Biogeochemical Role of Mangroves: Carbon Sequestration, Oxygen Release, and Their Contribution to Ecosystem Sustainability

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Abstract

Background: Mangroves play a crucial role in biogeochemical cycles, contributing significantly to the regulation of atmospheric gases, including carbon (C), carbon dioxide (CO_2), and oxygen (O_2). Through photosynthesis, mangrove species assimilate carbon dioxide, and their biomass formation, including both aboveground and belowground components, is a key indicator of their productivity. This study assesses the carbon sequestration potential and oxygen release of mangroves in Sukol River, Bongabong, Oriental Mindoro, Philippines, focusing on the allometric data of various mangrove species. The primary objective of this study was to quantify the carbon stock and oxygen release of mangrove species in Sukol River through biomass estimation. This was achieved by using an allometric approach to determine the aboveground biomass (AGB) and belowground biomass (BGB), followed by calculating carbon stock and carbon dioxide equivalent (CO_2-eq), as well as estimating oxygen release from photosynthesis. Methods: A quantitative research design was employed, utilizing the tree allometry protocol for mangrove biomass estimation. A total of six mangrove species — *Sonneratia alba*, *Rhizophora mucronata*, *Rhizophora apiculata*, *Avicennia marina*, *Avicennia officinalis*, and *Bruguiera sexangula* — were assessed within a 125-meter transect line divided into six circular plots. Biomass data were collected, and the carbon stock was estimated using established equations for mangrove carbon and oxygen assessments (Kauffman & Donato, 2012; Zakaria et al., 2021). Results: The mangrove species in the study site had varying biomass, with *Sonneratia alba* exhibiting the highest AGB of 7,078.50 $Mg \cdot Ha^{-1}$ and BGB of 21.63 $Mg \cdot Ha^{-1}$, while *Bruguiera sexangula* showed the lowest values of 7.71 $Mg \cdot Ha^{-1}$ AGB and 0.0905 $Mg \cdot Ha^{-1}$ BGB. The combined biomass of all species in the study site totaled 4,031.04 $Mg \cdot Ha^{-1}$ of carbon stock, equating to 14,793.90 $Mg \cdot Ha^{-1}$ CO_2-eq. Additionally, based on carbon stock, the mangrove species in Sukol River can release 10,749.43 $Mg \cdot Ha^{-1}$ of oxygen. Conclusions: Mangroves in the Sukol River ecosystem demonstrate substantial carbon sequestration capacity and oxygen release, contributing significantly to the global carbon cycle and atmospheric oxygen balance. The results emphasize the potential of mangrove restoration in enhancing carbon sink functions and mitigating greenhouse gas emissions. Effective management and conservation of these ecosystems are essential for maintaining their biogeochemical roles in combating climate change.

Keywords: Mangroves, Photosynthesis, Carbon Sequestration, Oxygen Release, Biomass

Significance | This study highlights mangroves' critical role in carbon sequestration and oxygen release, contributing significantly to ecosystem and climate regulation.

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Introduction

Biogeochemical cycles are essential for sustaining life on Earth

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by facilitating the movement of nutrients and elements required for energy consumption by biotic factors. These cycles interact with abiotic components, forming a cohesive system that maintains environmental balance. For example, the hydrological cycle regulates weather patterns through evaporation and precipitation, stabilizing temperature and pressure on Earth's surface. Similarly, the carbon-oxygen cycle facilitates gaseous exchange between plants and animals, contributing to energy flow and ecosystem stability. During photosynthesis, plants absorb atmospheric carbon dioxide (CO_2) to produce glucose and release oxygen, which animals use for respiration, releasing CO_2 back into the atmosphere—a process ensuring the continuity of the cycle (Fernández-Remolar, 2011; Rotmans & den Elzen, 1999).

One notable function of biogeochemical cycles is the regulation of Greenhouse Gases (GHGs), such as water vapor, methane, nitrous oxide, and CO_2. Among these, CO_2 has the most significant impact due to its various sources. These gases trap solar heat within Earth's atmosphere, maintaining a habitable temperature for life and driving energy production (Singh, 2024). However, an imbalance in GHG levels can lead to global warming, resulting in climate change, extreme weather events, and the melting of polar ice, which contributes to rising sea levels.

The carbon-oxygen cycle naturally mitigates excessive greenhouse effects by reabsorbing atmospheric GHGs. This biogeochemical process ensures only the necessary amounts of heat-trapping gases remain in the atmosphere. Unfortunately, industrialization and anthropogenic activities, such as deforestation and fossil fuel combustion, have disrupted this balance, amplifying greenhouse effects and global warming (Rackley, 2023; Finzi et al., 2011).

Plants, in both terrestrial and aquatic ecosystems, are pivotal in regulating the carbon-oxygen cycle. Through photosynthesis and cellular respiration, they capture and store carbon nutrients while releasing oxygen, effectively moderating GHG levels in the atmosphere (López-Pacheco et al., 2021; Grace, 2013; Franck & Stadelhofer, 1989). However, extensive exploitation of autotrophs, including upland forests and marine ecosystems, has severely reduced their capacity to facilitate this process.

Among the ecosystems affected, mangroves, flourishing in tropical coastal zones, hold exceptional ecological significance. These salt-tolerant halophytes possess pneumatophores that filter nutrients from various sources, enabling them to thrive in saline conditions. Mangroves are unmatched in their ability to sequester carbon, storing more carbon per unit area than upland forests. Furthermore, their ability to absorb large amounts of CO_2 and release substantial volumes of oxygen enhances their ecological importance (Nizam et al., 2022).

Despite their critical role, mangroves are increasingly threatened by human activities, including wood extraction, aquaculture, and urban development. These activities have led to an annual decline in mangrove cover ranging from 0.16% to 0.39% globally over the past century (Hamilton & Casey, 2016). This loss has significant implications for GHG regulation and the overall productivity of coastal ecosystems.

Quantifying the contributions of mangroves to the carbon-oxygen cycle is vital for understanding their ecological value. As key nutrient pathways in marine environments, mangroves enhance the productivity of coastal organisms and play an integral role in sustaining biodiversity. Presenting communities near mangrove ecosystems with comprehensive data on their ecological importance can foster conservation efforts. Such data can guide policy formulation, emphasizing the need for protective measures and sustainable practices to preserve these critical ecosystems (Richards & Friess, 2016).

This study seeks to evaluate the role of mangroves in the carbon-oxygen cycle by collecting baseline data to estimate their productivity in carbon sequestration and oxygen release. Detailed assessments of mangrove ecosystems can inform conservation strategies and reinforce their ecological significance as facilitators of biogeochemical processes.

Biogeochemical cycles, particularly the carbon-oxygen cycle, are indispensable in regulating atmospheric GHG levels and sustaining life on Earth. Mangrove ecosystems, with their unparalleled capacity for carbon sequestration and oxygen release, are critical components of this process. However, the exploitation of mangroves necessitates immediate attention to quantify their ecological contributions and implement conservation measures. Protecting mangroves will not only mitigate the adverse effects of global warming but also ensure the resilience of coastal ecosystems and their invaluable services to humanity.

2. Materials and Methods

2.1 Study Area

The research was conducted at Sukol River in the Municipality of Bongabong, Oriental Mindoro, Philippines (Figure 1). This site hosts a fringe mangrove forest classified as riverine mangroves, located adjacent to the shoreline. The mangroves in this area are well-suited for ecological assessments due to their accessibility and clear zonation patterns. Their pneumatophores and buttressed trunks enable the trapping of nutrients, including carbon materials, in the estuarine environment, making them ideal for studying their role in the carbon-oxygen cycle.

2.2 Research Design

The study employed a quantitative research design, utilizing protocols for tree allometry as a data collection and assessment tool. Tree allometry provided the framework for estimating the live biomass of mangroves in the identified sampling stations. This data was critical for quantifying the mangroves' carbon sequestration rate and net oxygen release, thereby highlighting their contribution to biogeochemical cycles.

2.3 Data Collection

The study followed the circular plot method for mangrove allometry, as outlined by Kauffman and Donato (2012). A 125-meter transect line was established to delineate the sampling areas. The transect line was secured at both ends using 22 mm PVC poles, which helped maintain clear demarcation of sampling plots. Along this transect, six circular plots with a radius of 7 meters were laid out at 25-meter intervals, beginning from the zero point.

Within each plot, trees located up to 2 meters from the center of the radius were measured. Data collection focused on allometric parameters, including the girth and height of the mangroves, using a tape measure and a modified meter pole. A field guide was utilized to accurately identify mangrove species, enabling the selection of species-specific wood densities for biomass computation.

To safeguard data integrity during the damp conditions in the mangrove forest, measurements were recorded on a slate, ensuring legibility and preventing data loss. Post-fieldwork, the allometric data were processed to compute live biomass, carbon sequestration, CO_2 equivalent, and net oxygen release using established equations.

2.4 Data Analysis and Unit Conversion

The collected data underwent standardization through unit conversion to ensure uniformity across results. Simplified figures were prepared to enhance the readability and usability of result tables for analysis and reporting. This approach minimized overlapping data in graphical and tabular representations, facilitating effective communication of findings.

2.5 Equations and Biomass Estimation

The study applied equations from Rahman et al. (2023), Maulana et al. (2021), Kauffman and Donato (2012), and Schöngart et al. (2011) to estimate key ecological metrics, including:

Aboveground Biomass (AGB): Represents the biomass stored in trunks, branches, and leaves.

Belowground Biomass (BGB): Accounts for root biomass.

Carbon Sequestration: Quantifies the carbon stored in the biomass.

CO_2 Equivalent (CO_2-eq): Measures the contribution to reducing atmospheric CO_2.

Net Oxygen Release: Calculates the amount of oxygen released during photosynthesis.

These computations provided robust insights into the productivity and ecological contributions of mangroves in Sukol River, reinforcing their role in global carbon and oxygen cycles.

Live Biomass

$$AGB = 0.0509 * \rho * D^2 * H \quad (1)$$

$$BGB = 0.199 * \rho^{0.899} * D^{2.22} \quad (2)$$

(ρ= wood density; D= maximum tree diameter; H= maximum tree height) (Kauffman and Donato, 2012)

Carbon sequestration and CO_2-eq

Carbon sequestration= 0.47 (Carbon fraction) x biomass (3)

$$CO_2\text{-eq} = \frac{44 \text{ (relative molecular weight of Carbon dioxide)}}{12 \text{ (relative atomic weight of carbon)}} \times \text{carbon sequestration} \quad (4)$$

= 3.67 x carbon sequestration

Net Oxygen (O_2) release

Net O_2 release = Net Carbon sequestration × 2.67 (ratio of atomic weights of Oxygen to Carbon) (5)

3. Results and Discussion

3.1 The role of photosynthesis in the Biogeochemical activities of Mangroves

Photosynthesis is crucial to the biogeochemical processes of mangroves and other autotrophs, facilitating the circulation of essential gases such as carbon (C), carbon dioxide (CO_2), and oxygen (O_2) in marine ecosystems. These gases are vital for maintaining biodiversity and ecosystem health. The productivity of mangroves, reflected in their photosynthetic efficiency, is often assessed through biomass content, underscoring their ecological importance.

Mangroves assimilate atmospheric CO_2 into cellular components through photosynthesis, a process mediated by chloroplasts. These specialized structures capture sunlight, enabling the conversion of light energy into chemical energy. During photosynthesis, CO_2 is absorbed through leaves, while water (H_2O) is taken up by roots. In this process, water is oxidized, losing electrons, and CO_2 is reduced, gaining electrons. This transformation results in the production of oxygen (O_2) and glucose ($C_6H_{12}O_6$). The glucose, a carbon-based simple sugar, serves as a precursor for various cellular components, particularly carbohydrates.

Carbohydrates accumulate in the plant's structure, forming cellulose ($C_6H_{10}O_5$), a polysaccharide polymer composed of β-1,4-linked glucose units. Cellulose is closely associated with hemicellulose, a heterogeneous sugar polymer, and lignin, a complex oxygen-containing polymer. Together, these three polymers constitute the primary components of plant biomass, playing critical roles in structural integrity and carbon storage (Bhatla & Lal, 2023; Zhang et al., 2021; Berglund et al., 2020).

In mangroves, this biomass represents not only an ecological function but also a biogeochemical indicator, linking carbon sequestration with atmospheric dynamics. The synthesis of cellulose, hemicellulose, and lignin underscores the central role of photosynthesis in sustaining mangrove ecosystems and their contributions to global carbon and oxygen cycles.

3.2 Biomass and Carbon Storage in Mangroves

Biomass forms the fundamental physiological structure of all living organisms, including plants. It consists of organic material created through processes integral to the biogeochemical cycle. This cycle, a complex atmospheric phenomenon, heavily relies on autotrophs

Figure 1. Map of the Sukol River, Bongabong, Oriental Mindoro

Table 1. Sukol Mangroves Aboveground Biomass and Belowground Biomass Results

Mangrove Species	Tree Density	Aboveground Biomass ($Mg{\cdot}Ha^{-1}$)	Belowground Biomass ($Mg{\cdot}Ha^{-1}$)
Sonneratia alba	220	7, 078.50	21.63
Rhizophora mucronate	93	667.54	4.67
Rhizophora apiculata	47	4, 51.45	1.20
Avicennia marina	52	121.67	0.98
Avicennia officinalis	13	220.56	0.67
Bruguiera sexangula	2	7.71	0.0905
Total	**427**	**8, 547.43**	**29.24**

Table 2. Sukol Mangroves Carbon Stock and Carbon dioxide Equivalent (CO_2-eq) Results

Mangrove Species	Total Biomass per species ($Mg{\cdot}Ha^{-1}$)	Carbon Stock ($Mg{\cdot}Ha^{-1}$)	CO_2-eq ($Mg{\cdot}Ha^{-1}$)
Sonneratia alba	7100.13	3337.06	12247.01
Rhizophora mucronata	672.21	315.94	1159.50
Rhizophora apiculata	452.65	212.75	780.78
Avicennia marina	122.65	57.65	211.56
Avicennia officinalis	221.23	103.98	381.60
Bruguiera sexangula	7.80	3.67	13.46
Total	**8, 576.67**	**4, 031.04**	**14, 793.90**

Table 3. Sukol Mangroves Oxygen Release Results

Mangrove Species	Net Oxygen Release ($Mg{\cdot}Ha^{-1}{\cdot}year^{-1}$) *carbon stock of each species x 2.67 (ratio of atomic weights of Oxygen to Carbon)*
Sonneratia alba	8898.83
Rhizophora mucronata	842.50
Rhizophora apiculata	567.32
Avicennia marina	153.72
Avicennia officinalis	277.27
Bruguiera sexangula	9.78
Total	**10, 749.43**

like mangroves, underscoring their crucial role in regulating and maintaining the exchange of elements within ecosystems. Specifically, mangroves, through their biomass, act as bioindicators, enabling the estimation of critical gaseous exchanges, such as carbon capture and net oxygen release, in both aquatic and atmospheric systems.

To illustrate the role of mangrove biomass in the biogeochemical cycle, allometric data from the mangroves of Sukol River, Bongabong, Oriental Mindoro, were collected. Using protocols endorsed by the scientific community for mangrove ecosystems, accurate and reliable biomass estimates were generated. Field observations identified six true mangrove species in the study area: *Sonneratia alba*, *Rhizophora mucronata*, *Rhizophora apiculata*, *Avicennia marina*, *Avicennia officinalis*, and *Bruguiera sexangula*. Among these, *Sonneratia alba* exhibited the highest aboveground biomass (AGB) and belowground biomass (BGB) at 7,078.50 Mg·Ha^{-1} and 21.63 Mg·Ha^{-1}, respectively. Conversely, *Bruguiera sexangula* recorded the lowest biomass, with an AGB of 7.71 Mg·Ha^{-1} and a BGB of 0.0905 Mg·Ha^{-1}. This disparity reflects the distribution pattern of mangroves within the riverine ecosystem, where *Bruguiera sexangula* is less prevalent.

Other mangrove species also demonstrated notable biomass contributions and nutrient filtration efficiencies. For example, *Rhizophora mucronata* showed AGB and BGB values of 667.54 Mg·Ha^{-1} and 4.67 Mg·Ha^{-1}, respectively, while *Rhizophora apiculata* recorded 451.45 Mg·Ha^{-1} (AGB) and 1.20 Mg·Ha^{-1} (BGB). *Avicennia marina* had an AGB of 121.67 Mg·Ha^{-1} and a BGB of 0.98 Mg·Ha^{-1}, and *Avicennia officinalis* exhibited an AGB of 220.56 Mg·Ha^{-1} and a BGB of 0.67 Mg·Ha^{-1} (Table 1). These findings emphasize the importance of mangrove biomass in capturing carbon and releasing oxygen, integral to maintaining ecological balance.

3.3 Carbon Sequestration and CO_2 Equivalent

The biomass stored in mangroves is a fundamental indicator for estimating their carbon stock content. Biomass, composed of carbon-based components such as the trunk, branches, stems, leaves, and roots, serves as a reservoir of organic carbon. By utilizing carbon data obtained through tree allometry, researchers can calculate the Carbon Dioxide Equivalent (CO_2-eq). This measurement helps estimate the potential carbon dioxide that mangroves have captured or prevented from entering the atmosphere. Importantly, the CO_2-eq calculation for mangroves is based on species-specific carbon stock values, reflecting their absorption capacity rather than contributing to greenhouse gas emissions (Zakaria et al., 2021).

At the study site, the combined biomass of the mangrove species totaled 4,031.04 Mg·Ha^{-1} of carbon stock, corresponding to 14,793.90 Mg·Ha^{-1} of equivalent carbon dioxide (Table 2). This calculation is grounded in the chemical relationship between carbon (atomic mass 12) and oxygen (atomic mass 16). When combined, carbon and oxygen form CO_2, with a molecular mass of 44. Consequently, one kilogram of carbon generates 3.67 kilograms of carbon dioxide (Junaedi et al., 2019).

This distinction between pure carbon and carbon dioxide is critical for understanding their respective roles in the carbon cycle. While carbon undergoes recycling in various forms, carbon dioxide primarily manifests as an emission within this cycle. Mangroves, through their biomass, effectively sequester carbon, mitigating its atmospheric concentration and thereby reducing potential greenhouse gas impacts. This highlights the importance of preserving and restoring mangrove ecosystems, as their role in the global carbon cycle is pivotal for climate regulation and ecological balance.

3.4 Oxygen Release and Photosynthetic Efficiency

The release of oxygen by plants, particularly mangroves, occurs during the light-dependent reactions of photosynthesis. These reactions take place in the chloroplast thylakoids, where chlorophyll pigments are concentrated. When light energy excites these pigments, electrons are activated and transported through an electron transport chain within the thylakoid membrane. This process facilitates the generation of two key energy molecules: Adenosine Triphosphate (ATP) and Nicotinamide Adenine Dinucleotide Phosphate (NADPH). As electrons lose energy during transport, ATP is synthesized, while the reduction of $NADP^+$ to NADPH occurs simultaneously. Each chlorophyll molecule that loses an electron regains one from water molecules, causing the water to split and releasing oxygen as a byproduct, which is then emitted into the atmosphere (Bowyer & Leegood, 1997).

In terms of oxygen release, estimates based on Table 3 indicate that mangrove species along the Sukol River collectively contribute 10,749.43 Mg·Ha^{-1} of oxygen. This calculation derives from the carbon stock measurements of mangroves in the study area. Remarkably, the oxygen released by mangroves is more than half of the sequestered carbon stored in their biomass.

These findings underscore the critical role mangroves play in the biogeochemical cycle. The substantial oxygen output highlights their contribution to atmospheric balance, particularly in regulating greenhouse gas levels. Restoring and conserving mangrove ecosystems could enhance their ability to function as efficient carbon sinks and oxygen producers, thereby improving their overall impact on mitigating climate change and maintaining ecological equilibrium.

4. Conclusion

In conclusion, the mangroves of Sukol River play a vital role in the biogeochemical cycles, particularly in carbon sequestration and oxygen release. Through photosynthesis, mangroves capture carbon dioxide and release oxygen, contributing to atmospheric balance and climate regulation. Their biomass, which includes both aboveground and belowground components, serves as a significant indicator of their carbon stock and sequestration capacity. The findings from this study emphasize the importance of preserving and restoring mangrove ecosystems, as they can enhance their biogeochemical processes, reduce greenhouse gas emissions, and support the health of both terrestrial and marine environments.

Author contributions

R.A.Q. contributed to the conceptualization, methodology, and supervision of the study. Additionally, R.A.Q. was involved in the analysis and interpretation of data, as well as in drafting and revising the manuscript for intellectual content.

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Competing financial interests

The authors have no conflict of interest.

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