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The Ecological Role and Carbon Sequestration Potential of the Mangrove Ecosystem in Sondaken for Climate Change Mitigation

Wawan Nurmawan[1*], Tommy B. Ogie [2], Marthen T. Lasut[1].

[1)]*Program Studi Kehutanan, Universitas Sam Ratulangi Manado, Indonesia*
[2)] *Agrotechnology Study Program, Sam Ratulangi University Manado, Indonesia*

*Corresponding author:
wawan2828@unsrat.ac.id

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Abstract. Mangrove ecosystems play an important ecological role in maintaining coastal environmental balance and contribute significantly to climate change mitigation through carbon sequestration. This study aims to analyze the vegetation structure, zoning, biomass potential, and carbon storage of mangrove ecosystems in Sondaken, South Minahasa Regency, North Sulawesi, as well as to examine their ecological role in climate change mitigation. Data collection was conducted on ten plots arranged perpendicular to the coastline. The identification results showed that there were ten true mangrove species with a strong dominance of *Rhizophora apiculata* at all growth levels. The highest Importance Value Index (IVI) was achieved by R. *apiculata* with 97.83 at the tree level, indicating good adaptability and regeneration.

Mangrove zoning is divided into three main parts, namely the back zone (Avicennia and *Bruguiera spp*.), the middle zone (*Rhizophora apiculata* and *R. mucronata*), and the front zone (*Sonneratia alba* and *Avicennia alba*). The average biomass value reached 489.37 tons/ha, while the average stored carbon was 230 tons/ha, indicating high potential as a blue carbon sink.

Ecologically, the Sondaken mangrove plays an important role in absorbing atmospheric carbon, protecting the coast from abrasion, and providing habitat for various coastal biota. The results of this study confirm that the Sondaken mangrove ecosystem has high strategic value in climate change mitigation and adaptation and needs to be managed sustainably through conservation and rehabilitation based on natural zoning.
Keywords: Mangrove, blue carbon, biomass, zoning, climate change mitigation, Sondaken

INTRODUCTION

Mangrove forests are coastal ecosystems that play an important role in maintaining environmental balance, ecologically, economically, and socially. One of the main functions of this ecosystem is as an effective carbon sink, making it part of the natural solution to climate change mitigation. Mangroves have the ability to absorb carbon from the atmosphere and store it in biomass and sediments for a very long time. This potential makes mangroves part of the “blue carbon” concept, which is the storage of carbon in coastal and marine ecosystems (Bouillon et al. 2008 and Alongi (2012).

Manado Bay is a coastal area with a mangrove ecosystem that has various ecological functions, including as a habitat for various species of flora and fauna, a provider of environmental services, and a protector of the coastline from erosion and abrasion. However, pressure from human activities such as land conversion, resource exploitation, and environmental pollution threatens the sustainability of mangrove forests in this region. In addition, climate change, which causes sea level rise and temperature increase, also has the potential to accelerate the degradation of mangrove ecosystems (Friess et al. (2019), Donato et al. (2011), and Murdiyarso et al. (2015).

Along with increasing global awareness of the importance of climate change mitigation, the conservation and rehabilitation of mangrove ecosystems have become strategic measures that need to be taken. Scientific studies on the carbon sequestration potential of mangrove forests in Manado Bay are urgently needed to provide a scientific basis for more sustainable mangrove management and conservation policies. By understanding the carbon storage capacity and other benefits, it is hoped that the community and stakeholders will be more supportive of efforts to preserve this ecosystem.

Research Objectives

This study aims to:

1. Analyze the vegetation structure and composition of mangrove species in the Sondaken area.
2. Determine the zoning of mangrove species based on ecological characteristics and position relative to the sea.
3. Calculate the biomass potential and carbon storage of the mangrove ecosystem in each observation plot.
4. Assess the ecological role and contribution of the Sondaken mangrove ecosystem in climate change mitigation.

METHODOLOGY

This research was conducted in the Sondaken mangrove ecosystem area, Tatapaan District, South Minahasa Regency, North Sulawesi Province. This area was chosen because it still has a fairly extensive and varied natural mangrove cover from the back zone to the front zone of the coast. The research was conducted from May to July 2025, which represents the general dry season conditions in the region, facilitating field observations and vegetation sampling.

The tools used in this study included measuring tapes, raffia ropes, GPS, clinometers, calipers, writing instruments, and documentation cameras. The materials used included field data recording forms, mangrove species identification tables, and Microsoft Excel software for data analysis.

Data collection was carried out using 10 m × 10 m plots placed perpendicular to the coastline. There were 10 observation plots, ranging from the rear zone (plot 1) to the front zone (plot 10) directly facing the sea. Each plot was divided into subplots for three levels of vegetation growth:

- Trees: diameter ≥10 cm (main plot 10 m × 10 m)

- Stakes: height 1.5–<10 cm (5 m × 5 m subplot)

- Seedlings: height <1.5 m (2 m × 2 m subplot)

Vegetation data was then analyzed to calculate the Importance Value Index (IVI), which consists of Relative Density (RD), Relative Frequency (RF), and Relative Dominance (RD) at the tree level.

Tree biomass estimates were calculated using the general mangrove allometric equation (Komiyama et al., 2005):

$$\mathbf{B = 0.251 \times \rho \times D^{2.46}}$$

where:

B = tree biomass (kg)

ρ = wood density (g/cm³)

D = stem diameter (cm)

Biomass values were converted to tons/ha by summing the total biomass per plot and converting it based on the observation area. Carbon content was calculated using a conversion factor of 0.47 from the total biomass (IPCC, 2006):

$$\mathbf{C = 0.47 \times B}$$

The carbon yield per hectare is then averaged to determine the carbon sequestration potential of the Sondaken mangrove ecosystem.

Zoning is determined based on the distribution of species dominance in each plot, distance from the coastline, and substrate and salinity conditions. Zoning is divided into three categories according to Bengen (2000), namely:

1. Front Zone – close to the sea, dominated by Sonneratia alba and Avicennia alba.
2. Middle Zone – medium distance, dominated by Rhizophora apiculata and R. mucronata.
3. Back Zone – far from the sea, consisting of Bruguiera spp. and Avicennia officinalis.

This zoning helps explain the relationship between environmental conditions and vegetation composition, while also supporting the analysis of the ecological role of mangroves in coastal protection.

Data Analysis and Interpretation

All data were analyzed descriptively and quantitatively. INP values were used to determine dominant species and ecosystem stability, while biomass and carbon were used to measure climate change mitigation potential. The results of the study were interpreted by comparing plots and mangrove zones to assess the relationship between vegetation structure, carbon potential, and the ecological function of the Sondaken mangrove area.

RESULTS

Composition and Structure of Mangroves in Sondaken

The results of vegetation analysis in the Sondaken mangrove area show that there are ten true mangrove species belonging to five main genera, namely Rhizophora, Avicennia, Sonneratia, Bruguiera, and Ceriops. Based on the results of identification in ten observation plots, the most commonly found species was *Rhizophora apiculata*, followed by *Avicennia alba*, *Sonneratia alba*, and *Avicennia officinalis*. Other species such as *Rhizophora mucronata*, *Sonneratia ovata*, *Sonneratia caseolari*, *Bruguiera sexangula*, *Bruguiera cylindrica*, and *Bruguiera parviflora* were found with lower frequencies.

The presence of ten true mangrove species in Sondaken indicates a relatively good and natural ecosystem condition. The dominance of *Rhizophora apiculata* at all growth levels reflects its high adaptability to muddy substrate conditions and moderate to high salinity. This species generally dominates protected coastal areas in tropical regions and plays an important role in stabilizing sediments and providing habitat for aquatic fauna (Alongi, 2012; Basyuni et al., 2017).

Based on field observations, Rhizophora apiculata dominates not only because of its regeneration ability, but also because of its adaptive strategy through an efficient prop root system that captures sediment, which in turn expands the colonization area and increases substrate stability (Komiyama et al., 2008).

The mangrove vegetation structure in Sondaken consists of three growth levels, namely seedling, sapling, and tree. At these three growth levels, *Rhizophora apiculata* is the most dominant species with the highest INP values of 113.47 (seedling), 86.20 (sapling), and 97.83 (tree), respectively. This dominance indicates good regeneration and adaptation capabilities to coastal environmental conditions. *Avicennia alba* and *Sonneratia alba* also play an important role, especially in the front zone. The vertical structure consisting of three strata (seedlings, saplings, trees) indicates continuous natural regeneration, as also reported in other natural mangrove areas in North Sulawesi such as Tombariri (Langi and Nurmawan, 2023).

The diversity of mangrove species in Sondaken is moderate to high. The presence of Bruguiera species in the back zone indicates stable and natural conditions. The dominance of Rhizophora apiculata at all growth levels indicates a strong ecosystem stability. This finding is in line with the report by Friess et al. (2019), which states that Southeast Asia, including Indonesia, has the highest mangrove species diversity in the world, with Rhizophora and Avicennia as indicators of a healthy mangrove ecosystem. Thus, the structure and composition of mangrove vegetation in Sondaken exhibit the characteristics of a dynamic, resilient ecosystem that plays an important role in supporting coastal ecological functions.

Mangrove Zoning

The mangrove ecosystem in Sondaken has a clear zoning pattern from land to sea. Based on observations of ten plots, three main zones were identified, namely the back zone, the middle zone, and the front zone.

The back zone is dominated by *Avicennia alba*, *Avicennia officinalis*, and *Bruguiera spp*. The substrate in this zone is relatively dry with low to moderate salinity. The middle zone is dominated by *Rhizophora apiculata* and *Rhizophora mucronata*, which have strong prop roots and contribute significantly to the biomass and stability of the ecosystem. The front zone is dominated by *Sonneratia alba*, *Sonneratia ovata*, and *Avicennia alba*, which are able to grow in flooded areas with high salinity

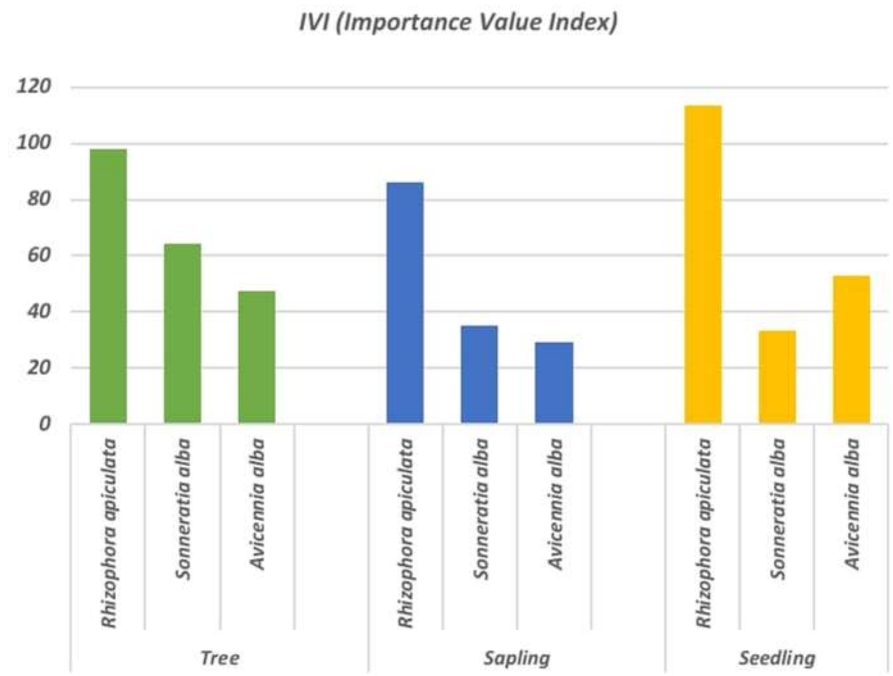

Figure 1. Highest importance index at the seedling, sapling, and tree levels

The pattern of mangrove zoning in Sondaken reflects the ecological adaptation of each species to environmental gradients such as salinity, tides, and substrate stability. The front zone, dominated by *Sonneratia alba* and *Avicennia alba*, shows adaptation to flooded conditions and high salinity. These two species have a pneumatophore root system that aids gas exchange in anaerobic environments and tolerance to high salt levels (Tomlinson, 2016; Kathiresan & Bingham, 2001). This zone functions as a first line of defense that reduces wave energy and prevents coastal erosion (Alongi, 2008).

The middle zone is dominated by *Rhizophora apiculata* and *Rhizophora mucronata*, which are species with strong prop roots that stabilize sediments and accelerate the process of mud accumulation (Komiyama et al., 2008). The presence of Rhizophora species in the middle zone also plays an important role in carbon sequestration due to the high biomass above ground (Donato et al., 2011). This zone is usually a transition area with moderate salinity fluctuations and regular flooding, allowing for optimal growth of species with moderate salinity tolerance (Basyuni et al., 2017).

Meanwhile, the back zone in Sondaken, which is dominated *by Bruguiera spp*., *Ceriops tagal*, and *Avicennia officinalis*, indicates more stable substrate conditions, better soil aeration, and low flooding intensity. Species in this zone generally have knee roots or support roots that are effective in maintaining plant balance in dense substrates (Bengen, 2000; Friess et al., 2019). The back zone also plays an important role as a buffer for terrestrial ecosystems and contributes to the decomposition of leaf litter, which enriches soil nutrients (Alongi, 2014).

The clear zoning in Sondaken indicates that the ecosystem is still in a natural and stable condition. A similar pattern has also been reported in the mangrove areas of Sulawesi and Kalimantan, where the zoning composition shows an ecological balance between geomorphological processes, tides, and vegetation colonization (Arifin et al., 2020; Feller et al., 2010). In addition, the regularity of the zoning also indicates minimal anthropogenic disturbance, which usually results in vegetation fragmentation or shifts in species dominance (Alongi, 2015). Thus, the mangrove zoning pattern in Sondaken can be used as an important indicator in assessing coastal ecosystem health and as a basis for natural zoning-based management.

Biomass Potential and Carbon Storage

The results show that mangrove biomass in Sondaken ranges from 167.90 to 929.46 tons/ha, with an average of 489.37 tons/ha. Meanwhile, carbon content ranges from 78.92 to 436.85 tons/ha, with an average of 230.00 tons/ha. Plot 1 has the highest biomass and carbon values, while plot 10 has the lowest values. This pattern shows a gradient from the rear zone to the front zone.

The species *Rhizophora apiculata* contributes the most to total biomass and carbon because it has high wood density and large stand density. Compared to other areas in Indonesia, the average biomass value in Sondaken is relatively high. The potential carbon storage reaches around 845 tons of CO_2/ha. This confirms that the Sondaken mangrove forest is an important blue carbon sink that contributes significantly to climate change mitigation.

The biomass and carbon storage potential in the Sondaken mangrove ecosystem is relatively high, with an average biomass of 489.37 tons/ha and carbon content of 230 tons/ha. These values demonstrate the ability of the Sondaken mangrove ecosystem as a significant blue carbon sink in climate change mitigation. These results are in line with the findings of Donato et al. (2011), who stated that mangrove forests are one of the tropical forest ecosystems with the highest carbon reserves in the world, ranging from 102 to 1,200 tons C/ha, depending on geographical conditions and dominant species.

The largest contribution to biomass and carbon in Sondaken comes from *Rhizophora apiculata*, as this species has high wood density and large stand density. Rhizophora is known to have a biomass potential of over 300 tons/ha in healthy ecosystems (Komiyama et al., 2008; Alongi, 2012). In addition, the complex prop root system plays an important role in trapping organic sediments, slowing erosion, and increasing carbon sequestration underground (Alongi, 2014).

The distribution of biomass values, which decrease from the rear zone to the front zone, indicates an ecological gradient influenced by water depth, salinity, and substrate texture (Kauffman et al., 2011). The rear zone, which is more physically stable and has better soil aeration, tends to support higher biomass accumulation than the front zone, which is often flooded. A similar pattern was also found in the Segara Anakan mangrove ecosystem (Central Java) and the Mahakam Delta (East Kalimantan), where topography and water inundation variations greatly determine biomass accumulation (Murdiyarso et al., 2015; Sasmito et al., 2020).

In addition to above-ground biomass, underground carbon in mangroves also contributes significantly to the total carbon storage of the ecosystem. According to Kauffman et al. (2020), approximately 50–70% of the total carbon reserves in mangroves are stored in organic sediment layers that have been stable for thousands of years. The slow decomposition process due to anaerobic conditions below the surface causes carbon to accumulate over the long term, making this ecosystem more efficient than terrestrial forests in storing carbon (Donato et al., 2011; Lovelock & Reef, 2020).

Assuming an average carbon content in Sondaken of 230 tons/ha, the total CO_2 equivalent absorption could reach around 845 tons CO_2/ha. This figure places the Sondaken area as one of the important locations in the coastal ecosystem-based climate change mitigation strategy in North Sulawesi. To maintain this potential, sustainable management based on natural zoning and rehabilitation of degraded areas is needed to maintain long-term carbon sequestration capacity (Friess et al., 2019; Alongi, 2020).

The Ecological Role of the Sondaken Mangrove Ecosystem in Climate Change Mitigation

The Sondaken mangrove ecosystem plays a very important ecological role in climate change mitigation through long-term carbon sequestration, storage, and stabilization mechanisms. With an average carbon content of 230 tons/ha, these mangroves are classified as a carbon-dense ecosystem, which has a high capacity to absorb atmospheric CO_2 and store it in both biomass and sediments (Donato et al., 2011; Murdiyarso et al., 2015). The anaerobic muddy substrate conditions under the mangrove canopy inhibit the decomposition of organic matter, allowing carbon to be stored stably for thousands of years (Alongi, 2014).

In addition to their function as carbon sinks, the vegetation structure of the Sondaken mangroves, which is dominated by Rhizophora apiculata and Avicennia alba, provides natural protection against erosion, waves, and coastal storms. The stilt roots and pneumatophores play a role in reducing wave energy by up to 66% at a distance of 100 meters from the coastline (Mazda et al., 2006). This protective function makes the Sondaken mangroves an important component in climate change adaptation, particularly in protecting coastal communities from the impacts of sea level rise and tropical storms (Alongi, 2008; Spalding et al., 2014).

In addition to their physical and biogeochemical functions, the Sondaken mangroves also play a role in supporting biodiversity and coastal water productivity. Fallen leaves and mangrove litter contribute to the detritus food chain that supports the life of various organisms such as fish, shrimp, crabs, and water birds (Kathiresan & Bingham, 2001; Nagelkerken et al., 2008). This creates ecological connectivity between mangrove, seagrass, and coral reef ecosystems, which is important in maintaining the overall balance of coastal ecosystems (Lee et al., 2014).

Socio-ecologically, the existence of the Sondaken mangrove ecosystem also provides direct benefits to local communities through ecosystem services such as the provision of firewood, building materials, and traditional fishing products. Thus, sustainable mangrove management not only contributes to climate change mitigation but also to improving the welfare of coastal communities (Rahman et al., 2025).

The combination of mitigation (carbon sequestration), adaptation (coastal protection), and ecosystem service provision functions makes the Sondaken mangroves a strategic ecosystem in the nature-based solutions agenda for climate change. Therefore, the conservation and rehabilitation of mangroves in this region need to be supported by science-based conservation policies, community participation, and integration with regional carbon emission reduction policies (Alongi, 2020; Taillardat et al., 2018).

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CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The mangrove ecosystem in Sondaken has a relatively complete structure and composition dominated by *Rhizophora apiculata*, indicating a stable and natural ecosystem. Vegetation zoning is clearly formed from land to sea with mutually supportive ecological roles. The average biomass potential of 489.37 tons/ha and carbon storage of 230 tons/ha position this area as an important blue carbon sink for climate change mitigation. In addition, the Sondaken mangroves serve as a natural coastal protector and provide habitat for coastal biodiversity.

Recommendations

Natural zoning-based management and rehabilitation of degraded areas are needed to maintain the ecological functions and carbon potential of the Sondaken mangroves. Science-based conservation policy support and active community involvement need to be enhanced so that this area can function optimally as a nature-based solution for climate change mitigation and adaptation..

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