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Estimation of carbon stock and economic valuation of mangrove ecosystem in Ngurah Rai Grand Forest Park, Bali, Indonesia

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Abstract. *Lestari AD, Patria MP. 2025. Estimation of carbon stock and economic valuation of mangrove ecosystem in Ngurah Rai Grand Forest Park, Bali, Indonesia. Biodiversitas 26: 2821-2831.* Ngurah Rai Grand Forest Park (GFP), Bali, is considered one of Indonesia's successful examples of mangrove forest restoration, yet it remains ecologically vulnerable due to persistent anthropogenic pressures. An essential component of mangrove restoration is ecosystem monitoring, which includes both ecological assessments and economic valuation to determine carbon sequestration potential. The mangrove ecosystem in Ngurah Rai GFP provides tangible ecological, physical, and economic benefits to the local community, necessitating comprehensive evaluation to support long-term sustainability. This study aimed to assess the economic value of mangroves and estimate their carbon sequestration potential to better understand their contribution to climate change mitigation. Fieldwork was conducted from March to September 2024. Carbon sequestration was estimated using a non-destructive allometric model to measure mangrove tree biomass and sediment carbon content was analyzed using the Loss on Ignition (LOI) method. The Total Economic Value (TEV) of the mangrove ecosystem was estimated by incorporating direct use values (ecotourism, fisheries, and processed mangrove products); indirect use values (carbon sequestration, coastal protection, and ecological functions such as spawning, feeding, and nursery grounds); option values (biodiversity benefits); existence values (willingness to pay); and bequest values. The results revealed that the average carbon sequestration potential in Ngurah Rai GFP is 1,742.08 tons CO_2/ha/year. The Direct Use Value (DUV) was IDR 675,615,035,500/year; the Indirect Use Value (IUV) was IDR 862,383,525,618/year; and the Existence Value (EV) was IDR 185,158,788,000/year. The Option Value (OV), derived from biodiversity benefits, was IDR 722,958,245/year, while the Bequest Value was estimated at IDR 67,561,503,550/year. The total TEV of the mangrove ecosystem in Ngurah Rai GFP was IDR 1,791,441,810,913/year, equivalent to approximately USD 107,918,182/year.

Keywords: Allometric equation, biodiversity, biomass, restoration, total economic value

INTRODUCTION

Indonesia possesses the largest mangrove resource globally, covering approximately 3.36 million hectares or 20.37% of the world's total mangrove area (Tomlinson 2016; Arifanti et al. 2022). Despite its ecological significance, the mangrove ecosystem faces escalating challenges, including global climate change and anthropogenic disturbances (Olewiler et al. 2016). The Intergovernmental Panel on Climate Change (IPCC 2021) issued a stark warning regarding critical greenhouse gas emission levels, identifying them as the principal driver of global warming. Sivan and Veil (2021) reported that persistently high emission rates could push global temperatures beyond the 1.5°C or 2°C targets, thereby undermining climate change mitigation efforts.

In this context, ecosystem-based strategies such as the conservation and restoration of carbon-rich ecosystems like mangroves, are increasingly vital. Mangrove ecosystems deliver a range of ecosystem services: provisioning (e.g., food, timber, and resources for local livelihoods), regulating (e.g., nutrient cycling, soil formation, coastal protection, and climate regulation), cultural (e.g., ecotourism, recreation, and aesthetic value), and supporting services (e.g., nursery, spawning, and feeding grounds) (Olewiler et al. 2016; Rizal et al. 2018; Lamb et al. 2021). However, degradation caused by land conversion and overexploitation continues to threaten the sustainability of these coastal ecosystems. Such degradation not only diminishes biodiversity and the services provided by these ecosystems but also results in the release of stored carbon, further accelerating climate change (Rivera-Monroy et al. 2017; Sambu and Amrudin 2018).

Since the late 1990s, global mangrove cover has declined by an estimated 35%. Between 2000 and 2016, an additional 2.1% decline (equivalent to 3,363 km²) was recorded, largely due to conversion for aquaculture and agriculture (Goldberg et al. 2020). This ongoing loss has spurred interest in more effective mangrove management and restoration strategies (Rivera-Monroy et al. 2017). Restoration efforts have shown greater success when local communities are actively involved and derive direct economic benefits (Patria et al. 2021).

Ngurah Rai Grand Forest Park (GFP), located in Denpasar City and Badung District, Bali, Indonesia, is a designated mangrove conservation area covering 1,373.50 hectares. Its strategic location, amid Bali's main business and tourism zones, makes it particularly vulnerable to anthropogenic pressures such as pollution, land conversion, and the continual discharge of contaminated water (Almeida et al. 2016; Dimyati et al. 2022). In response, the

Indonesian government has initiated climate actions centered on mangrove restoration.

Conservation of mangroves through their restoration and rehabilitation is a priority under Indonesia's national environmental programs aligned with the Sustainable Development Goals (SDGs) (Sasmito et al. 2023). The restoration of Ngurah Rai GFP stands out as one of Indonesia's notable successes in mangrove rehabilitation (Kardana et al. 2023). Effective monitoring is essential for evaluating the success of such restoration efforts (Kodikara et al. 2017). This includes assessing various ecological indicators such as growth rate, physical conditions (e.g., temperature, pH, and salinity), vegetation dynamics, fauna presence, sustainable resource use, ecosystem services, and carbon sequestration (Rivera-Monroy et al. 2017). The carbon sequestration capacity of mangrove ecosystems plays a pivotal role in mitigating the greenhouse effect and buffering climate change impacts (Lamb et al. 2021).

Consequently, the economic valuation of carbon stocks and sinks in terrestrial ecosystems has gained increasing attention. Such valuation helps to quantify the benefits provided by mangroves and offers a practical tool to monitor restoration success. Economic assessments can also contribute to alleviating anthropogenic pressures by demonstrating the tangible benefits of restoration initiatives. This information can be used to inform and persuade local communities of the economic advantages of mangrove conservation (Bhomia and Murdiyarso 2021). Ignoring the full spectrum of economic benefits risks unsustainable resource use and further environmental degradation (Rivera-Monroy et al. 2017). Therefore, the present study aims to quantify the ecological and economic significance of the mangrove ecosystem in Ngurah Rai GFP. Specifically, it investigates the park's role in responding to global climate change and evaluates the economic value of mangrove services to enhance awareness and promote sustainable management practices within local communities.

MATERIALS AND METHODS

Study area

This study was conducted from March to September 2024 in Ngurah Rai Grand Forest Park (GFP), located in Bali, Indonesia (Figure 1). Sampling sites were selected using purposive sampling, based on the presence and distribution of mangrove vegetation. Data were collected from five observation stations representing diverse ecological and anthropogenic conditions. Station 1 covered mangrove areas near tourist attractions, Station 2 was situated close to the sea, Station 3 represented the inner mangrove zone, Station 4 was located near the Badung River, and Station 5 was positioned adjacent to residential areas.

Procedures

Literature study

Various literatures were reviewed related to the study topic including documents owned by Government, books, journals, official and trusted pages, as well as scientific references (Azzahra et al. 2020).

Data collection

Data collection for physical environmental parameters and carbon analysis was carried out along two 100-meter line transects, each containing three quadrats spaced 20 meters apart, with each quadrat measuring 20×20 meters. The data collection process involved identifying mangrove species, collecting sediment samples from a depth of 20 cm, and measuring the Diameter at Breast Height (DBH) at approximately 1.3 meters above ground level (Andini et al. 2021; Pricillia et al. 2021).

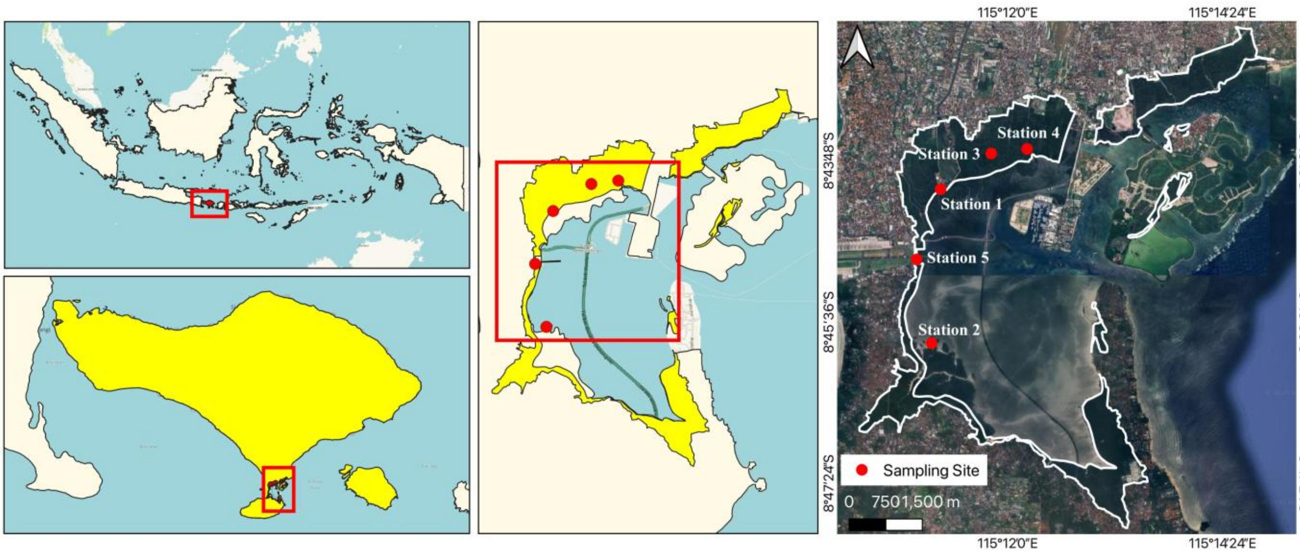

Figure 1. Study area in Ngurah Rai Grand Forest Park, Bali, Indonesia and five sampling stations

In-depth interview

Semi-structured interviews were conducted with 46 respondents to obtain information on their demographic profiles and perceptions regarding the economic value of mangrove ecosystems. The interviews focused on direct and indirect uses of mangroves, as well as respondents' willingness to pay for the continued sustainability of mangrove forests.

Data analysis

Data were analyzed using descriptive quantitative methods. This study applied the Total Economic Valuation (TEV) framework to estimate the economic value of various mangrove uses (Rizal et al. 2018). TEV categorizes economic values into use and non-use values, mathematically expressed as:

TEV = Use Value + Non-Use Value.

Use values are further classified into Direct Use Value (DUV), Indirect Use Value (IUV), and Option Value (OV), while non-use values include existence and heritage values. Specifically, DUV was estimated based on the market value of fishery products, processed mangrove products, and ecotourism. IUV comprised the potential benefits from carbon sequestration, coastal protection (water breaker), and nursery, spawning, and feeding grounds (Rizal et al. 2018).

Carbon sequestration was estimated by measuring mangrove tree biomass using a non-destructive allometric model (Table 1). Sediment carbon content was analyzed using the Loss on Ignition (LOI) method (Nelson 2020). The carbon content of organic material was assumed to be 47%. Thus, the approximate carbon stored in the biomass of trees, saplings, and seedlings was calculated by multiplying the biomass value (B) by the carbon content coefficient of 0.47 (Carong et al. 2024).

Carbon content in sediments was determined using the Loss on Ignition (LOI) method. Initially, sediment samples were oven-dried at 80°C for 48 hours until a constant weight was achieved, followed by ashing at 600°C for 4 hours (Nelson 2020). According to Carong et al. (2024), the estimated carbon stock was calculated using the following formulas:

Bulk density (g/cm^3) = Oven-dry weight : volume sample

Organic carbon content (%C) = (dry weight (%) - ash weight (%)/ dry weight) × 0.58

Soil C (tons/ha) = Bulk density × soil deep interval × %C

The total carbon sequestration value was calculated by summing the estimated carbon stored in sediments and biomass, then converting to USD at a rate of 20 USD per metric ton of carbon (Ma et al. 2024).

The mangrove ecosystem's role as a natural breakwater was evaluated by estimating the cost of constructing a coastal breakwater, based on the Indonesian Minister of Public Works Regulation (2022), multiplied by the Ngurah Rai GFP coastline length of 26,100 meters (Agustriani et al. 2023). The value of the mangrove ecosystem as a nursery, feeding, and spawning ground was assessed using the benefit transfer method, which applies economic valuations from similar studies to the current context. This was conducted by multiplying Kusumastanto's (2002) estimated value of USD 146.62 per hectare per year by the mangrove area of Ngurah Rai GFP.

Existence value was derived from semi-structured interviews, assessing respondents' Willingness to Pay (WTP) for mangrove conservation programs. Bequest value was estimated as 10% of the Direct Use Value (DUV) of the mangrove ecosystem (Rizal et al. 2018). Option Value (OV) was also assessed through the benefit transfer method, calculated by multiplying the biodiversity value per hectare (USD 15, according to Rizal et al. (2018); Patria et al. (2021)) by the area of Ngurah Rai GFP. All USD values were converted to Indonesian Rupiah (IDR) using an exchange rate of IDR 16,600 per USD, as of August 8th, 2024 (Bank Indonesia).

To effectively implement the benefit transfer method, economic values from reference studies were adjusted for temporal changes and regional differences using compound interest calculations to estimate present values (Agustriani et al. 2023):

$$FV = PV \times (1 + i)^n$$

Where,
FV : The future value
PV : The present value
i : The rate of interest
n : The number of compounding periods

Table 1. Allometric equation for calculating biomass (Lestari and Aswin 2017; Carong et al. 2024)

Species	Allometric equation for aboveground biomass	Allometric equation for belowground biomass	p
Ceriops tagal	Wag: $0.251pDBH^{2.46}$	WR: $0.199^{0.899}D^{2.22}$	0.97
Rhizophora spp.	Wag: $0.235*DBH^{2.42}$	WR: $0.00698*DBH^{2.61}$	-
Bruguiera spp.	Wag: $0.186*DBH^{2.31}$	WR: $0.0188(D^2H)^{0.909}$	-
Avicennia spp.	Wag: $0.308*DBH^{2.11}$	WR: $1.28*DBH^{1.17}$	-
Sonneratia alba	Wag: $0.251pDBH^{2.46}$	WR: $0.199^{0.899}D^{2.22}$	0.78
Sonneratia caseolaris	Wag: $0.251pDBH^{2.46}$	WR: $0.199^{0.899}D^{2.22}$	0.5
Xylocarpus granatum	Wag: $0.251pDBH^{2.46}$	WR: $0.199^{0.899}D^{2.22}$	0.7
Mangrove association	Wag: $0.2064*DBH^{2.34}$	WR: $0.2064*DBH^{2.34}$	-

Note: Wag: Above-ground biomass (tons/ha), WR: Below-ground biomass value (tons/ha), D: Stem diameter, DBH: Diameter at Breast Height, p: Bulk density (kg/cm^3)

Further adjustment for purchasing power parity between Bali Province and the reference area (West Papua Province) was performed using:

SSi = FV× LM_i × (PMWs: PMWr)

Where,
SSi : Total current value;
FV : Future Value (2024);
LM_i : Mangrove Area of Village-i;
PMWs : Provincial Minimum Wage in the study area district
PMWr : Provincial Minimum Wage in the reference district (Agustriani et al. 2023)

RESULTS AND DISCUSSION

Geographically, Ngurah Rai GFP is located between 08˚41'-08˚ 47'S and 115˚10'-115˚15'E, covering 1,373.5 ha. The results of the physical ecosystem parameter measurements at each station are presented in Table 2.

Mangrove density

The mangrove ecosystem in the study area consisted of 13 species (Table 3), with an average mangrove density of 3,419 individuals/ha. Based on Table 3, Station 3, located in the inner mangrove area, had the highest density (6,095 ind/ha), while the lowest density was observed at Station 2 (1,335 ind/ha).

Carbon stock value

The amount of biomass carbon sequestration in Ngurah Rai GFP ranged from 441.90 to 1,308.31 tons CO_2/ha/year. Soil carbon sequestration ranged from 379.91 tons to 1,273.34 tons of CO_2/ha/year. The total carbon sequestration in the mangrove forest varied between 1,034.54 tons and 2,230.15 tons CO_2/ha/year, with an average value of 1,742.08 tons CO_2/ha/year, as shown in Table 4.

Table 2. Physical parameters at the study area

Area	Temperature (ºC)	pH	Salinity (%)
Station 1 (Near tourist attractions)	27	7.5	22.6
Station 2 (Near the sea)	29.5	7.7	22.7
Station 3 (Inner mangrove)	26.5	7.2	28
Station 4 (Near Badung River)	29	7.3	29
Station 5 (Near residential area)	28.5	7.1	24

Table 3. Mangrove vegetation in Ngurah Rai GFP, Bali, Indonesia

Types of mangroves	Species name	Mangrove density (individuals/ha)				
		Station 1	Station 2	Station 3	Station 4	Station 5
True mangrove	*Sonneratia alba*	775	710	185	-	-
	Sonneratia caseolaris	75	-	-	350	255
	Rhizophora stylosa	210	-	-	-	415
	Rhizophora mucronata	1,340	90	2,945	2,170	1,565
	Bruguiera gymnorhiza	60	-	-	315	50
	Xylocarpus granatum	80	-	185	305	-
	Rhizophora apiculata	170	235	2,435	990	-
	Ceriops tagal	-	70	245	-	-
	Avicennia marina	-	230	-	-	-
Mangrove association	*Leucaena leucocephala*	-	-	-	-	80
	Calophyllum inophyllum	-	-	-	-	55
	Thespesia populnea	-	-	-	190	35
	Excoecaria agallocha	-	-	100	180	-
Total mangrove density (individuals/ha)		2,710	1,335	6,095	4,500	2,455

Table 4. Details of carbon storage in Ngurah Rai GFP, Bali, Indonesia

No	Station	Total carbon stock on biomass (ton/ha)	Total carbon sequestration in biomass (ton/ha/year)	Total carbon stock in sediment (ton/ha)	Total carbon sequestration in sediment (ton/ha/year)	Total carbon sequestration (ton/ha/year)	Density (individuals/ ha)
1	Station 1	164.81	604.86	346.96	1273.34	1878.20	2710
2	Station 2	356.49	1308.31	251,18	921,84	2230,15	1335
3	Station 3	185.81	681.91	326,21	1197,19	1879,10	6095
4	Station 4	120.41	441.90	339,64	1246,50	1688,40	4500
5	Station 5	178.37	654.63	103.52	379.91	1034.54	2455
Average value		201.18	738.32	273,50	1003,76	1742.08	3419
Total carbon stock (biomass and sediment)				474.68 tons C/ha			
Total carbon sequestration* (biomass and sediment)				1742.08 tons CO_2/ha/year			

Note: *The coefficient of determination (r^2) between biomass and total carbon sequestration (Total carbon sequestration (ton/ha/year)) is 0.999

Economic valuation of mangrove ecosystem

This study obtained the Total Economic Value (TEV) by summing five values: Direct Use Value (DUV) (ecotourism, fishery products, and processed mangrove products), Indirect Use Value (IUV) (water breaker, carbon sequestration, and feeding, nursery, and spawning ground), Optional Value (OV) (biodiversity benefits), existence value, and bequest value. The TEV of the Ngurah Rai GFP mangrove ecosystem is evaluated as follows.

Direct use value: Ecotourism

The total Direct Use Value (DUV) of Ngurah Rai GFP was determined through interviews with respondents, showing a value of IDR 675,615,035,500/year. This value represents the total of ecotourism, fishery products, and processed mangrove products. Ecotourism in Ngurah Rai GFP has developed well and generated a value of IDR 295,440,000/ha/year or IDR 405,786,840,000/year. This value is obtained by summing the revenues from various ecotourism activities, including canoe rental, small boat rental, large boat rental, mangrove seed purchases, and mangrove tour programs. Each revenue source is multiplied by the number of visitors per ha per year, as shown in Table 5.

Direct use value: Fishery and processed mangrove products

Local communities use mangrove forest products such as fish, crabs, shrimp, and processed products. The value of this ecosystem service is IDR 196,453,000/ha/year or IDR 269,828,195,500/year, as shown in Table 6.

Indirect Use Value (IUV)

In this study, IUV includes the function of the mangrove ecosystem as a water breaker, carbon sequestration, and feeding, nursery, and spawning ground. As shown in Table 7, IUV at Ngurah Rai GFP is calculated using the replacement cost method and benefit transfer, which is worth IDR 581,394,271/ha/year or IDR 862,383,525,618/year.

Option Value (OV)

Option Value (OV) of Ngurah Rai GFP mangrove ecosystem was estimated using the benefit transfer method for biodiversity value. The reference value used was USD 15/ha/year, following to the study conducted by Ruitenbeek at Bintuni Bay, Papua, in 1992 (Rizal et al. 2018). After adjusting for inflation from 1992 to 2024 (increasing from USD 15 to USD 33.54), the value was converted to IDR at an exchange rate of 16,600 per USD (Bank of Indonesia, August 8, 2024). Following this calculation, the value was further adjusted based on prevailing prices in Bali Province, leading to OV of Rp 526,362/ha or Rp 722,958,245/year for the entire area.

Existence value

Existence value measures the economic worth assigned by communities, showing their concern for natural resources and the environment. This value was calculated using the Contingent Valuation Method (CVM) by asking how much WTP from the communities in maintaining the existence of mangrove. Furthermore, economic value was obtained by adding the average value (IDR) provided by respondents to the presence of mangrove per ha per year. Through the CVM method to 46 respondents, an average WTP of IDR 20,500/person/year was obtained. Based on the interviews, Ngurah Rai GFP had 6,576 visitors/year, showing that the existence value of the mangrove ecosystem was IDR 134,808,000/ha/year or IDR 185,158,788,000/year.

Table 5. Details of ecotourism calculation

Tour services	Average rate (IDR)	Average number of visitors per year	Nominal (IDR/ha/year)	Nominal (IDR/year)
Canoe rental	30,000	4488	134,640,000	184,928,040,000
Small boat rental	300,000	120	36,000,000	49,446,000,000
Large boat rental	350,000	48	16,800,000	23,074,800,000
Mangrove seedlings sale	7,500	1200	9,000,000	12,361,500,000
Mangrove forest guided tour	137,500	720	99,000,000	135,976,500,000
Total ecotourism value of Ngurah Rai GFP			295,440,000	405,786,840,000

Table 6. Details of fisheries and processed mangrove products calculation

Types of non-timber forest products	Average catch (kg/ha/year)	Average market price (IDR/kg)	Nominal (IDR/ha/year)	Nominal (IDR/year)
Fish catch	3,366	37,500	126,255,000	173,370,037,500
Shrimp catch	635	60,000	38,100,000	52,330,350,000
Crab catch	134.4	120,000	16,128,000	22,151,808,000
Processed mangrove products	12 months	1,000,000	16,000,000	4,395,200,000
	5 events	800,000		
Total value of mangrove fisheries and processed fruits			196,453,000	269,828,195,500

Table 7. Details of indirect use value calculation

Ecosystem services	Nominal (IDR/ha/year)	Nominal (IDR/year)
Water breaker	-	63,838,494,600
Carbon sequestration	578,370,560	794,391,964,160
Feeding, nursery, and spawning ground	3,023,711	4,153,066,858
Total indirect value	581,394,271	862,383,525,618

Bequest value

Bequest value of the mangrove ecosystem is estimated to be 10% of DUV (Efendi et al. 2024). Based on the results, the bequest value of the mangrove ecosystem in Ngurah Rai GFP is IDR 49,189,300/ha/year or IDR 67,561,503,550/year.

Total Economic Value (TEV)

TEV can be estimated by summing all the calculated use values and non-use values. Based on the results shown in Table 8 and Figure 2, the TEV of the mangrove ecosystem in Ngurah Rai GFP in 2024 reached IDR 1,791,441,810,913/year.

Discussion

Characteristic of Ngurah Rai GFP

The mangrove ecosystem of Ngurah Rai GFP is influenced by various physical factors, such as temperature, salinity, waves, and tidal duration (Kodikara et al. 2017). These physical factors play a crucial role in supporting the survival of organisms and are measured in situ, with the results shown in Table 2. Based on observation, salinity, pH water, and temperature in Ngurah Rai GFP provide an optimal environment for the sustainable existence and ecological function of mangrove ecosystems. Mangroves along the coastlines of subtropical and tropical areas grow optimally at salinities of 5-35‰ and temperatures between 19-35°C (Kodikara et al. 2017; Wang et al. 2024b).

Mangrove density

This study found 13 species from 33 species of mangrove in Ngurah Rai GFP (Irawati et al. 2021). The species richness is higher compared to Nusa Lembongan, Bali, which supports 10 mangrove species, however, is comparable to the China's Shankou National Mangrove Nature Reserve and Beilun Estuary National Mangrove Nature Reserve which has record of 14 species (Pricillia et al. 2021; Wang et al. 2024a). Higher species richness, as observed in Ngurah Rai GFP, offers numerous ecological advantages. More importantly, a diverse mangrove ecosystem enhances habitat stability and resilience, contributing to greater resistance against environmental stresses such as climate change, sea-level rise, and anthropogenic disturbances (Olewiler et al. 2016).

Table 8. Details of TEV in Ngurah Rai GFP, Bali, Indonesia

Typology of values	Types of benefits	Ecosystem services	Nominal (IDR/year)	Percentage (%)
Use value	Direct use value	Ecotourism	405,786,840,000	22.65
		Fishery and processed mangrove products	269,828,195,500	15.06
	Indirect use value	Breakwater	63,838,494,600	3.56
		Carbon sequestration	794,391,964,160	44.34
		Feeding, nursery, and spawning ground	4,153,066,858	0.23
	Option value	Biodiversity value	722,958,245	0.04
Non-use value		Existence value	185,158,788,000	10.34
		Bequest value	67,561,503,550	3.77
Total economic value			1,791,441,810,913	100

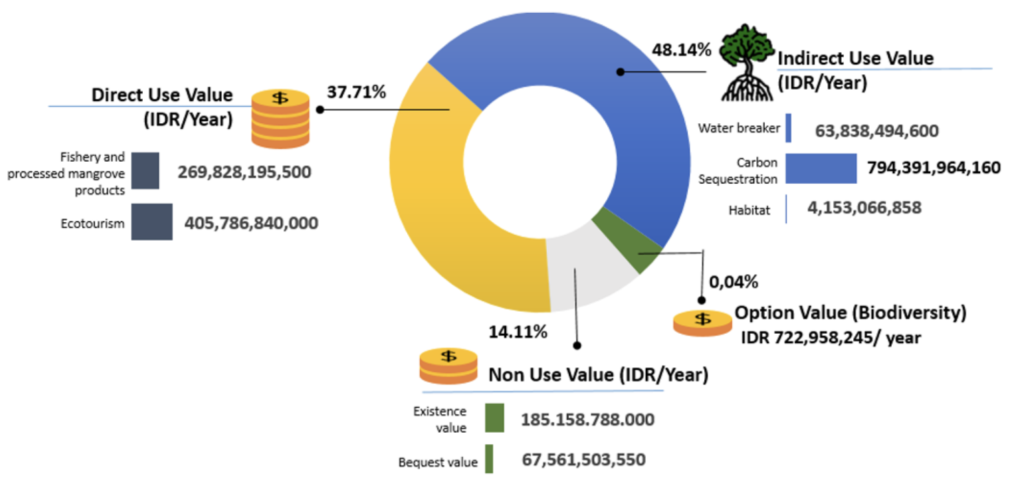

Figure 2. TEV in Ngurah Rai GFP, Bali, Indonesia

The average mangrove density in the study area was 3,419 individuals/ha. The highest density was observed at Station 3 (6,095 ind/ha), located in the inner mangrove area, while the lowest density was observed at Station 2 (1,335 ind/ha), near the sea. Detailed data on mangrove density at each station are presented in Table 3. The variation in mangrove density can be attributed to differences in their environmental characteristics. Specifically, Station 3 with the highest mangrove density, was located in the inner mangrove area, originating from intentional planting efforts. The restoration program at Ngurah Rai GFP primarily included mangrove species from the genus *Rhizophora*. The relative density of *Rhizophora mucronata* and *R. apiculata* at Station 3 was significantly high, reaching 48.61% and 38.9%. According to communities, species *R. apiculata* and *R. mucronata* are known for their rapid growth, ease of propagation, and resilience against wave and pest invasion. These results are consistent with Pricillia et al. (2021), where *R. mucronata* and *R. apiculata* show high tolerance and adaptability to diverse geographical conditions of mangrove forests, including variations in salinity, tidal exposure, and soil substrate.

In comparison, Station 2 located near the sea, had the lowest density at 1,335 individuals/ha. Observations indicated that Station 2 was characterized by fewer trees with lower densities, but larger trunk sizes compared to others. *Sonneratia alba* dominated this station, with a relative density of 55.48%, and DBH up to 45 cm. Kamruzzaman et al. (2017) reported that mangrove communities dominated by smaller trees tended to have higher stand densities, while areas with larger trees showed lower stand densities.

Mangrove density in Ngurah Rai GFP was classified as dense, indicating the success of ecosystem restoration efforts. This high density shows the healthy and rapid growth of mangrove vegetation in the area. High density can provide effective coastal protection and increase ecosystem productivity (Arfan et al. 2023). The criteria for classification reference the Decree of the Indonesian Minister of Environment No. 201 of 2004 (Table 9).

Carbon stock value

The high value of carbon sequestration (1,742.08 tons CO_2/ha/year) in Ngurah Rai GFP is due to the elevated biomass and density of mangroves (Table 4). In this study, Pearson's correlation analysis was used to determine the relationship between carbon sequestration with biomass (p: 0.999; sig. 2 tailed: 0.000). This result is supported by a few studies, which show a positive correlation between carbon sequestration and biomass (Azzahra et al. 2020; Carong et al. 2024; Ma et al. 2024). Plants absorb CO_2 from the atmosphere through photosynthesis and store it in biomass. Consequently, biomass calculations can be used to estimate amount of carbon stock. The carbon stock increases as the tree biomass increases (Azzahra et al. 2020; Carong et al. 2024).

The results showed that Station 2 had the highest total carbon sequestration (2,230.15 tons CO_2/ha/year) and biomass carbon sequestration (1,308.31 tons CO_2/ha/year) due to larger tree diameters, causing the greatest carbon absorption rate among all stations. Similarly, Ma et al. (2024) observed that stem diameter positively correlated with biomass and carbon storage. Larger stem diameters generally correspond to older and more mature trees, leading to higher carbon storage.

Station 3, located in the inner mangrove, showed the second-highest total carbon sequestration rate (1,879.10 tons CO_2/ha/year). This could be attributed to the highest stand density (6,095 individuals/ha) observed at all stations. However, Station 5, located near the residential area, showed the lowest total carbon sequestration rate (1,034.54 tons CO_2/ha/year), possibly due to reduced density (2,455 individuals/ha) and the lowest sediment carbon stock (103.52 ton/ha). Stand density has a significant influence on carbon stocks and accumulation rates. This is because higher densities can slow down water flow and turbulence in mangrove forest, facilitating the deposition of mangrove litter and enhancing organic matter accumulation in the soil (Azzahra et al. 2020).

Species composition significantly impacts mangrove carbon sequestration, as shown by variations between *Rhizophora* spp. and *Sonneratia* spp. dominated areas. The high density of *Rhizophora* spp. in the inner mangrove enhances carbon storage through robust growth and sediment trapping. Meanwhile, larger *Sonneratia* spp. trees near the sea contribute through higher individual biomass. Both tree density and individual biomass play crucial roles in determining overall carbon storage, showing the need for diverse mangrove management strategies (Kamruzzaman et al. 2017; Ma et al. 2024).

In this study, total carbon sequestration from aboveground biomass and soil of mangrove Ngurah Rai GFP was found to be 1,742.08 tons CO_2/ha/year. This carbon sequestration value was greater than in Nusa Lembongan, where the value was 249.95 tons CO_2/ha/year. The higher carbon value was due to higher aboveground biomass of 201.18 tons C/ha, which was 59.95 tons C/ha in Nusa Lembongan. Furthermore, the higher aboveground biomass is due to saplings, which have DBH <10 cm, dominating in all of the mangrove stations in Nusa Lembongan (Pricillia et al. 2021). In comparison, carbon sequestration in mangrove Ngurah Rai GFP is higher than in Sanjiangyuan National Park, where the value is 30.91 tons CO_2/ha. The low storage value can be attributed to a declining carbon trend in the area, driven by factors such as rapid tourism development, livestock expansion, the impact of climate change, and the expansion of snow-covered areas (Ma et al. 2024).

Table 9. Standard criteria for tree density

Standard criteria	Density (individuals/ha)
Dense	>1.500
Moderate	1.000-1.500
Rare	<1.000

Carbon sequestration is smaller than in Baluno mangrove forest, West Sulawesi, which has a value of 3,629.79 tons of CO_2/ha, with a total biomass of 1,558.15 tons/ha. This biomass is significantly higher than the 201.18 tons/ha recorded in Ngurah Rai GFP. The predominance of *Sonneratia* sp., a species known for its high carbon absorption ability and superior biomass content with a large DBH, contributes significantly to this higher carbon storage capacity (Carong et al. 2024). DBH is a critical determinant of tree biomass and carbon storage. A positive correlation exists between increasing DBH and rising biomass accumulation, indicating that larger trees sequester more carbon. Consequently, high DBH is directly related to increased aboveground carbon storage (Andini et al. 2021).

Direct use value: Ecotourism

Economic valuation of mangrove ecosystem services, including ecotourism, fisheries, and processed mangrove products, was conducted using the market price method. This method was favored for its simplicity and direct correlation to economic contributions or estimates of the total annual economic loss (Campos et al. 2023). Based on the results, the estimated annual economic value of ecotourism in Ngurah Rai GFP was IDR 295,440,000/ha/year or a total of IDR 405,786,840,000/year. This valuation was derived from the summation of revenue generated by various ecotourism activities, including canoe and boat rentals, mangrove seedling sales, as well as mangrove forest guided tours. Subsequently, the annual revenue per ha was multiplied by 1,373.5 ha to obtain the total economic DUV.

The results showed that Ngurah Rai GFP had a high DUV as an ecotourism destination, emphasizing the need to maintain the mangrove ecosystem's sustainability and cleanliness to continue attracting tourists. This value was significantly higher than the valuation of ecotourism in Sari Ringgung mangrove forest, Lampung, which was IDR 2,105,967,600/year. Despite the valuation, the ecotourism value remained low due to insufficient management and infrastructure to enhance tourist interest in mangrove ecotourism (Efendi et al. 2024). This is quite detrimental, as mangrove forests can enhance the coastal scenery and have significant potential to become high-value ecotourism destinations. Additionally, ecotourism has the potential to help protect the coastline and generate income for local communities (Rivera-Monroy et al. 2017).

In comparison, the ecotourism value of Ngurah Rai GFP was lower than in Phang Nga Bay, part of Ao Phang Nga National Park, Thailand, which was at USD 144.6 million or equivalent to IDR 2,400,360,000,000/year. This discrepancy could be attributed to several factors, including the unique geological formations such as a stunning landscape of limestone karsts and mangrove forests, attracting a significant number of tourists and generating substantial revenue from tourism activities (Olewiler et al. 2016).

Direct use value: Fishery and processed mangrove products

The fisheries sector in Ngurah Rai GFP contributes significantly to communities' livelihoods, particularly through the harvesting of crab, shrimp, and fish. Based on the interview, the mangrove ecosystem serves as a valuable recreational fishing ground, attracting numerous anglers. Crab and shrimp aquaculture, including the cultivation of *Scylla* spp., *Penaeus monodon*, and *Metapenaeus* spp., further enhances the economic value of the area. However, traditional fishing methods including those dependent on natural stocks, limit the potential for increased production.

Through respondent interviews, local communities possess indigenous knowledge regarding the seasonal availability of marine resources. Specifically, the fruiting season of the Buni trees (*Antidesma bunius*) is predicted to coincide with the peak abundance of crabs, prompting fishermen to intensify their efforts. Shrimp and crab cultivation in Ngurah Rai GFP can be maximized with various environmentally friendly methods, such as silvofishery to achieve greater benefits.

To diversify income sources and promote sustainable resource use, the local communities have initiated value-added processing of mangrove fruits. Information regarding these fruits is obtained through primary interviews with respondents. The results of interviews show that *Sonneratia caseolaris* (local name: *Pidada*) is processed into various products, including syrup, jam, ice cream, and candy. Meanwhile, extracts from the fruits and seeds of *Xylocarpus granatum* (local name: *Nyirih* or *Banang-banang*) are used in the production of facial masks and scrubs. Leaves of *Rhizophora* sp. can be used as eco-printing for clothes, bags, and tumblers, while fruit extracts are processed into tea and coffee useful for increasing stamina. Although the economic value of processed mangrove products is currently lower than fisheries products, there is a promising avenue for sustainable livelihood development, particularly for coastal communities. The commitment to sustainable practices is also evident in community adherence by collecting 20% of the available fruit for production, to ensure the sustainability of the ecosystem. By diversifying income sources and adopting sustainable practices, local communities can secure their livelihoods and preserve the valuable ecosystem services provided through mangrove forests.

The value of fishery and processed mangrove products in Ngurah Rai GFP is higher than in Zamboanga City, Philippines, which is worth USD 661,703.47/year or IDR 10,984,277,602/year. The relatively low economic value of fisheries in Zamboanga City can be attributed to the limited scale of commercial fish production, with only shrimp aquaculture being the primary driver of the sector's value (Alvarez and Otadoy 2023). In Ngurah Rai GFP, the fishery value is relatively high and contributes significantly to economic growth driven by the abundance of crab, shrimp, fish, and processed mangrove products. However, the value of fishery value is smaller compared to the Guangxi mangrove ecosystem, in China, which is USD 125.47 million/year or IDR 2,082,802,000,000/year. Fishery sectors are quite dominant and contribute 32% of the area TEV (Wang et al. 2024a).

Indirect Use Value (IUV)

The results showed that IUV, including the benefit value of breakwater, carbon sequestration, feeding, nursery, and spawning ground, contributed IDR 862,383,525,618/year. Using the same components, the mangrove ecosystem in Cimalaya Wetan, West Java, Indonesia, is IDR 415,195,703,043/year (Purida and Patria 2020). This value is smaller compared to the USD 93.05 million or equivalent with IDR 1,544,630,000,000/year obtained in Guangxi, China (Wang et al. 2024a). One significant factor contributing to the higher IUV in China is the substantial difference in size of the area compared to others. Guangxi has a vast expanse of mangrove forests, covering approximately 6,750.01 ha, while Ngurah Rai GFP (1,373.5 ha) and Cimalaya (738 ha). This larger area translates to a greater potential for ecosystem services, such as carbon sequestration, habitat for various species, and coastal protection. Similarly, Duijndam et al. (2020) reported that differences in size of the area, assessment methods, characteristics of ecosystem, and socio-economic context could lead to differences in the result of economic value.

The largest component of TEV in Ngurah Rai GFP is the mangrove ecosystem's role in carbon sequestration (44.34%). The valuation of the mangrove ecosystem as carbon sequestration in Ngurah Rai GFP is higher than in Cilamaya Wetan, West Java, which is at IDR 398,507,730,750/year. This higher valuation is due to the elevated carbon sequestration rate compared to Cilamaya Wetan, which has 1,742.08 tons CO_2/ha/year and a smaller mangrove forest area of 738 ha. Another factor that contributes to the lower carbon value is the reduced average stand density of 863.89 individuals/ha (Purida and Patria 2020).

In comparison, Ngurah Rai GFP has a much higher average density of 3,419 individuals/ha. Lower stand density often indicates less biomass, leading to decreased carbon storage potential (Andini et al. 2021). However, the carbon sequestration value is still lower compared to Sembilang National Park in South Sumatra, which is at IDR 6,364,901,267,188/year. This higher value is due to a larger area of 88,556 ha and a total carbon storage rate of 478.43 tons/ha (Agustriani et al. 2023).

Aside from carbon sequestration, the mangrove ecosystem provides IUV as natural breakwaters, protecting coastal communities from erosion and storm surges. The economic value of these ecosystem services can be estimated by comparing with the cost of constructing artificial breakwaters. According to the Minister of Public Works Regulation No. 1 of 2022, the construction cost of a 150-meter long breakwater with a 20-meter width and 5-meter height is approximately IDR 366,887,900/year. Given the 26,100-meter coastline (Dimyati et al. 2022), the total annual cost of constructing equivalent artificial breakwaters is IDR 63,838,494,600. This significant economic value shows the critical role of the mangrove ecosystem in coastal protection and disaster risk reduction. Furthermore, the value of the mangrove ecosystem as a wave breaker is greater compared to Gerung District, West Nusa Tenggara, Indonesia, which is worth IDR 2,557,867,440. The difference is primarily attributed to the longer coastline of Ngurah Rai GFP (26,100 meters) compared to the shorter area in Gerung District (2,190 meters) (Patria et al. 2021).

Option Value (OV)

Option Value in Ngurah Rai GFP was found to be IDR 526,362/ha/year or IDR 722,958,245/year, which is higher than Gerung District at IDR 6,510,000/year (Patria et al. 2021). Although Ngurah Rai GFP offers significant OV, its valuation was considerably lower compared to extensive mangrove ecosystems in other areas, such as Guangxi, China, which has approximately USD 11.7 million annually (equivalent to IDR 194,220,000,000) (Wang et al. 2024a). The variation in the result of OV is caused by the difference in the factors used in the valuation, such as the size of the mangrove ecosystem. This suggests that a larger size of mangrove ecosystem allows for greater biodiversity, higher productivity, and a wider range of services (Almeida et al. 2016; Wang et al. 2024a). Ngurah Rai GFP covers 1,373.5 ha, which is larger than the 31-ha mangrove ecosystem in Gerung District, but smaller compared to Guangxi mangrove ecosystem with 6,750.01 ha.

Existence value

Based on the results of interviews with 46 visitors, 100% showed WTP for the preservation of the mangrove ecosystem in Ngurah Rai GFP. This showed strong community awareness of the importance of mangrove conservation and environmental benefits. Furthermore, the results showed that communities were aware and willing to actively support conservation efforts, satisfying the ecosystem services, with an average WTP of IDR 20,500/year/person. With an average annual visitor count of 6,576/year, the existence value in Ngurah Rai GFP is IDR 134,808,000/ha/year or IDR 185,158,788,000/year. The same calculation method was used by Alvarez and Otadoy (2023) in Zamboanga mangrove forest, Philippines, which obtained a lower value of USD 942.99/year or IDR 15,653,634/year. This was because only 52.2% of communities WTP and are concerned with the sustainability of the mangrove ecosystem.

Bequest value

The bequest value of the mangrove ecosystem is estimated at 10% of DUV (Efendi et al. 2024). In Ngurah Rai GFP, bequest value was found to be IDR 49,189,300/ha/year or IDR 67,561,503,550/year. This value is higher compared to Ca Mau mangrove ecosystem, estimated at USD 96.43/ha/year or equivalent to IDR 1,600,738/ha/year. The lower value observed in Ca Mau mangrove ecosystem is due to the restoration project in Vietnam that has not been optimally used by local communities (Nguyen 2015). The variation in the result is caused by the difference in the factors used in the valuation, such as the size of the mangrove ecosystem, economic activities in the surrounding areas, and DUV amount of mangrove in the area by local communities.

Total Economic Value (TEV)

The Total Economic Value (TEV) of the Ngurah Rai GFP mangrove ecosystem, calculated by summing various direct, indirect, optional, existence, and bequest values, was found to be substantial, amounting to IDR 1,791,441,810,913/year in 2024 (Table 8), highlighting the importance of the ecosystem's services. While some benefits, such as water filtration, education, oxygen provision, genetic resources, and biochemistry, were not explicitly quantified in this study, the estimated TEV still exceeded IDR 1 trillion, highlighting the immense economic contribution of the mangroves. The potential loss of these valuable services due to ecosystem degradation emphasizes the urgent need for conservation and sustainable management (Rivera-Monroy et al. 2017).

Comparing the TEV of Ngurah Rai GFP, it is notably higher than that of Cimalaya Wetan, West Java (IDR 419,233,914,343/year), and Zamboanga City, Philippines (USD 1,559,918.88/year or IDR 25,894,653,408/year) (Purida and Patria 2019; Alvarez and Otadoy 2023). However, it is smaller when compared to Sembilang National Park, which boasts a TEV of IDR 6,961,126,186,194/year (Agustriani 2023). These variations are attributable to several factors, including differences in the size, quantity, and specific types of values measured, the current ecological condition of the mangrove areas, and the focus of each respective study (Alvarez and Otadoy 2023).

The largest contribution to the TEV of Ngurah Rai GFP comes from Indirect Use Value (IUV), which accounts for 48.14% of the total. This emphasizes the critical ecological functions performed by the mangrove ecosystem, particularly coastal protection, and carbon sequestration. Simultaneously, Direct Use Value (DUV), encompassing ecotourism, fishery, and processed mangrove products, contributes a substantial 37.71%. This demonstrates the successful adaptation of local communities in utilizing the natural potential of the mangrove ecosystem. By effectively managing visitor attractions and processing marine catches and mangrove fruits, local communities generate income and contribute to the ecosystem's sustainability. This approach exemplifies how ecosystem-based adaptation can foster a balance between economic growth and environmental conservation (Olewiler et al. 2016).

In conclusion, The Ngurah Rai Grand Forest Park mangrove ecosystem was recognized to possess significant ecological and economic value. Investigations indicate an average carbon sequestration value of 1,742.08 tons CO2/ha/year, suggesting a substantial contribution to carbon regulation within the atmosphere. Furthermore, the Total Economic Value has been estimated at IDR 1,585,382,050,450/year, encompassing direct, indirect, and non-use values. This comprehensive valuation broadly illustrates the multifaceted benefits attributed to this ecosystem. However, the ecosystem's integrity was noted to be challenged by various stressors, including land conversion, pollution, and the broader impacts of climate change. Such pressures potentially compromise biodiversity and the sustained provision of ecosystem services, implying considerable economic ramifications. Consequently, the findings suggest that the integration of economic valuation could serve as a valuable instrument for guiding decision-making processes by policymakers and relevant stakeholders. Acknowledging the ecological and economic contributions of these mangroves may be conducive to developing and implementing management protocols and conservation strategies that promote their long-term viability and benefit provision for future generations. This perspective could foster integrated, collaborative approaches towards mangrove protection and regional sustainable development.

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