p-ISSN 2012-3612 | e-ISSN 2782-8824
www.edjournal.cfnr-uplb.org

Ecosystems and Development Journal
Volume 11 | Numbers 1 & 2 | pp. 48–60 | 2021

Assessment of blue carbon stock of mangrove vegetation in Infanta, Quezon, Philippines

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ABSTRACT. Mangroves provide a natural solution for sequestering atmospheric carbon. Quantifying the potential carbon storage in mangrove ecosystems is crucial in harnessing mangrove's function for climate change mitigation. The objective of this study is to assess the carbon stock of mangrove vegetation in Infanta, Quezon through remote sensing. To determine the spatiotemporal changes in mangrove area by vegetation density (bare, sparse, and dense) of different barangays, Normalized Difference Vegetation Index (NDVI) analysis was done using corrected satellite images through ArcGIS. The annual rate of change (%) of mangrove forests was computed. Accuracies of the NDVI images were calculated using semi-automatic classification plugin (SCP) of QGIS, which showed a high accuracy of the classification process. Secondary data on aboveground mangrove carbon stocks in San Juan, Batangas, and the computed mangrove area of Infanta were utilized in the computation of aboveground carbon stock and its corresponding CO_2 equivalent. Over the 20-year study period, dense mangrove cover changed by –11.7%. Although there was an increase in dense mangroves of 2.6% over the 2000–2010 period mainly in Barangay Binonoan and Dinahican, the following decade (2010–2020) recorded a decrease of –14.2% implying that gradual mangrove deforestation or degradation persisted outweighing the reforestation efforts of various agencies in the study area. For the municipality as a whole, the estimated aboveground carbon stock for the years 2000, 2010, and 2020 were 304.3 Gg C, 310.7 Gg C, and 286.6 Gg C, respectively with corresponding translated equivalent values of 1,115 Gg CO_2, 1,139.4 Gg CO_2, and 1,050.8 Gg CO_2. Mangroves of Infanta are worth at least USD 4.5 million at USD 4.3 ton^{-1} CO_2 (prevailing market price as of 2020). As a result, mangrove forests in the research area should be continuously conserved to ensure sustained carbon sequestration and other equally important ecosystem services.

Keywords: *coastal, cover change, climate change mitigation, rehabilitation, remote sensing*

INTRODUCTION

Mangrove stands are perceived as muddy wastelands, but they actually provide a vast range of ecosystem goods and services (Songcuan *et al*. 2015). Ecosystem goods and services include provisioning (food, water, fisheries, dyes, timber, and medicine), cultural (ecotourism, cultural heritage, and religious sites), regulating (blue carbon, flood reduction, sediment trapping, and land–sea barrier), and supporting (habitat for fauna such as tigers, fruit bats, crocodiles, and migratory birds to name a few, as well as acting as nursery grounds for various fishes, and crustaceans) (Marschke 2012). The Philippines have almost 50% of the world's known `mangrove species, as well as it holds the top 15 mangrove–rich countries spot (Garcia *et al*. 2014). Being an archipelagic country where most of the population lives near or on the shore, mangroves are used mostly as a source of fuelwood and food. Mangrove fish and shellfish offer coastal populations with protein, as well as livelihood opportunities for some (Fitri *et al*. 2018).

Long-term alteration of temperature and typical weather patterns brought by global climate change have already been observed and experienced, which is induced by greenhouse gas emissions, particularly carbon dioxide. Amidst climate change, many of the mangroves' regulatory functions are becoming increasingly vital. Mangrove forests are one of the planet's most carbon–dense ecosystems, and its blue carbon has been identified and researched as part of climate change mitigation initiatives focused on reducing human greenhouse gas emissions (USAID 2017; Muhd-Ekhzarizal *et al*. 2018; Valenzuela *et al*. 2020). The term "blue carbon" was coined to emphasize the significant carbon storage capacity of coastal vegetated ecosystems. When healthy, Philippine mangroves (national average of 624 Mg C ha^{-1}; Salmo 2019) may sequester 180 teragrams (Tg) of carbon (1 Tg = 1,000,000 Mg), which equates to roughly 661 Tg of avoided CO_2 emissions (Gevaña *et al*. 2018; Salmo *et al*. 2019a).

Despite their critical role in climate change mitigation and adaptation, mangroves are at risk of destruction (Ahmed & Glaser 2016; Gevaña *et al*. 2017; Ellison *et al*. 2020). Tacio (2012) stated that during the previous century, the Philippines has lost about three-fourths of its mangroves owing to a continual deforestation rate of almost 2,000–3,000 ha yr^{-1}. Mangrove forests worldwide have been degraded and converted to make room for more profitable industrial and agricultural productions. These activities contributing to the loss of numerous mangroves were aquaculture development, agriculture, urbanization, reclamation, climate change and environmental degradation, charcoal production, as well as timber and fuelwood over-harvesting (Garcia *et al*. 2014; Basyuni 2018). Given that mangroves grow and thrive in highly stressed and disturbed ecosystems, this also adds to the vulnerability of mangroves to many types of devastation. Significant cover loss suggests a substantial decline in critical ecosystem services, most notably climate change mitigation (Ahmed & Glaser 2016; Gevaña *et al*. 2018). Although a promising research endeavor, there is still a dearth of research and studies on mangroves due to unfavorable site location and conditions.

To address the country's catastrophic rate of mangrove deforestation and degradation, numerous projects and undertakings relating to mangrove restoration and conservation have been initiated (Primavera & Esteban 2008; Pulhin *et al*. 2017; Gevaña *et al*. 2021). Blue carbon ecosystems, especially mangroves, are now being included in climate change mitigation strategies, most notably in the Reducing Emissions from Deforestation and Forest Degradation, or REDD, and United Nations Framework Convention on Climate Change, or UNFCCC (Gevaña *et al*. 2019; Salmo 2019). Mapping these blue carbon ecosystems and quantifying their capacity to sequester carbon are among the first stages toward carbon credit. This value is critical for conservation and restoration to achieve climate resilience. Rapid and accurate assessments of mangroves over a range of spatial and temporal scales can be offered by utilizing geospatial technology (GST) analysis tools such as geographic information system (GIS) and remote sensing (RS) (Dahdough-Guebas 2002; Vaiphasa 2006; Omar *et al*. 2019). These tools can also be used to evaluate the effectiveness of various reforestation projects and mangrove-related policies. Gathered accurate information is essential for sustainable mangrove conservation and management, integrated land and sea use planning, and crafting of mangrove-related policies.

The study aimed to assess the blue carbon stock of mangrove vegetation in Infanta, Quezon using remote sensing techniques. Specifically, it intended to: 1) characterize spatiotemporal changes and the annual rate of change of mangrove vegetation density in the year 2000, 2010, and 2020; 2) assess the estimated aboveground carbon stock of mangroves; and 3) identify the potential drivers of mangrove cover and carbon stock changes for consideration in designing future carbon conservation strategies.

METHODOLOGY

Methodological framework

Mangrove cover and carbon stock change were determined following the methodological framework (**Figure 1**). This framework portrays arranged and simplified methods performed in this study. Characterization of vegetation density changes was done through NDVI analysis. Mangrove areal extent obtained from NDVI analysis as well as secondary data of aboveground carbon stock of San Juan, Batangas acquired from the study of Gevaña *et al*. (2008) were utilized in the estimation of blue carbon. Lastly, determining potential drivers of change will aid in crafting future carbon conservation strategies.

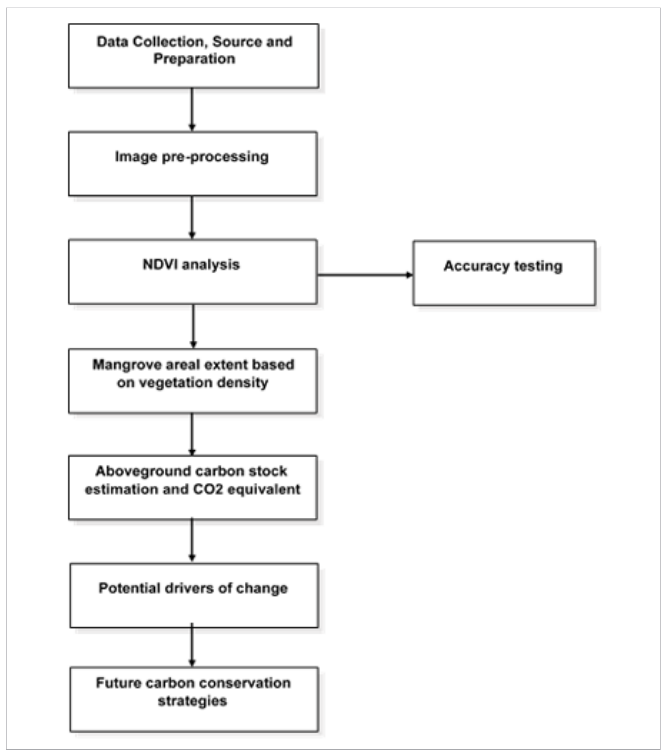


Figure 1. Methodological framework of the study.

Site description

Infanta is located 144 km northeast of Manila, and 136 km north of Lucena City, the capital of Quezon Province. It is situated in the northern part of the Quezon province, lying along the shore of the Philippine Sea. Infanta's northern limit was the Umiray River in the north and Magasawang

Bato in the southeast. It is bounded on the northwest by the Municipality of General Nakar, and on the southwest by the Municipality of Real, Quezon (**Figure 2**).

Following the DENR Cadastral Survey, roughly 19,934 ha of the municipality is subdivided into urban barangays, rural barangays, and mangrove zone. The five urban barangays are 227.9 ha, which is 1.1% of the total land area of the municipality. Rural barangays account for 84.5% (16,844.6 ha) of the total land area. Of the remaining 2,861.8 ha, 14.4% is mangrove forest. Many households have their shelters near or adjacent to mangroves for various livelihoods and fuelwood sources. Out of the total mangrove area, only 139 ha are with tenure *i.e*. CBFM Agreements of the Binulasan Fisheries and Aquatic Resources (BFARMA) and Binonoan Producers Cooperative (BIPCO), and the remaining mangrove areas are open access or untenured.

The climate of Infanta falls in the tropical rainforest (Af) category, a type of tropical climate with no dry season where all months receive mean precipitation of 60 mm (2.36 in). Further, the municipality falls under Type II of the Modified Coronas Classification (MCC) which means no dry season but there is a pronounced wet season from November to April. In terms of soil, Hydrosol, Quingua Silt Loam, Buguey Loam Sand, Antipolo Sandy Clay, and Mountain Soils were found common. Hydrosol is a prevalent component of mangrove and nipa swamps in southern Lamon Bay.

In terms of mangrove–related livelihoods, Infanta primarily consists of light and cottage–based industries that predominantly produce food, lambanog (nipa wine), tuba (fermented coconut wine), suka sa sasa (nipa vinegar), and pawid or nipa shingles. These are the principal mangrove–related products that are being marketed locally and abroad. The municipality is also home to 29 accredited non–government organizations (NGOs), civil society organizations (CSOs), and POs that collaborate in developing rural livelihoods. Some of these contribute to mangrove management and rehabilitation such as the Binonoan Producers Cooperative (BIPCO), Alitas Farmers Association (AFA), Binulasan Fisheries and Aquatic Resources (BFARMA), Maralitang Mangingisda ng Munting Sabang (MMMSA), and Haribon Foundation.

Data collection, source, and preparation

Band–specific Landsat scenes for the municipality of Infanta were procured from the United States Geological Survey (USGS) along with a 2015 Philippine Land Cover map from the National Mapping and Resource Information Authority (NAMRIA). Specifically, Landsat 5, 7, and 8 for the years 2000, 2010, and 2020 respectively were obtained. Information and details on these satellite images are summarized in **Table 1**.

Table 1. Satellite data used in the analysis of the study.

Satellite	Sensor	Date	Path/Row
Landsat 7	ETM	06/09/2000	115/050
Landsat 5	TM	07/06/2010	116/050
Landsat 8	OLI_TIRS	12/24/2020	116/050

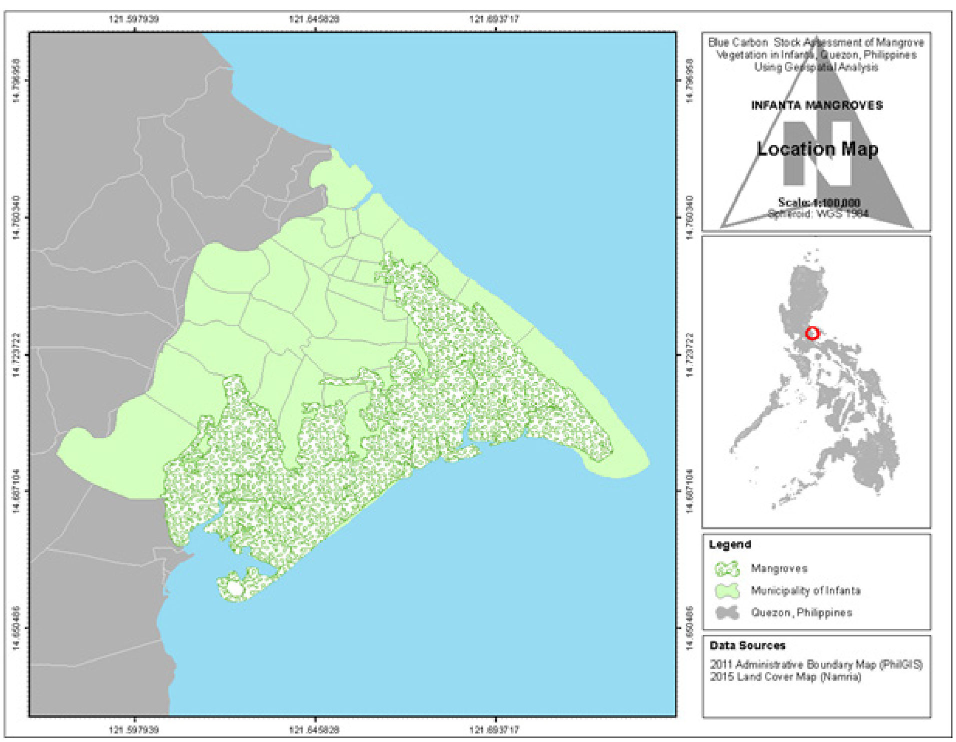


Figure 2. Location map of Infanta, Quezon, Philippines and its mangroves *(Source: PhilGIS and NAMRIA).*

These raster images were selected based on availability and the least amount of cloudiness to avoid estimation errors in the Normalized Difference Vegetation Index (NDVI) analysis. Collected along with these were metadata text files for each raster image. Metadata files include specific satellite information including solar elevation necessary for the first process, which is conversion to radiance. Through ArcGIS (V.10.8), these digital numbers were converted to radiance and further corrected to Top of atmosphere (TOA) reflectance with the following equations (Chander & Markham 2003):

Digital number (DN) to radiance (Landsat 5 and 7)

$$L_\lambda = \left(\frac{LMAX\lambda - LMIN\lambda}{Qcal\ max}\right) Q_{cal} + LMIN_\lambda \qquad \text{(Equation 1)}$$

where:

L_λ Spectral Radiance (sensor's aperture)
Q_{cal} Quantized calibrated pixel value (DN)
Q_{calmax} maximum quantized calibrated pixel value
$LMAX_\lambda$ Spectral radiance that is scaled to Qcalmax
$LMIN_\lambda$ Spectral radiance that is scaled to Qcalmin

Radiance to TOA Reflectance (Landsat 5 and 7)

$$\rho_\lambda = \frac{\pi \cdot L_\lambda \cdot d^2}{Esun_\lambda \cdot \cos\theta_s} \qquad \text{(Equation 2)}$$

where:

ρ_λ TOA planetary reflectance
L_λ Spectral radiance (sensor's aperture)
d distance of earth from the sun
$E_{sun\lambda}$ mean solar atmospheric irradiance
θ_s solar zenith

Converting digital numbers into radiance is an essential prerequisite in compiling multiple sensory data (Chander & Markham 2003). Moreover, radiometric correction through the conversion of radiance to TOA reflectance has made Landsat scenes comparatively clear and better as solar irradiances are adjusted and refined. However, the difference in sensors between Landsats 5, 7, and 8 caused a variation not in the method but in the manner of conversion and correction. The following are adopted equations contextualized to Landsat 8 scenes.

Digital number (DN) to radiance (Landsat 8)

$$\rho_\lambda = \frac{\rho_\lambda'}{\sin(\theta)} \qquad \text{(Equation 3)}$$

where:

ρ_λ TOA planetary spectral reflectance
θ Sun elevation

Radiance to TOA reflectance (Landsat 8)

$$\rho_\lambda = M_\rho \cdot Q_{cal} + A_\rho \qquad \text{(Equation 4)}$$

where:

ρ_λ TOA planetary spectral reflectance
M_ρ Band-specific multiplicative rescaling factor
A_ρ Band-specific additive rescaling factor
Q_{cal} Quantized calibrated pixel value (DN)

Through the TOA Reflectance, prior digital numbers were converted to well-suitable values for NDVI, that is –1 to 1. NDVI values were then calculated using the corrected bands from the TOA reflectance with the equation (Myeong *et al*. 2006):

$$NDVI = \left(\frac{NIR - Red}{NIR + Red}\right) \qquad \text{(Equation 5)}$$

where:

Red red in-band planetary albedo
NIR near infrared in-band planetary albedo

Additionally, site-specific mangrove boundaries were then extracted into shapefiles from the 2015 Land Cover map by NAMRIA. These maps are necessary in the NDVI process in distinguishing site-specific cover change in mangroves.

Data processing

Processed NDVI corrected images for the mangroves of Infanta were reclassified into a range of three indices for identification of vegetation densities, namely: a) bare (0.00–0.10), b) sparse (0.11–0.50), and c) dense (0.51–1.00) mangrove cover. These vegetation densities refer to the condition of in-land vegetation and are contextualized to mangrove areas in this study. As such, these may refer to bare and sparse covers as open or barren lands and partially vegetated areas respectively. Similarly, dense cover refers to vegetated mangrove areas which may either be adults or past the sapling stage to which in the range is relatively advised to be above the index 0.5 to a fully vegetated area. Vegetation densities on barangay-level boundaries were also obtained through the Identity toolbar in ArcGIS software along with the pre-extracted mangrove boundaries. This would lead to enhanced and more specific values for bare, sparse, and dense mangrove cover within the municipality of Infanta. Additionally, identity rectified maps were then projected to a recommended coordinate system, that is WGS 1984. Accuracy assessment of the reclassified NDVI images was calculated using overall percentage and Kappa coefficient and evaluated through the Semi-automatic Classification plugin (SCP) of QGIS software (v.3.16). The annual rate of change of forest cover between two time periods was computed using the equation developed by Puyavaud (2003):

$$r = \left(\frac{1}{T2 - T1}\right) * \ln \frac{A2}{A1} \qquad \text{(Equation 6)}$$

where:

A area (ha)
T time (year)

Aboveground blue carbon stock and equivalent CO_2 determination

In the absence of actual ground data, aboveground carbon stock estimates from the study of Gevaña *et al*. (2008) for natural mangrove stands in San Juan, Batangas were used. Infanta and San Juan mangroves, which are roughly 115 km apart, belong to the same geographical region of Luzon Island, Philippines. Aboveground carbon stock estimates (Mg ha^{-1}) were multiplied by the maximum NDVI values observed that are representative of the percentage mangrove vegetation density (*i.e.* 0.1, 0.5, and 1.0 for bare, sparse, and dense, respectively). The total aboveground carbon stock (Mg ha^{-1}) and the mangrove area (ha) for each vegetation density were multiplied to obtain the aboveground carbon stock, expressed in gigagram (Gg). Aboveground carbon stock values (Gg C) were multiplied by 3.667 (conversion factor of carbon to carbon dioxide) to obtain their respective carbon dioxide (CO_2) equivalencies.

RESULTS AND DISCUSSION

Mangrove vegetation cover change analysis

Infanta's mangrove area was estimated to be 2,556.8 ha, which is about 18% of Quezon's total mangrove area based on the study of Long & Giri (2011). This estimated mangrove area conformed to the 2012–2017 Forest Land Use Plan (FLUP) of Infanta's Local Government Unit (LGU) where the mangrove area was around 2,341 ha. It is interesting to note that out of the total 36 barangays of Infanta, 27 barangays are with mangroves (**Table 3**).

Vidhya *et al*. (2014) stated that vegetation density shows the health status of the forest which depends on the percentage of the canopy cover of the mangrove forest in the area. The NDVI analysis of mangrove forests showed that vegetation cover and patterns indicated the quantity of actively photosynthesizing mangrove biomass. The higher the NDVI value, the denser the vegetation with higher photosynthetic activities (Burgan & Hatford 1993; Burgan *et al*. 1999; Ibrahim *et al*. 2013). Dense mangrove is indicative of healthy mangroves with 50–100% tree cover.

NDVI maps of Infanta mangroves for the three periods were created to visualize the numbers shown in **Figure 3** and **Table 3**. Reclassified NDVI images based on vegetation density were evaluated and obtained an overall accuracy of 96.24% with an associated Kappa value of 0.93 (**Table 2**). These values indicated a high rate of classification accuracy.

Reclassified NDVI as shown in **Figure 3** exhibited a dark green area reflecting more dense vegetation in Barangay Binonoan amounting to 496.5 ha in 2000, 516.4 ha in 2010, and 452.1 ha in 2020. These barangays are both CBFM and reforestation sites of DENR.

In 2000, the areal percentages of bare, sparse, and dense were 2.1% (53.5 ha), 7.0% (179.0 ha) and 90.9% (2,324.4 ha).

Table 2. Accuracy of the reclassified NDVI images.

Layer	Overall accuracy (%)	Kappa value
2000	92.31	0.89
2010	96.43	0.92
2020	100	1.00

A decade after, bare and sparse areas decreased to 7.8 ha (0.3%) and 159.1 ha (6.2%), respectively, while dense vegetation increased to 2,389.9 ha (66.3%) in the year 2020. However in 2020, there was a significant increase in both bare and sparse areas to about 34.0 ha (1.3%) and 496.3 ha (19.4%), respectively, and a substantial decrease in dense areas to 2,026.5 (79.5%) (**Table 4**). Actual photos of bare, sparse, and dense areas are shown in **Figure 4** and **Figure 5**. Further, similar methods of detecting cover change using NDVI were also featured in several studies. For instance, in a related study by Shimu *et al*. (2019), NDVI was used to determine areas in the Sundurban Mangrove Forest with the highest amount of vegetation, water changes, areas with little vegetation as well as to account for the cover changes between 2011 and 2019. Additionally, in the study by Gevaña *et al*. (2015), the cover change in Banacon Island, Bohol was accounted for using the Maximum Likelihood Estimation (MLE) supported by multiple ground-truthing, existing data on forest cover types, and accuracy tests through the Kappa Index. In this study, three major classifications were identified including forest (dense and sparse), coastal sand, and sea. About 9% increase in dense stands from 1993 to 2004 was determined. In another study by Aburas *et al*. (2015) in Seremban, Malaysia from 1990 to 2010, NDVI categories used include sparse, moderate, high, dense, and non-vegetated areas. Despite the differences in approaches, these indices were noted to be reliable in describing specific cover changes.

The forest cover change and the annual rate of change (%) in three time periods are shown in **Table 4**. Results showed a cover change of –11.7% in dense mangroves over the 20–year–period. Although there was an increase in dense mangroves of 2.6% over the 2000–2010 period mainly in Barangay Binonoan and Dinahican, the following decade (2010–2020) recorded a decrease of 14.2%. This could indicate that gradual mangrove deforestation and degradation persisted that negated the gains of reforestation efforts of various national government agencies and NGOs in the study area. In terms of the annual rate of change in mangrove cover, 0.3% increase in dense cover was noted between 2000 and 2010. This is reflective of the annual decrease in bare and sparse cover by almost 19.2% and 1.2%, respectively. The decrease in bare areas and partially opened areas could indicate that these areas have become vegetated over the years. However, for the 20–year–period dense mangrove areas declined by 0.7% annually. The annual increase in dense forest cover between 2000 and 2010 notwithstanding, roughly 27.2% of the land was cleared and partially opened between 2010 and 2020, which led to an annual decrease of 1.6% in dense areas during the period. The annual rate of change in vegetation densities is summarized in **Table 4**.

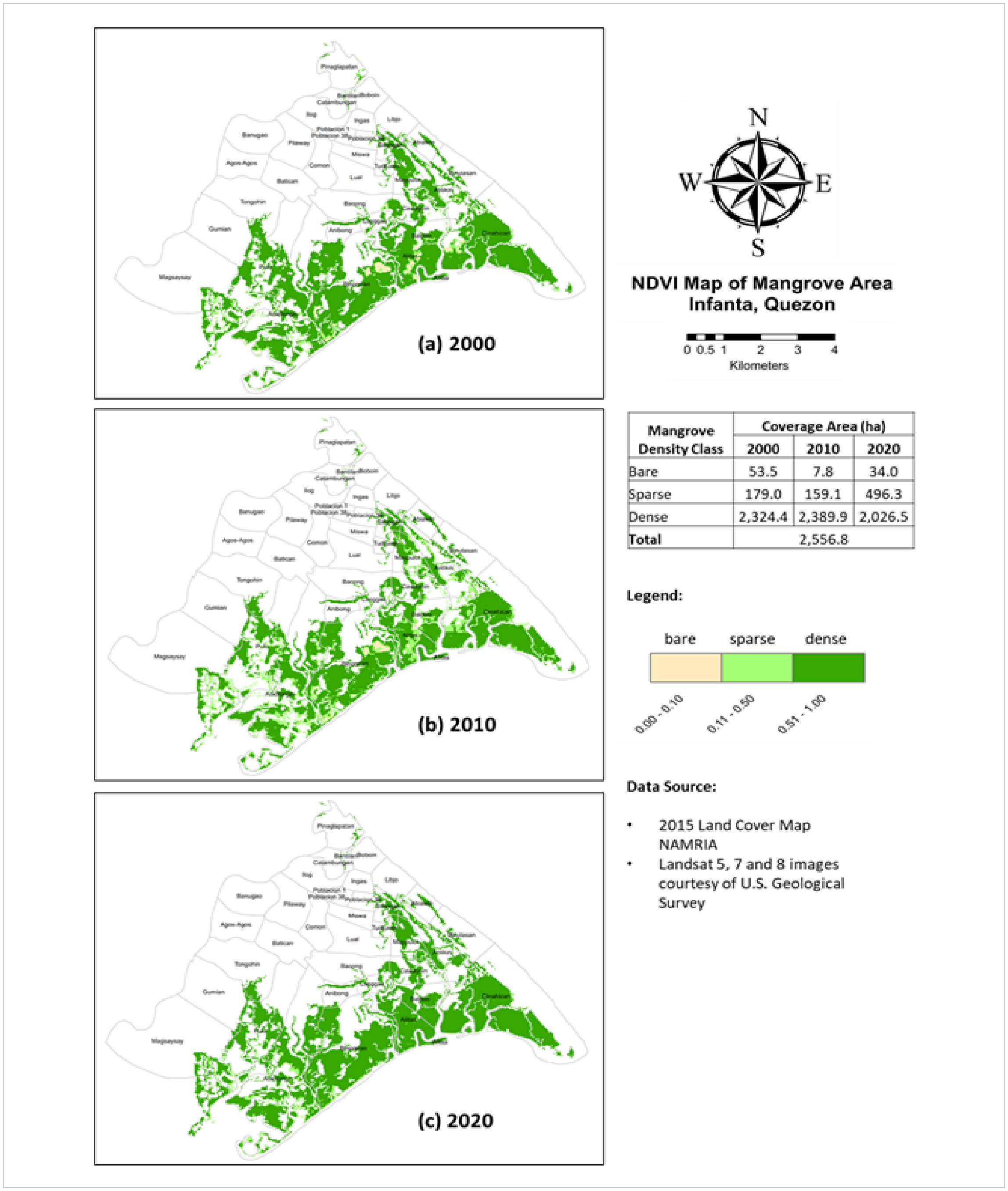
Table 3. Spatiotemporal changes in mangrove forest density of different barangays in Infanta, Quezon.

Barangay	2000			2010			2020		
	Mangrove forest (ha)								
Vegetation density	Bare	Sparse	Dense	Bare	Sparse	Dense	Bare	Sparse	dense
NDVI values	(0–0.10)	(0.11–0.50)	(0.51–1.00)	(0–0.10)	(0.11–0.50)	(0.51–1.00)	(0–0.10)	(0.11–0.50)	(0.51–1.00)
Abiawin	-	-	14.5	-	0.1	14.4	0.0	0.3	14.2
Alitas	11.5	15.2	166.8	0.0	2.1	191.4	2.1	43.2	148.1
Amolongin	5.8	46.3	427.7	3.8	72.5	403.4	6.8	121.2	351.8
Anibong	-	0.1	16.7	-	0.1	16.6	-	0.6	16.2
Antikin	1.9	12.8	87.1	0.4	6.9	94.5	1.1	37.2	63.5
Bacong	0.6	3.8	8.7	-	0.2	12.9	0.0	1.0	12.2
Balobo	1.5	9.5	106.1	0.0	3.2	113.9	1.7	26.3	89.0
Bantilan	-	0.2	1.1	0.0	0.2	1.1	0.0	0.3	1.0
Binonoan	24.3	24.0	496.5	2.3	26.1	516.4	19.5	73.3	452.1
Binulasan	0.1	0.8	28.2	0.1	0.7	28.3	0.1	4.3	24.7
Boboin	-	0.0	0.1	-	0.1	-	-	0.1	0.0
Catambungan	-	0.1	0.4	-	-	0.5	-	0.1	0.3
Cawaynin	0.1	3.9	65.6	0.0	2.7	66.9	0.7	11.6	57.3
Dinahican	7.0	24.1	473.7	0.4	5.7	498.7	0.5	66.5	437.7
Gumian	-	0.1	16.9	0.0	0.5	16.4	-	1.3	15.7
Ingas	-	-	0.8	-	0.0	0.8	-	-	0.8
Langgas	0.2	2.1	16.1	0.0	1.7	16.7	0.0	4.6	13.8
Libjo	-	-	2.3	-	0.1	2.3	-	0.0	2.3
Lual	-	-	2.5	-		2.5	-	-	2.5
Magsaysay	0.1	7.6	27.9	0.1	4.6	30.9	0.0	11.9	23.6
Maypulot	0.0	4.5	71.9	0.0	2.6	73.8	0.7	18.3	57.4
Pinaglapatan	0.0	1.7	4.5	0.1	0.2	5.9	0.0	1.0	5.2
Poblacion 39	-	0.1	3.2	-	0.3	2.9	-	0.3	2.9
Pulo	0.5	22.1	207.7	0.6	27.9	201.9	0.7	71.3	158.3
Silangan	-	0.0	34.9	-	0.3	34.6	-	0.3	34.6
Tongohin	-	0.1	27.7	-	0.3	27.4	-	0.4	27.3
Tudturan	-	-	15.0	-	0.1	14.8	-	1.0	13.9
TOTAL	53.5	179.0	2,324.4	7.8	159.1	2,389.9	34.0	496.3	2,026.5

**Values were rounded to one decimal place.*

Table 4. Areal extent and annual rate of change of forest cover of Infanta mangroves according to vegetation density.

Vegetation density	Mangrove area (ha) and percentage						Annual rate of change of forest cover (%)		
	2000		2010		2020		2000–2010	2010–2020	2000–2020
Bare	53.5	2.1%	7.8	0.3%	34.0	1.3%	-19.2	14.7	-2.3
Sparse	179.0	7.0%	159.1	6.2%	496.3	19.4%	-1.2	11.4	5.1
Dense	2,324.4	90.9%	2,389.9	93.5%	2026.5	79.3%	0.3	-1.6	-0.7
Total	2,556.8	100%	2,556.8	100%	2,556.8	100%	-	-	-



Mangrove Density Class	Coverage Area (ha)		
	2000	2010	2020
Bare	53.5	7.8	34.0
Sparse	179.0	159.1	496.3
Dense	2,324.4	2,389.9	2,026.5
Total	2,556.8		

Figure 3. Processed NDVI maps of mangroves in Infanta showing the areas of bare, sparse, and dense for the years (a) 2000, (b) 2010, and (c) 2020.

A comparable study by Sazon *et al*. (2018), focused on the land cover classification in General Nakar and Infanta, Quezon from 1994 to 2014. In this study, mangroves for both municipalities accounted for about 415 ha or around 20% increase in vegetation. This is consistent with NDVI where mangrove cover change from 2000 to 2020 accounts for a 13% increase in a sparse and dense cover which is roughly 500 ha.

Aboveground blue carbon stock and equivalent CO_2

The potential of carbon stock from the aboveground (AGB) or mangrove vegetation layer is shown in **Table 5**. The estimated aboveground carbon stock values from bare areas were around 0.7 Gg C (2000), 0.1 Gg C (2010), and 0.4 Gg C (2020). In terms of the sparse mangroves, values were likely to be around 11.3 Gg (2000), 10.0 Gg C (2010), and 31.2 Gg C (2010). Lastly, estimates for dense areas suggested 292.4 Gg C (2000), 300.6 Gg C (2020), and 254.9 Gg C (2020). A slight increase of 6.4 Gg C was

Figure 4. Drone photo of mangrove vegetation cover (center) with actual photographs of bare, sparse, and dense vegetation covers.

Figure 5. Geotagged photos collected at CBFM area in Binonoan, Infanta, Quezon: aquasilviculture pond area for bare (a), natural mixed mangrove stand (b.1) and seedling nursery area (b.2) for sparse, and *Rhizophora mucronata* (c.1) and *Rhizophora apiculata* (c.2) stands for dense.

noted between 2000 and 2010, which could be reflective of the increase in dense mangrove cover. However, a substantial drop of –24.1 Gg C between 2010 and 2020 is likely attributable to the decrease in dense mangrove areas and the increase of sparsely vegetated and bare areas.

The total estimates of the aboveground carbon stock for the years 2000, 2010, and 2020, respectively, were 304.3 Gg C, 310.7 Gg C, and 286.6 Gg C. These could also be translated to 1,115.9 Gg CO_2, 1,139.4 Gg CO_2, and 1,050.8 Gg CO_2 (**Table 5**). Key findings could imply that as the forest cover increases, the more aboveground biomass is produced, and the larger the amount of blue carbon is being sequestered. This is expected as physiologically, trees continue to accumulate biomass as it gets older although the rate varies by species. In comparison with other ecosystems, the carbon stored by Infanta mangroves is 89% higher than a forest plantation in Bohol (Reyes 2019) and 93% in the agroforestry system in Bukidnon (Labata *et al*. 2012) but is 5% lower than seagrass meadows in Kenya (Juma *et al*. 2020).

Table 5. Estimated blue carbon stock from various aboveground mangrove vegetation densities in three time periods in Infanta, Quezon.

Vegetation density	Aboveground total carbon stock (Mg ha^{-1})*	Above ground carbon stock (Gg)	CO_2 potential (Gg)	%CO_2 (Gg)
		2000		
Bare	12.6	0.7	2.5	0.22
Sparse	62.9	11.3	41.3	3.70
Dense	125.8	292.4	1,072.2	96.08
Total	-	304.3	1,115.9	100.00
		2010		
Bare	12.6	0.1	0.4	0.03
Sparse	62.9	10.0	36.7	3.22
Dense	125.8	300.6	1,102.4	96.75
Total	-	310.7	1,139.4	100.00
		2020		
Bare	12.6	0.4	1.6	0.15
Sparse	62.9	31.2	114.5	10.89
Dense	125.8	254.9	934.8	88.96
Total	-	286.6	1,050.8	100.00

**Values adopted from the study of Gevaña et al. (2008)*

If this blue carbon stock potential will be valued at USD 4.3 ton^{-1} CO_2, based on the prevailing voluntary carbon market price (Donofrio *et al*. 2020), Infanta can sustain at least USD 4.5 M worth of mangrove forests ecosystem services. Such value could substantiate the need for its commitment to conservation to ensure the continuous delivery of climate change mitigation function together with other ecosystem services and benefits. According to Holder (2021), as more organizations adopt net-zero emissions targets, forest carbon stock prices are likely to rise tenfold over the next decade *i.e.*, between USD 20 and USD 50 metric ton^{-1} of CO_2 by 2030. This suggests a huge potential for Infanta to venture into a carbon offset project in the future. Further, no actual ground sampling was done to account for carbon stock. Straightforward and rough estimation was done using data/ values from other studies.

Potential drivers of mangrove cover and carbon stock changes

The negative trend in the area of mangrove dense cover over the 20–year–period could be attributed to land use conversion to aquaculture (**Figure 6b**), agriculture, nipa plantation, mangrove harvesting for fuelwood, and calamity (specifically typhoon Winnie in 2004). The remaining bare areas in 2020 implies that there are still operational fishponds. According to Infanta's FLUP 2012–2017, about 633 ha of mangrove forests were converted to fishponds. Among which, 554 ha remain operational, and 141 ha have an existing fishpond lease agreement (FLA). Only 79 ha are abandoned, unproductive, and unutilized (AUUs). Some abandoned fishponds are likely to be undergoing natural regrowth, which is reflective of the sparse mangrove areas. Further, since most of the town's production is centered on cottage-based industry and wine-making, this has urged the conversion of mangrove areas to nipa plantations based on production demand while raw materials are sourced out. While rice hull is promoted as a substitute for mangrove fuelwood in the wine distillery processing, some settlers prefer mangrove fuelwood due to its rapid ignition time and longer burning rate thus may contribute to the increase of sparse areas from 179 ha in 2000 to 496.3 ha in 2020. Additionally, with a total population of 64,866 which can be translated to 1/10 of a hectare per capita of A&D per watershed, illustrates why settlers are encroaching on protected areas and timberlands to cultivate the land for a living.

The most common cause of mangrove loss is the conversion of mangroves to other land uses (Infanta LGU 2018). However, cover changes may not be entirely attributable to anthropogenic causes such as planting and cutting. The observed improvement in forest cover could be indicative of the natural ecological succession process where mangrove colonizes open areas for expansion. On the other hand, cover losses may also be attributed to the harmful impacts of storm events.

Although the degradation or deforestation outpaced the increase of mangrove areas, continued efforts of LGU, national government agencies (NGAs), and NGOs were instrumental in the conservation and rehabilitation of mangroves (**Figure 6a**). These NGA programs include CBFM and the National Greening Program (NGP). NGO programs such as the Haribon Foundation's Road to 2020 in coordination with Infanta LGU and MMMSA resulted in 3,500 seedlings planted in 11.3 ha. This three-year initiative of Haribon was funded by the Birdlife International Tokyo and Ricoh Company, Ltd. which aimed to restore the community's mangrove ecology, promote biodiversity, and mitigate the

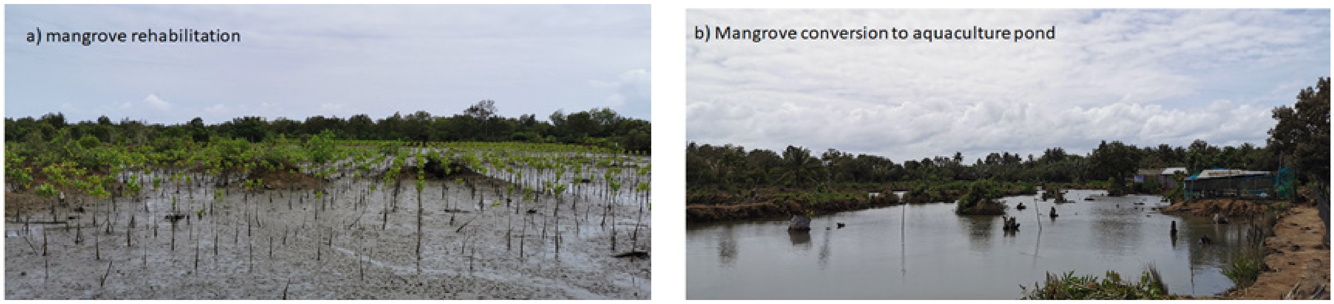


Figure 6. Mangrove rehabilitation (a) and mangrove conversion to fishpond (b) activities in Barangay Alitas, Infanta, Quezon.

effects of climate change. It enabled MMMSA to contribute to the progressive regeneration of mangrove forests in Brgy. Dinahican. The MMMSA also received livelihood and operational support from the project's funding, which was used to produce and maintain seedlings in a nursery, out-plant hardened seedlings, and three-year maintenance. This helped reduce deforestation and forest degradation due to the mangrove-dependent livelihoods of the people (Lacson 2015). Likewise, the granting of CBFM area to BIPCO in Brgy. Binonoan encouraged intense rehabilitation of the mangrove area in the barangay as well as opened income-generating opportunities to the PO such as aquasilviculture production (**Figure 5a**). The biodiversity assessment of the BIPCO-CBFM area revealed that the distribution of species bakauan babae (*Rhizophora mucronata*) and tangal (*Ceriops tagal*) were found in almost all of the established plots (ERDB 2020). The high stocking density of about 31 trees per plot could be attributed to minimal human disturbances within the CBFM area since the PO was only allowed to use a small portion of the mangrove forests for livelihood. Most of the mangrove tree species observed within the CBFM area are seedlings to saplings with few matured trees.

As for the carbon stock, changes in mangrove cover equates to mangrove's potential capacity to help mitigate climate change. As bare areas are being covered with either sparse or dense vegetation, an increase in aboveground carbon stock is expected.

Implications to mangrove management

Results of the study affirm the need for the active involvement of all local stakeholders including the DENR, LGUs, and POs for more successful mangrove conservation and restoration. Particularly, stakeholder participation in the formulation of a mangrove management plan is essential to capture and harmonize the various needs and interests over the mangrove resources, be it for livelihood, protection, and other uses. To address the observed threats to mangroves, rehabilitation and protection activities could be sustained. Rehabilitation efforts could focus on bare areas such as abandoned, underutilized, and undeveloped fishponds. It could also employ science-based approaches such as 1) integrated assessment of the bio-physical and socio-economic conditions of the sites as the basis for planning; 2) conduct of participatory rehabilitation planning that sufficiently captures the needs, interests, and roles of local communities; 3) careful ecological considerations in planting based on correct site-species matching; 4) local capacity development on correct nursery management practices and field planting; 5) participatory project implantation led by the POs, and 6) participatory monitoring and evaluation (Camacho *et al*. 2020).

Further, active protection activities (*e.g.* forest patrol, stand monitoring, and information campaign on mangrove conservation and forest policies) may be done over the sparse and dense mangrove areas. Protecting these sites will allow the natural recolonization process to prosper, hence, essential to restoring biodiversity and other ecosystem functions therein. Monitoring and protection of growing regenerants and mother trees against any forms of cutting or harvesting may also be considered.

Forest conservation could also complement the existing mangrove-based livelihoods such as nipa wine, vinegar, and thatch production. The local government could support the marketing of these products as well as the community-based mangrove ecotourism enterprises that some POs are interested to pursue. This may contribute to effective protection of mangroves, broadening of local awareness, and increasing local income of mangrove-dependent local communities. To further capitalize on the economic potentials, payment for ecosystem services (PES) schemes may also be explored by the local stakeholders. One of which is through a voluntary carbon offset project. Several countries such as Kenya, Colombia, and India have developed blue carbon offset projects for their mangroves. These were generally perceived to have greatly benefited the local communities in terms of income, livelihoods, and tenure security (Wylie *et al*. 2016). Pursuing this will necessitate expanding collaboration with NGOs, academe, and private sectors for technical and funding support.

CONCLUSIONS

Infanta contributes around 18% of the Quezon Province's mangrove forest cover. This ecosystem provides goods and services and is the primary location of the municipality's cottage-based industry on nipa vinegar and wine. One of the mangrove's critical ecosystem functions is climate change mitigation. Infanta's mangrove blue carbon stock was assessed through NDVI analysis and the calculation of the annual rate of change of forest cover. Results showed that there was a decrease in bare and dense mangrove areas and an increase in sparse areas over a two-decade period. These could be attributed to the increasing conversion of mangroves to other land uses such as aquaculture and nipa plantation, which could account for the municipality's slow mangrove recovery and degradation. Blue carbon stock is currently estimated at 286.6 Gg C and about 89% is stored by the dense mangrove stands, thus implying the need to seriously protect these areas. If valued, Infanta's mangrove blue carbon is worth USD 4.5 million. With minimal ground measurements done, remote sensing appeared to be a cost-effective approach for monitoring mangrove areas and their associated blue carbon pool. Key findings could guide the local stakeholders towards robust future mangrove conservation programs and carbon offset projects.

ACKNOWLEDGEMENTS

This study was partially supported by Graduate Research and Education Assistantship for Technology (GREAT) Program of the Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development (DOST–PCAARRD), and the National Academy of Science and Technology (DOST-NAST) thru the Grants in Aid Program (DOST-GIA) for the project Land Use Change and Blue Carbon Stock Potential of Mangrove Forests Along Verde Island Biodiversity Corridor in Luzon, Philippines (LUCBlueVerde). Special thanks to Ms. Larlyn Faith Aggabao of the Forest Management Bureau for assisting us in the spatiotemporal change analysis of mangrove cover.

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