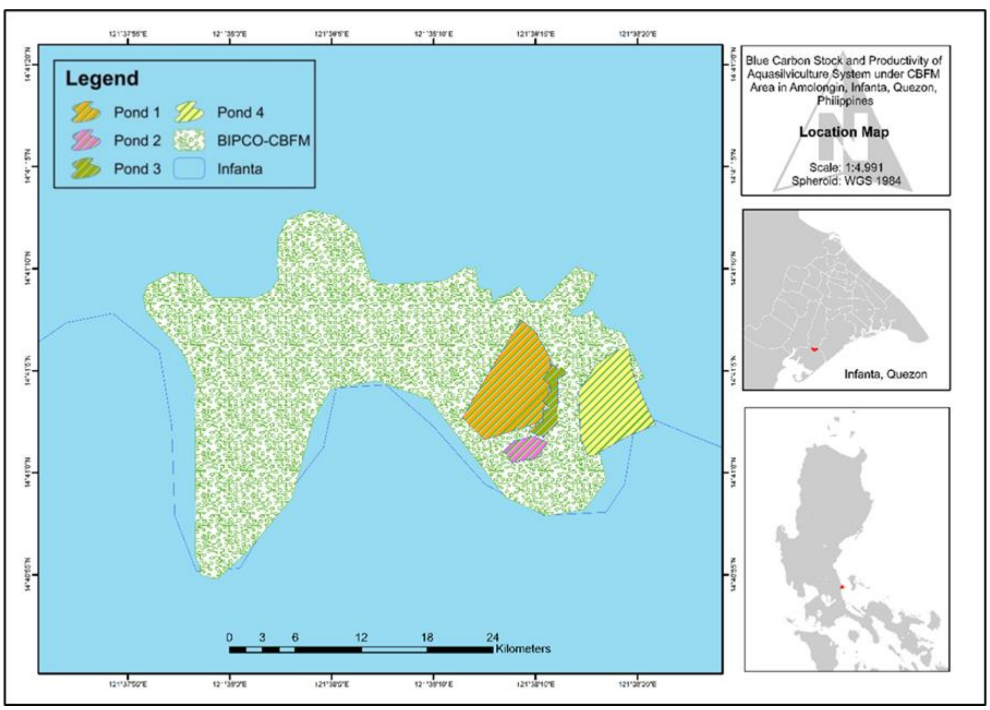

Figure 1. Location map of the study site (BIPCO-CBFM)

Sampling procedure for blue carbon stock estimation of AQS

The sampling area for the study was determined by measuring ten meters starting from the dike or boundary perimeter of the aquasilviculture pond onwards. Buffering of ten meters (Figure 2a) from the pond dike was done using ArcGIS Desktop 10.8 (version 10.8.12790). A plot of 10 meters by 10 meters surrounding the aquasilviculture pond (Figure 2b) was established using Google Earth Pro (version 7.3.4.8248). The total number of plots in each aquasilviculture system was used to calculate the number of sample plots (n).

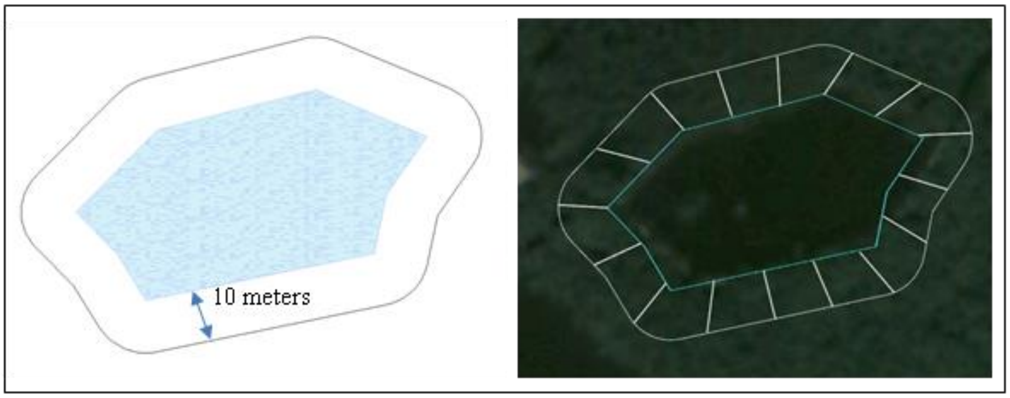

Figure 2. (a) Establishment of a ten-meter buffer and (b) 10m x 10m plots from the pond dike/perimeter to determine the total number of plots in each aquasilviculture system

The number of sample plots (n) for each AQS was determined using Winrock's CDM A/R Sample Plot Calculator Spreadsheet Tool (Walker *et al.*, 2007). In the calculation of sample plots, the error level was set to 1.0% and the confidence level to 99%. A preliminary sample of six plots (two plots each for AQS 1 and AQS 4, and one plot each for AQS 2 and AQS 3) was used for the initial inputs to the sample plot calculator. After the calculation of the number of sample plots, simple random sampling was utilized in the final selection of which particular plot to sample. The area, total number of plots, and number of sample plots for each AQS is shown in Table 1.

Table 1. Area and number of plots for each aquasilviculture system

AQS System	Area (ha)	Total no. of plots (N)	No. of sample plots (n)
AQS 1	1.38	49	6
AQS 2	0.16	16	2
AQS 3	0.20	30	2
AQS 4	1.14	33	4

Estimation of AQS mangrove biomass carbon stock

In each sample plot, mangrove tree species and associate mangroves were identified using the Field Guide to Philippine Mangroves (Primavera and Dianala, 2009) and Handbook of Mangroves in the Philippines-Panay (Primavera *et al*., 2004). The diameter at breast height (dbh) was measured using a diameter tape for each mangrove tree.

Aboveground biomass carbon

The obtained tree diameter and the corresponding specific wood density (Table 2) were plugged into the allometric equation developed by Komiyama *et al*. (2005) to calculate the aboveground biomass for each mangrove species. The data used to derive the Komiyama allometric equation originated in Asia. The coefficient of determination (R^2) value of the data was 0.98, and the sample size was 104 trees with a maximum diameter of 49 cm. Carbon stock is computed by multiplying aboveground biomass by 45.4% after finding the total biomass. The formula is as follows (Komiyama *et al*. 2005):

$$\boldsymbol{ABG = 0.251\,\rho\,D^{2.46}}$$

where: ABG aboveground biomass (kg)
ρ wood density (g cm^{-3})
D diameter at breast height (cm)

Table 2. Wood density values of the different mangrove species found in the study site (Malabrigo *et al*., 2017)

Species	**Scientific Name**	**Family**	**Wood density**
Saging-Saging	*Aegiceras corniculatum* (L.) Blanco	Myrsinaceae	0.5100
Tinduk-Tindukan	*Aegiceras floridum* Roem & Schult.	Myrsinaceae	0.6800
Bungalon	*Avicennia marina* (Forsk.) Vierh.	Acanthaceae	0.6500
Pi-api	*Avicennia marina* (Forsk.) Vierh. var. rumphiana (Hallier) Bakh.	Acanthaceae	0.6051
Api-api	*Avicennia officinalis* L.	Acanthaceae	0.7200
Pototan lalake	*Bruguiera cylindrica* (L.) Blume	Rhizophoraceae	0.7100
Busain	*Bruguiera gymnorrhiza* (L.) Lamk.	Rhizophoraceae	0.7700
Tangal	*Ceriops tagal* (perr.) C.B. Rob.	Rhizophoraceae	0.7800
Malatangal	*Ceriops zippeliana* Blume	Rhizophoraceae	0.7580

Table 2. (Con.)

Tui	*Dolichandrone spathacea* (L.f.) K. Schum.	Bignoniaceae	0.4100
Buta-buta	*Excoecaria agallocha* L.	Euphorbiaceae	0.3200
Dungon	*Heritiera littoralis* Ait.	Malvaceae	0.4300
Kulasi	*Lumnitzera racemosa* Willd.	Combretaceae	0.8700
Alai	*Mallotus tiliifolius* (Lamk) Muell. - Arg.	Euphorbiaceae	0.6982
Tawalis	*Osbornia octodonta* F. Muell.	Myrtaceae	0.8200
Bakauan Lalaki	*Rhizophora apiculata* Blume	Rhizophoraceae	0.8500
Bakauan Babae	*Rhizophora mucronata* Lamk.	Rhizophoraceae	0.8200
Bakauan Bato	*Rhizophora stylosa* Griff.	Rhizophoraceae	0.8400
Nilad	*Scyphiphora hydrophyllacea* Gaertn. f.	Rubiaceae	0.6850
Pagatpat	*Sonneratia alba* (L.) Smith	Lythraceae	0.5100
Tabigi	*Xylocarpus granatum* Koen.	Meliaceae	0.7002
Piagau	*Xylocarpus moluccensis* (Lamk.) M. Roem.	Meliaceae	0.5711

NOTE: ρ = wood density, either in the unit of g cm^{-3} or t m^{-3} (1 gram per cubic centimeter = 1 ton per cubic meter)

Belowground (Root Biomass) carbon

Similar to the calculation of aboveground biomass, the root biomass (RB) of the trees was also calculated using the allometric equation described by Komiyama *et al.* (2005). The data used to derive the allometric equation for root biomass determination was from 26 sampled trees, where the R2 was 0.949 between the weight of prop roots and the aboveground weight of the tree. After determining the root biomass, carbon stock is also calculated by multiplying the value by 45.4%. The formula is described as follows:

$$\boldsymbol{RB = 0.199\rho^{0.899}D^{2.22}}$$

where: RB Root biomass (kg)
ρ is the wood density of each species (g cm^{-3})
D the total diameter of each species (cm)

Estimation of AQS mangrove sediment carbon stock

Mangrove sediment sampling and analysis

Three parameters were quantified to accurately measure the sediment carbon pool: sediment depth, soil bulk density, and organic carbon concentration. When mangrove sediment is deeper than 1 meter, it is recommended that at least the top 100 cm are sampled. This study sampled mangrove sediment at depths of 0-15 cm, 15-30 cm, 30-50cm, and 50-100 cm (Kauffman *et al*., 2011; Donato *et al.*, 2011).

A specialized auger was used to obtain sediment samples for bulk density and carbon analysis. At the sampling location, the organic litter was removed from the surface. Then the auger was steadily inserted vertically into the soil until the top of the sampler was level with the soil surface. Once at depth, the auger was twisted in a clockwise direction a few times to cut through any remaining fine roots. After which, the auger gently pulled out of the soil while continuing to twist it to assist in retrieving a complete sediment sample.

Once an undisturbed soil core had been extracted, a meter stick was used to determine the depths from which the samples were collected. Subsamples representing a given depth range are generally adequate for mangroves (versus collecting the entire depth range) because carbon content changes much more slowly with depth than in upland forests (Donato *et al*., 2011; Kauffman *et al*., 2011). For each depth, a 5-cm sample was obtained for bulk density measurement, and the remaining was analyzed for carbon. Upon removal of subsamples from the auger, they were carefully placed in a labeled plastic bag with AQS number, plot number, and sediment depth range.

Labeled samples were oven-dried for 11 hours at 105 ℃ for bulk density samples, while the Loss of ignition (LOI) method was employed to analyze the carbon content of the sediment sample. Using the LOI method, the sediment samples were oven-dried for 11 hours and then subjected to ignition at 450 ℃ for eight hours. The weight of the samples before and after the LOI method was used to calculate the percent organic carbon (%OC). The percent organic carbon was calculated using the formula below (ERDB, 2015):

$$\%\,\boldsymbol{OC} = -\mathbf{0.33} + (\mathbf{0.43}\ \boldsymbol{x}\ \%\boldsymbol{LOI})$$

where: %OC is the percent organic carbon content of the sediment sample
%LOI is the change in sample weight after oven-drying and ignition

Calculation of total sediment carbon stored

Bulk density and sediment carbon are needed to calculate the total sediment carbon stored. The following equations were used in the calculation (Donato *et al*., 2011):

$$\boldsymbol{Bulk\ density}\ (\boldsymbol{g\ cm^{-3}}) = \frac{\boldsymbol{oven-dry\ weight}\ (\boldsymbol{g})}{\boldsymbol{volume\ of\ cylinder}\ (\boldsymbol{cm^3})}$$

$$\boldsymbol{Soil\ carbon\ density}\ (\boldsymbol{Mg\ ha^{-1}}) = \boldsymbol{Bulk\ densty\ x}\ \%\boldsymbol{Carbon\ x\ soil\ depth}\ (\boldsymbol{cm})\boldsymbol{x}\ \mathbf{100}$$

Total carbon stock and CO_2 equivalent of AQS systems

For the calculation of the total carbon stock of the aquasilviculture study areas, the aboveground (ABG) biomass carbon, root biomass (RB) carbon, and sediment carbon density (soil) were used.

$$Total\ Carbon\ Stock\ (Mg\ ha^{-1}) = C_{ABG} + C_{RB} + C_{SEDIMENT}$$

In addition to the total carbon stock of each aquasilviculture study area, the total carbon dioxide (CO_2) equivalents were calculated. This was done by multiplying the total carbon stock by 3.67. The factor was derived by obtaining the ratio of the molecular weight of the carbon dioxide compound and carbon molecule (Kauffman and Donato, 2012; Harishma *et al.*, 2020). The resulting value of CO_2 equivalent can be monetized by multiplying it by USD 4.3, which is the average current price of blue carbon stock according to Donofrio *et al.*, (2020).

$$CO_2\ equivalent\ (Mg\ ha^{-1}) = Total\ carbon\ stock\ (Mg\ ha^{-1})\ x\ 3.67$$

Statistical analysis

The data collected in the field were encoded in Microsoft Excel. Shapiro-Wilk test was used for testing the normality of data. Upon passing the Shapiro-Wilk tests, analysis of variance (ANOVA) was used to analyze the differences among means. A Tukey's range test was used to determine means that are significantly different from each other. Otherwise, Kruskal-Wallis one-way ANOVA and Dunn’s test were used.

Results

General characteristics of each aquasilviculture system

AQS 1 had the largest area among the AQS, having 1.38 hectares and a perimeter of 490 meters. The model type of AQS 1 is mixed. The stands of the bakauang lalaki (*Rhizophora apiculata*), which were approximately 19 years old, served as home to fruit bats who migrated to the area since the year 2014. With that, the PO developed this area as an ecotourism site through the help of various organizations, especially the local government units of Infanta. The pond age is 19 years. The average water depth is 2 meters. The culture/production system is pen-silviculture. Currently, the main type of operation in the pond is mangrove crab grow-out culture. The production scale is extensive. This is characterized by no aeration; little to almost no labor; a current stock density of up to 70 individuals only; and the feeding rate of crabs is only every other day of one kilogram only. In terms of fertilization, the bat’s guano is considered the source of nitrogen in this AQS.

AQS 2 was the smallest among the four AQS in the CBFM area, with an area of 0.16 hectares and a perimeter of 163 meters. Mangroves are in the boundary of the pond dike. Thus, AQS 2 exemplifies the peripheral or separate AQS model type. The mangroves in this area were naturally planted and were approximately more than 20 years old. Also, there are no silviculture treatments employed in this pond. The age of the pond is 17 years. The water depth is 2 meters. The culture/production system is pond because it is fully enclosed with a dike. At present, milkfish and shrimp grow-out and mangrove crab fattening are the operations in the pond. The production scale for this pond is semi-intensive due to the application of fertilizer and lime inputs as well as the feeding of artificial and supplementary feeds. Fertilizer inputs such as 16-20-0, 14-14-14, chicken manure, and urea are used to grow *lablab* (natural food of fish). Side dressing is done by broadcasting four kilograms of 16-20-0 every other day to ensure lablab growth.

AQS 3 has an area of 0.20 hectares and a perimeter of 303 meters. The aquasilviculture model type of this pond is also mixed. Mangroves were found inside the pond dike along with the fish culture. Stand age of AQS 3 mangroves is more than 20 years old. The pond age of AQS 3 is only two years. The culture/production system is pond. Milkfish and *samaral* grow-out polyculture is the main type of operation in this pond. Similar to AQS 2, AQS 3 is also a semi-intensive production scale. Fertilizer inputs such as 14-14-14, 16-20-0, urea, and chicken manure were being applied to grow natural food such as *lablab* and *lumot.* Four kilograms of mixed fertilizers are applied every other day as side-dressing to support *lablab* production.

AQS 4 was second to the largest AQS, with an area of 1.14 hectares and a perimeter of 435 meters. This AQS adopted a peripheral or separate model type of aquasilviculture. *Bakauang babae* (*Rhizophora mucronata*) dominated the area because of the soft mud of the AQS. The approximate stand age is 19 years. Unlike the other AQS, there is no intentional culture in this 20-year-old pond. The culture or production system is pen since only nets surround the pond. A fish net trap with an eye size of 14, *hilo* or thread size of 2, and a height of 2m was installed in the middle of the pond to catch wild fishes.

Mangrove flora characteristics

Different mangrove species were observed in each aquasilviculture system. Based on their population, the dominant mangrove communities were identified. In terms of true mangrove species, 15 species were observed in the four aquasilviculture sites. Closer inspection of the mangrove communities of the different AQS also revealed that there are two species: (*Aegiceras corniculatum* (L.) Blanco, *Avicennia officinalis* L.) that dominate AQS 1, whereas AQS 2 and 3 have relatively similar distribution for each observed species. AQS 4, similar to AQS 1, has a high number of observed mangrove species but with one or two more dominant populations (*Rhizophora apiculata* Blume and *Rhizophora mucronata* Lamk.).

Total blue carbon stock of aquasilviculture systems

The mean carbon stock of various carbon pools in each AQS and the potential value of their total blue carbon stock are presented in Table 3. There was a significant difference between AQS 1 and AQS 4 in terms of aboveground and belowground carbon stock ($p<0.05$). The aboveground and belowground carbon stock of AQS 2 and AQS 3 were not significantly different from each other. AQS 4 was observed to have the highest aboveground (101.12 Mg C ha^{-1}) and belowground carbon stock 48.05 Mg C ha^{-1}. For the sediment carbon stock, values for the four AQS ranged from 945.67 Mg C ha^{-1} to 1,023.00 Mg C ha^{-1}. The highest sediment carbon stock was observed in AQS 3 (1,023 Mg C ha-1), although there was no observed significant difference in the values of the four AQS ($p<0.05$). There were also no significant differences between the total carbon stock values and CO_2 equivalent of each AQS.

Table 3. Carbon stock of various carbon pools and the potential value of blue carbon in each aquasilviculture system

Parameter	**AQS 1**	**AQS 2**	**AQS 3**	**AQS 4**
Aboveground Carbon stock (Mg C ha^{-1})	67.83 [a]	77.00 [ab]	75.81 [ab]	101.12 [b]
Belowground Carbon Stock (Mg C ha^{-1})	32.74 [a]	36.32 [ab]	36.53 [ab]	48.05 [b]
Total Sediment Carbon (Mg C ha^{-1})	945.67 [a]	956.36 [a]	1,023.00 [a]	992.30 [a]
Total Carbon Stock (Mg ha^{-1})	1,046.25 [a]	1,069.68 [a]	1,135.34 [a]	1,141.47 [a]
CO_2 equivalent of Total Carbon Stock (Mg ha^{-1})	3,839.73 [a]	3,925.73 [a]	4,166.70 [a]	4,189.20 [a]
Potential value in USD	16,510.84	16,880.64	17,916.81	18,013.56
Potential value in PHP	901,491.86	921,682.94	978,257.83	983,540.38

Note: Means followed by the same letter in the row are not significantly different at the 5% level.

It can be observed that the highest total ecosystem carbon stock was calculated from AQS 4, with 1,141.47 Mg C ha^{-1} from aboveground, root, and sediment carbon stock. This was followed by AQS 3, with 1,135.34 Mg C ha^{-1}. The results of this study show that a large portion of the carbon stock potential of a mangrove ecosystem comes from the sediment carbon pool. In this study, the sediment carbon stock potential comprises more than 86% of the total ecosystem carbon stock. Among the four study areas, AQS 1 has the highest sediment carbon stock contribution to the total carbon stock, with 90.39% of the total ecosystem carbon stock of AQS 1 coming from the sediments. AQS 4, on the other hand, has 86.93% of its total ecosystem carbon stock contributed by the sediment carbon stock.

In terms of valuation of the total blue carbon stock in each AQS, the potential amount from carbon offset that the four AQS in this study can provide ranged from Php 901,491.86 to Php 983,540.38.

Discussion

Mangrove biomass carbon stock

Aboveground carbon stock

Differences can be explained by the type of mangroves dominant in the area. In AQS 4, the dominant mangrove species are *Rhizophora apiculata* Blume, *R. mucronata* Lamk., and *R. stylosa* Griff. Among the other species present in the study areas, these species have the highest wood density values, at 0.8500, 0.8200, and 0.8400, respectively. Since wood density is highly correlated with aboveground (ABG) biomass, higher wood density will also translate to higher biomass and, thus, higher carbon stock potential. The low calculated aboveground biomass and potential carbon stock in AQS 1 can also be attributed to the dominance of *Aegiceras corniculatum* (L.) Blanco, which had one of the lowest wood density values among the observed species (0.5100). The woody component of the mangrove tree is the highest accumulator of organic carbon; thus, higher aboveground biomass and wood density will result in higher carbon stock potential (Hidayah and Andriyani, 2019). Similarly, AQS 1 also had the lowest mean value for diameter at breast height (DBH), at 8.5604 cm. These parameters had a linear relationship with biomass, and therefore with potential aboveground carbon stock. Thus, low wood density and low DBH resulted in the lowest aboveground carbon stock of AQS 1 among the four AQS study areas. In addition to wood density and diameter at breast height, tree density can also be considered the main factor influencing the aboveground biomass and therefore, the aboveground carbon stock. AQS 4 was observed to have the highest tree density (4,525 trees ha^{-1}) and the highest aboveground carbon stock as well (Hidayah and Adriyani, 2019).

The mean aboveground carbon stock potential obtained in this study for the whole AQS system is also similar to the value obtained in the study of Gevaña *et al*. (2008). In one of their study areas, the Rhizophora-dominated mangrove area in Brgy. Catmon, San Juan, Batangas also has a mean carbon stock potential of 103.50 Mg C ha^{-1} from mangrove biomass. Their study also found a higher carbon stock potential for a mangrove community dominated by *Avicennia*, which was found to have 125.79 Mg C ha^{-1} from plant biomass.

Belowground carbon stock

Similar to aboveground biomass, wood density and DBH were used in the calculation of root biomass, and thus, the same trend was observed for the root biomass. Compared to other upland forests, mangrove forests have higher root biomass. Mangroves invest a large production allocation into their root systems, mainly because of the environmental stressors present in their habitat. The presence of a high water table, seasonal to daily inundation by seawater, high salinity, and lack of sturdy soil as growth medium results in the high root biomass production of mangroves (Kathiresan *et al.*, 2013). Jackson *et al.* (1997) noted that root biomass accounts for only 20% of the total plant biomass in upland forests such as temperate and boreal forests.

The majority of the carbon stock potential from mangrove tree is contributed by the aboveground (ABG) biomass. Carbon stock potential from aboveground biomass constitutes 67.68% of the total carbon stock from mangrove biomass, whereas the root biomass contributed to the remaining 32.32%. The mean potential carbon stock from mangrove biomass in the AQS systems in BIPCO-CBFM is 118.85 Mg ha^{-1}. This result is relatively higher, compared to Kerala mangroves in southwest India, with an average carbon stock potential of 58.56 tons (or Mg) C ha^{-1}. However, the mean carbon stock potential from mangrove biomass from the AQS site is slightly lower than the average carbon stock potential of the mangrove areas in the Northern region of Kerala, which has an estimated value of 123.28 Mg ha^{-1}. This is considered as the most carbon-rich mangrove region in the coast of Kerala. Though, the mean carbon stock potential in the Southern region of Kerala is considerably lower than the results of this study, with an estimated carbon stock potential of 28.13 tons (or Mg) ha^{-1} (Harishma *et al*., 2020).

Sediment carbon stock

The proximity of the four AQS to one another can be used to explain why the overall values for the AQS were close. AQS 3 having the highest sediment carbon stock is similar to the results from Gevaña *et al*. (2018), who found that older mangrove stands tend to have higher carbon stock potential, whether the aboveground or the sediment carbon stock. In this study, it was found that AQS 3 has only been two years operational as a community-managed aquasilviculture area; however, it has the oldest mangrove stand of more than 20 years old, whereas the other three AQS are relatively younger by a few years. In addition, the carbon stock potential from mangrove sediments from the four AQS was higher than the average range of values, from 115.5 to 939.3 Mg C ha-1 (Kauffman and Donato, 2012).

Total blue carbon stock of AQS

The findings were comparable to the study of Wang *et al*. (2019) in three mangrove forests in South China. While their observed total ecosystem carbon stock from three mangrove stands was lower than the calculated total ecosystem carbon stock from this study, they found that the largest contributor to ecosystem carbon stock is the organic carbon-rich soils of mangrove forests. Their study has shown that soil organic carbon accounted for more than 76% of the total ecosystem carbon stock, with as high as 89.99% in one of their study areas in Dongzhai Harbor, South China. Similar to the study conducted by Harishma *et al*. (2020), soil carbon stock also constitutes the majority of the total ecosystem carbon stock in the mangrove areas in Kerala, India. For instance, in the central zone of their study area, 80% of the total ecosystem carbon stock is contributed by mangrove sediments. In their study areas, only one area (northern zone) has a higher carbon stock from total plant biomass; in this case, it is only 15% higher than the soil carbon stock. The contribution of soil carbon to the total ecosystem carbon stock ranges from 42-80%. Kauffman and Donato (2012) also compared the total ecosystem carbon stock potential of different forests: tropical, temperate, boreal, tropical savannas, and mangrove forests, and found that the total carbon pool of mangroves is the highest and can store twice as much carbon as the carbon pool of upland tropical and temperate forests.

The results of this study also confirmed the high potential carbon stock of mangroves. The capability of mangroves to store and sequester carbon, from their high plant biomass and wood densities to the organic carbon they can sequester from litterfall and into the soil, makes them an important aspect for climate change mitigation. Carbon stock potential from aboveground biomass of mangroves can range from the lows of 8 Mg ha^{-1} of dwarf mangroves to more than 500 Mg ha^{-1} in riverine and fringe mangroves in the Indo-Pacific region (Kauffman and Donato, 2012).

Valuation of AQS' blue carbon

The potential value of the blue carbon stock in each AQS can serve as an additional income for the People's Organization (PO) managing the area. This is in addition to the revenue the PO generated from their culture of aquatic species. In the study of Thompson *et al*. (2017), payment of ecosystem services (PES) of blue carbon stock can also contribute an additional 2.3-5.8% of income for the local communities. For instance, a mangrove PES system in Indonesia generated 3% additional income for the whole community and was successfully implemented when livelihood is incorporated into the program. Therefore, aquasilviculture systems is a good climate mitigation strategy with socio-economic advantages.

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