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RIPARIAN VEGETATION OF MANINJAU LAKE, WEST SUMATRA, INDONESIA: A STUDY OF BIODIVERSITY AND ABOVE-GROUND CARBON STOCK

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Abstract

Maninjau Lake is one of the largest lakes in the West Sumatra Province and one of the priority lakes in Indonesia. This lake has an essential role in supporting the lives of local communities, including as a source of agricultural irrigation, aquaculture, a hydroelectric power plant and tourism. However, riparian areas have experienced various disturbances from anthropogenic activities such as deforestation and land use change. The present research aims to analyze the composition, diversity and above-ground carbon stock of riparian vegetation in Maninjau Lake. The result revealed that the riparian vegetation around Maninjau Lake consisted of 57 species from 27 families, eighteen of which are identified in The IUCN Red List of Threatened Species. The most dominant and essential species in the tree category were coconut (Cocos nucifera L.) and durian (Durio zibethinus), while on poles, saplings and seedlings were dominated by betel nut (Areca catechu), cinnamon (Cinnamon verum) and coromandel (Asystasia gangetica), respectively. The average of the above-ground carbon stock was 346.13 ± 62.15Mg C ha^{-1} or equivalent to 1,270.28 ± 228.09Mg CO_2e. The research findings indicate that anthropogenic activities such as land conversion and logging harm the distribution of above-ground carbon stock in the research area, where sites in forests that are protected from human activity have the highest above-ground carbon stock values compared to places affected by plantation and agricultural activities. Therefore, a sustainable riparian zone management strategy is needed through restoration and conservation efforts to protect biodiversity and support climate change mitigation.

***Keywords**: Vegetation; Riparian zone; Diversity index; Carbon stock, Conservation; Maninjau Lake*

Introduction

The riparian zone is a transitional zone between the terrestrial zones and the aquatic ecosystem (i.e., streams, lakes, rivers and other wetlands) [1]. Riparian vegetation has physiological characteristics, structure and composition that are relatively different from terrestrial vegetation because it is located in an environment that is a buffer zone between land and wetlands [2]. In addition to providing habitat for terrestrial wildlife, the riparian zone

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functions as a corridor that connects fragmented forest areas, facilitating species movement and supporting habitat continuity [3]. In lake environments, the riparian zone is crucial to preserving the stability of the lakeshore [4], maintaining the lake's water quality [5] and providing habitat for various species of plants and animals [6]. Riparian vegetation along lake margins provides essential ecosystem services that support local communities and livelihoods. Although these areas occupy only a small fraction of the land surface, their hydrological and ecological functions are critical and should be integral to effective lake management strategies [7, 8].

Riparian zones are among the most diverse and productive ecosystems, playing a vital role in carbon sequestration and contributing significantly to global carbon regulation and climate change mitigation [9]. Carbon sequestration is defined as the process by which ecosystems capture and store carbon within biomass and sediments, thereby sequestering greater amounts of carbon than are emitted back into the atmosphere through respiratory and decomposition processes [10]. However, the riparian zone is threatened by various natural disturbances, including floods and other anthropogenic disturbances that disrupt riparian zones [11]. Anthropogenic activities are the primary drivers of degradation in most riparian zones, including urban development [12], conversion of land to agriculture [13], Aquaculture ponds, plantations and settlements [14]. This degradation leads to a decline in riparian vegetation diversity and impairs the physical, biological, and chemical functions that support the surrounding ecosystems. Furthermore, the loss of riparian vegetation resulting from deforestation and land-use conversion around lakes substantially contributes to global greenhouse gas (GHG) emissions [15]. Currently, the restoration of degraded riparian zones through natural regeneration and active intervention strategies is widely recognized as an effective approach for enhancing carbon storage and biodiversity recovery [16].

Such concerns are particularly pertinent in Indonesia, where deforestation between 2000 and 2016 has been reported to contribute significantly to national GHG emissions, which reached 0.71 Gt CO_2e [17]. Approximately 60% of the anthropogenic GHG effect and climate change is caused by CO_2, which is partially emitted due to deforestation and land conversion in wetland areas [18]. Addressing these emissions is therefore critical, as they have become a major priority on national and global environmental and scientific agendas. The carbon sequestration capacity of vegetation and the potential for carbon storage in wetlands, including lake ecosystems, have consequently emerged as important areas of research aimed at supporting local and global CO_2 reduction strategies [19, 20]. However, studies that measure carbon stocks in the vegetation around lakes remain limited [15, 21, 22]. Understanding the relationship between carbon stocks and biodiversity is becoming more crucial because of the necessity to fulfil the requirements of global accords, particularly those concerning climate change mitigation [23]. Therefore, research regarding the potential for carbon accumulation in riparian vegetation biomass is essential, considering the limited data and information in this study area.

Lake Maninjau is one of the priority lakes in Indonesia, which has faced environmental pressure caused by the expansion of aquaculture and the widespread use of the lake's riparian lands for settlements, rice fields, plantations and tourism [24]. Vegetation in the riparian zone of Lake Maninjau is reported to be in a declining condition due to illegal logging and land conversion for agriculture and plantations, thus having a severe impact on people living around the lake [25]. Degradation of riparian vegetation, coupled with the expansion of aquaculture and agriculture around Lake Maninjau, has contributed to the deterioration of the lake’s water quality, which is currently classified as heavily eutrophic [26], which, in turn, impacted the local people's livelihood and public health [27]. This study aims to evaluate plant diversity structure and above-ground carbon stock potential in Lake Maninjau. The results are expected to support Sustainable Development Goals on climate action (13), terrestrial ecosystem protection (15), and sustainable water management (6).

Methods

Study area

The study was conducted in Maninjau Lake, West Sumatera, Indonesia. Geographically, Lake Maninjau is located at 0^0 17' 07.04" South (S) and 100^0 09'58.0" East (E) in Agam Regency, Tanjung Raya District. Maninjau is a tectonic volcano lake with an area of 9,785,6ha and a depth average of 105m at an altitude of 461.5m above sea level [25]. Lake Maninjau is one of 15 priority lakes in Indonesia that were chosen to be saved with integrated, environmentally sound and sustainable management [24]. The primary function of Lake Maninjau is as a hydroelectrical power plant, the electricity generated at 64MW to supply the electricity of the West Sumatra region. Maninjau Lake is also one of the tourist destinations and fisheries. Since 1992, the lake has been used for floating net cages (FNC) [26]. The number of FNCs in 2012 was 15,860 units, which tends to increase to 17,441 units in 2021 [28]. This sharp increase induced a heavy eutrophic condition [26].

The amount of rainfall in the wet month (> 200 mm/month) and the dry month (< 100 mm/month) in the Lake Maninjau area is classified into agro-climatic zone A, which can pose a risk or hazard to erosion and runoff. The average maximum temperature in the Lake Maninjau area is around 31.27ºC and the average minimum temperature is around 22.66ºC, with an average relative humidity of around 95.20%, wind speeds of about 23.5km/hour and annual rainfall ranging from 3,000 – 3,500mm per year. The catchment area of Maninjau Lake is 13,260ha, with a pattern of land use as forest 6,645.92ha (50.12%), mixed gardens 3,536.44ha (26.67%), rice fields 1,886.89ha (14.23%), settlements 847.31ha (6.39%), rivers 283.76ha (2.14%) and roads 35.80ha (0.27%) [25].

Data collection method

Three research sites were determined by random judgemental sampling method~~s t~~o identify different characteristics according to research objectives [29]. The accessibility and representation of each location were essential aspects of this study's decision to choose research sites. The three research sites were selected to represent riparian zones around Maninjau Lake with different conditions, where sites 1 (S1) (0^0 19' 56.58" S and 100^0 09' 53.93" E) are forest areas affected plantation activities, sites 2 (S2) (0^0 21' 49.87" S and 100^0 10' 05.65" E) are a forest area with minimal anthropogenic activity. Site 3 (S3) (0^0 20' 10.44" S and 100^0 13' 10.73" E) is an area near rice fields and settlements (Fig. 1).

Nine sampling plots at three research sites had a 100-meter-long transect line created from the area closest to the lake to the terrestrial area. The vegetation parameters collected for the tree and pole category comprised species, number of individuals and diameter at breast high (DBH) of 1.3m. In contrast, the parameters were species and numbers for seedlings and saplings. The sampling plot for vegetation observation size is 20 x 20m for trees (DBH ≥ 20cm), 10 x 10m for poles (DBH ≥ 10cm), 5 x 5m for saplings (DBH < 10cm) and 2 x 2m for seedlings category (height < 1.5m) (Fig. 2).

The vegetation species in the sampling plots were identified using a preference for vegetation identification including books [30, 31], PictureThis (2023) [32], TPL (2023) [33] and WFO (2023) [34]. The data collected from each sampling plot were analyzed to obtain density, basal area, Important Value Index (IVI), Species Diversity Index (H'), Evenness Index of species Pielou (J), above-ground biomass (AGB), above-ground carbon (AGC) stock and Carbon dioxide (CO_2) sequestered.

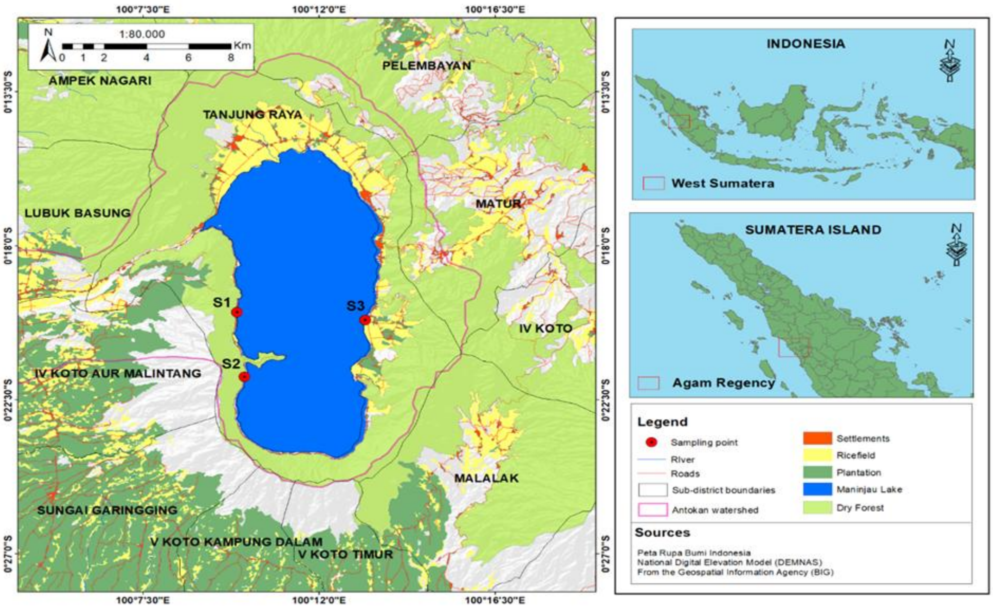

Fig. 1. Three research sites at Maninjau Lake

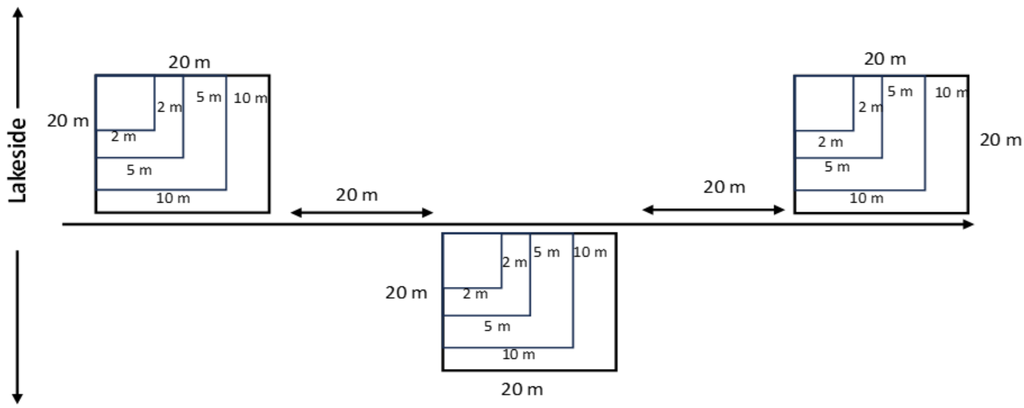

Fig.2. Design of sampling plots placement for riparian vegetation observation

Data analysis

The structure and composition of vegetation data were analyzed using the species' Important Value Index (IVI). The IVI value is obtained by summing the relative density (RDi), relative frequency (RFi) and relative cover (RCi) of each species [36]. The IVI value describes the influence and role of a species on the community; weight ranges from 0 to 300%. In this case, the species with the highest IVI shows dominance and strongly influences the community [36]. The vegetation analysis used the equation of density (D_i), RD_i, frequency (F_i), RF_i, dominance (C_i), RC_i and IVI [37]:

D_i = Number of individual species / total area of sampling (1)

RD_i = (Number individual species / total number of all species) x 100% (2)

F_i = Number of occurrence of species / total number of sampling plots (3)

RF_i = (Frequency of species / Frequency of all species) x 100% (4)

C_i = Basal area (BA) / total area of sampling plots (5)
BA = $\pi DBH^2/4$, (π = 3.14) (6)
RC_i = Species cover area/ Total cover area of all species x 100% (7)
IVI = RDi + RFi + RCi (for tree and pole category) (8)
IVI = RDi + RFi (for sapling and seedling category) (9)

where: D_i - Density (Ind ha^{-1}); RD_i - Relative Density (%); F_i - Frequency; RF_i -Relative frequency (%); C_i- Coverage of species (m^2 ha^{-1}); BA- Basal area (m^2); RC_i-Relative coverage (%); IVI - Important Value Index (%)

The species diversity of vegetation was calculated and interpreted using the Shanon-Wiener Index (H'). The H' value is categorized as very high (H' ≥ 4), high (H' ≥ 3-4), moderate (H' ≥ 2-3), low (H' ≥ 1-2) and very low (H' < 1) [38]. The calculation of H' was using the following equation by [39]:

$$H' = \sum_{i=1}^{n}\left(\left(\frac{ni}{N}\right) ln \left(\frac{ni}{N}\right)\right) \quad (10)$$

where: H'- Shannon-Wiener Index; ni - Species density; N - Total density of all species

The Evenness index of species Pielou (J) is also calculated to illustrate the distribution level for each species in the research area. The J value is classified as low (J < 0.3), moderate (0.3 < J < 0.6) and relatively high (J > 0.6) [38]. The J value was calculated using the following equation [39, 40]:

$$J = \frac{H'}{\ln(S)} \quad (11)$$

where: J - Evenness index of species Pielou; H' - Species diversity index; S - Total of species

For estimating AGC stock, AGB is calculated using the allometric equations. In this regard, the allometric equations, which were created using conventional carbon inventory concepts, are extensively applicable in tropical forests with three different types of trees (dry, moist and wet). The data calculates riparian vegetation's AGC stock, which is included in the pole and tree categories with DBH > 10cm. The AGB of vegetation at the riparian zone at Maninjau Lake was estimated using allometric equations designed for tropical mixed natural forest in Sumatra [41]:

$$AGB = 0.066 \times DBH^{2.59} \quad (12)$$

where: AGB - Above-ground biomass (kg); DBH - Diameter at breast high (cm)

In this regard, 50% of the biomass forms the carbon stock in the tropical forest [42]; the AGC stock is computed by multiplying the carbon conversion factor of 0.50 by the AGB of living vegetation. In addition, the amount of CO_2 sequestered in the vegetation biomass was calculated using a 3.67 factor [43]:

$$AGC = AGB \times 0.50 \quad (13)$$
$$CO_2 \text{ sequestered} = AGC \times 3.67 \quad (14)$$

where: AGC - Above-ground stocks (kg C); AGB - Above-ground biomass (kg)

Analysis of variation (ANOVA) was applied to determine the differences between AGC stock at each research site. When the ANOVA results were compelling, Tukey's honestly significant difference (HSD) test was applied to identify the significance of the mean difference. Data normality was assessed by the Shapiro-Wilk test. All statistical tests used a significance level 0.05 and were written in the mean ± standard error. IBM SPSS Statistics 20.0 and Microsoft Excel were used to perform statistical analyses.

Results and discussion

The composition, structure and species diversity of riparian vegetation in Maninjau Lake

Based on the identification of the riparian vegetation in the research area, at least 57 species from 27 families were identified in all research sites. The vegetation categorized as tree and pole is shown in Table 1, while the vegetation ordered as sapling and seedling is shown in Table 2. Thirteen species of riparian vegetation in Maninjau Lake are classified as *Least Concern* (LC), three species as *Data Deficient* (DD) and one species as *Endangered* (EN) on the IUCN Red List category. The species included in the LC category include *Ficus benjamina* [44], *Gmelina arborea* [45], *Gnetum gnemon* [46, 47], *Persea americana*, *Psidium guajava* [48], *Toona sureni* [49], *Ageratum conyzoides L.* [50], *Colocasia esculenta L.* [51], *Codiaeum variegatum*[52], *Cyperus rotundus* [53], *Melia azedarach* [54], *Mimosa pudica* [55], *Piper aduncum* [56]. Meanwhile, two species included in the DD category are *Mangifera indica* [57] and *Myristica fragrans* [58] and one species in the EN category is *Pterocarpus indicus* [59]. From highest to lowest, the number of species per family was as follows: Fabaceae (six species), Asteraceae (six species), Araceae (five species), Malvaceae (four species), Moraceae (four species), Poaceae (three species) and less than three species were found in each of the other families.

Table 1. Composition and densities of tree and poles around Maninjau Lake

No	Family	Species	Local name	Density (Ind ha⁻¹)						Red List IUCN
				Tree			Pole			
				ST1	ST2	ST3	ST1	ST2	ST3	
1	Fabaceae	*Abrus precatorius*	Saga	-	-	8,33	-	-	-	-
2	Arecaceae	*Areca catechu*	Pinang	-	-	-	433,33	833,33	-	DD
3	Moraceae	*Artocarpus heterophyllus*	Nangka	8,33	-	-	-	-	-	-
4	Poaceae	*Bambusoideae sp*	Bambu	-	-	-	-	-	200,00	-
5	Phyllanthaceae	*Bridellia sp*	Gandrik	-	-	-	-	166,67	33,33	-
6	Lauraceae	*Cinnamomum verum*	Kayu manis	-	-	-	66,67	-	133,33	-
7	Arecaceae	*Cocos nucifera L.*	Kelapa	16,67	58,33	166,67	-	-	-	-
8	Malvaceae	*Durio zibethinus*	Durian	66,67	58,33	-	-	33,33	-	-
9	Moraceae	*Ficus benjamina*	Beringin	8,33	-	8,33	-	33,33	33,33	LC
11	Verbenaceae	*Gmelina arborea*	Jati Putih	-	-	-	33,33	-	-	LC
12	Gnetaceae	*Gnetum gnemon*	Melinjo	-	-	8,33	-	-	-	LC
13	Anacardiaceae	*Mangifera indica*	Mangga	-	-	16,67	-	66,67	33,33	DD
14	Musaceae	*Musa paradisiaca*	Pisang	-	-	-	333,33	-	66,67	-
15	Myristicaceae	*Myristica fragrans*	Pala	41,67	108,33	-	500,00	500,00	-	DD
16	Lauraceae	*Persea americana*	Alpukat	8,33	-	-	66,67	-	-	LC
17	Myrtaceae	*Psidium guajava*	Jambu biji	-	-	-	33,33	-	-	LC
18	Fabaceae	*Pterocarpus indicus*	Angsana	-	-	8,33	-	-	-	EN
19	Myrtaceae	*Syzygium aromaticum*	Cengkeh	-	-	-	-	66,67	33,33	-
20	Malvaceae	*Theobroma cacao L.*	Cokelat	-	-	-	66,67	-	-	-
21	Meliaceae	*Toona sureni*	Suren	16,67	41,67	8,33	133,33	-	-	LC
		Total		**166,67**	**266,67**	**225,00**	**1666,66**	**1700,00**	**533,33**	

Table 2. Composition and densities of tree and pole around Maninjau Lake

No	Family	Species	Local name	Density (Ind ha^{-1})						Red List IUCN
				Sapling			Seedling			
				S1	S2	S3	S1	S2	S3	
1	Euphorbiaceae	*Acalypha siamensis*	Teh-tehan	-	-	1333,33	-	-	-	-
2	Amaranthaceae	*Achyranthes aspera Linn.*	Jarong	-	-	-	5833,33	-	-	-
3	Asteraceae	*Ageratum conyzoides L.*	Bandotan	-	-	-	4166,67	-	-	LC
4	Araceae	*Colocasia esculenta L.*	Talas	-	-	-	7500,00	2500,00	2500,00	LC
5	Arecaceae	*Areca catechu*	Pinang	-	400,00	-	833,33	-	-	DD
6	Acanthaceae	*Asystasia gangetica*	Bayaman	-	-	-	31666,67	2500,00	8333,33	-
7	Asteraceae	*Bidens pilosa*	Ketul	-	-	-	-	-	13333,33	-
8	Phyllanthaceae	*Bridellia sp*	Gandrik	-	-	400,00	-	-	-	-
10	Fabaceae	*Centrosema pubescens*	Sentro	-	-	-	6666,67	-	-	-
11	Lauraceae	*Cinnamomum verum*	Kayu manis	1200,00	533,33	666,67	1666,67	-	-	-
12	Lamiaceae	*Clerodendrum paniculatum*	Bunga pagoda	-	-	133,33	-	-	-	-
13	Fabaceae	*Clitoria ternatea*	Bunga telang	-	-	-	-	8333,33	2500,00	-
14	Euphorbiaceae	*Codiaeum variegatum*	Puring	-	1600,00	-	-	833,33	-	LC
15	Rubiaceae	*Coffea sp*	Kopi	-	1066,67	-	-	-	3333,33	-
17	Asteraceae	*Crassocephalum crepidioides*	Sintrong	-	-	-	-	833,33	-	-
18	Cyperaceae	*Cyperus rotundus*	rumput teki	-	-	-	-	-	2500,00	LC
19	Fabaceae	*Desmodium sp*	-	-	-	-	833,33	-	-	-
20	Araceae	*Differnbachia sp*	bunga bahagia	-	-	-	-	4166,67	-	-
21	Asteraceae	*Elephantopus scaber*	Tapak liman	-	-	-	-	-	7500,00	-
22	Poaceae	*Eleusine indica (L.) Gaertn.*	Rumput belulang	-	-	-	-	-	1666,67	-
23	Araceae	*Epipremnum aureum*	Sirih gading	-	-	-	-	2500,00	-	-
24	Moraceae	*Ficus montana*	Uyah-uyahan	-	-	-	833,33	-	-	-
25	Moraceae	*Ficus sp*	-	266,67	266,67	-	-	-	-	-
26	Campanulaceae	*Hippobroma longiflora*	Isotoma	-	-	-	-	19166,67	-	-
27	Araceae	*Homalomena occulta*	Nyampu	-	-	-	2500,00	-	-	-
28	Urticaceae	*Laportea sp*	Daun gatal	-	-	-	-	833,33	-	-
29	Euphorbiaceae	*Macaranga hypoleuca*	Pohon mahang	133,33	-	-	1666,67	-	-	-
30	Euphorbiaceae	*Manihot esculenta*	Singkong	-	-	933,33	-	-	-	-
31	Marantaceae	*Maranta arundinacea*	Garut	-	-	-	-	3333,33	-	-
32	Meliaceae	*Melia azedarach*	Mindi	-	-	-	3333,33	-	-	LC
33	Fabaceae	*Mimosa pudica*	Putri malu	-	-	-	-	-	3333,33	LC
34	Myristicaceae	*Myristica fragrans*	Pala	400,00	-	-	-	-	-	DD
35	Poaceae	*Pennisetum purpureum*	Rumput gajah	-	-	400,00	-	-	-	-

No	Family	Species	Local name	Density (Ind ha⁻¹)						Red List IUCN
				Sapling			Seedling			
				S1	S2	S3	S1	S2	S3	
36	Piperaceae	*Piper aduncum*	Sirihan	-	-	-	5833,33	-	-	LC
37	Piperaceae	*Piper Betle Linn*	Sirih	-	-	-	3333,33	-	-	-
38	Dryopteridaceae	*Nephrolepis cordifolia*	Paku pedang	-	-	-	4166,67	-	-	-
39	Malvaceae	*Pterospermum javanicum Jungh.*	Bayur	133,33	-	-	6666,67	-	-	-
40	Phyllanthaceae	*Sauropus androgynus*	Katuk	-	133,33	-		-	-	-
41	Selaginellaceae	*Selaginella sp*	Rane	-	-	-	833,33	-	-	-
42	Malvaceae	*Sida rhombifolia L*	Seleguri	-	-	266,67	-	-	-	-
43	Araceae	*Syngonium podophyllum*	mata panah	-	-	-	-	4166,67	-	-
44	Asteraceae	*Tithonia diversifolia*	Kipait	-	-	-	-	-	6666,67	-
45	Meliaceae	*Toona sureni*	Surian	400,00	-	-	-	-	-	LC
46	Asteraceae	*Tridax procumbens*	Gletang	-	-	-	6666,67	4166,67	5833,33	-
Total				**2533,33**	**4000**	**4133,33**	**95000**	**53333,33**	**57500**	

Cocos nucifera L. was the most dominant species in the three categories and had the highest IVI value (83.93%) among species discovered at the research site, then followed by *Durio zibethinus* (75.99%), *Myristica fragrans* (49.21%) and *Toona sureni* (38.21%) (Fig. 3). *Areca catechu* and *Myristica fragrans* were the two species that dominated at pole category with an IVI value of 63.05% and 58.47%, respectively. In contrast, the sub-dominant species comprised Bambusa sp., Toona sure and Musa paradisiaca, with IVI values ranging from 23.13 to 40.55 %. In the sapling category, *Cinnamon verum* was the dominant species and had the highest IVI value (36.29%), followed by *Myristica fragrans* (24.71%) and *Acalypha siamensis* (18.16%). Meanwhile, *Asystasia gangetica* was the dominant species in the seedling category (27.43%), with sub-dominant species including *Tridax procumbens* (16.00%), *Bidens pilosa* (12.43%) and *Colocasia esculenta L.* (12.29%). In this regard, *C. nucifera L., D. zibhetinus, M. fragrans, A. catechu* and *C. verum* are sub-sectors of horticultural commodities widely cultivated by local communities surrounding Lake Maninjau, so they dominate and are often found compared to other tree species.

The vegetation surrounding Maninjau Lake is crucial in preventing the erosion of the area's delicate sandy soils. The coconut tree (*C. nucifera L.*), a native species, has the most significant potential for protecting the riparian zone. The IVI of the coconut tree was the highest (Fig. 3). According to literature data [60], the IVI reflects the ecological roles of each species in supporting the landscape ecosystem. Monocotyledonous plants such as coconut have shallow, tightly packed roots perfect for retaining surface water. Due to their fruits and woody stems, which may be used for construction, local people have long planted coconut trees as riparian vegetation. Coconuts are a commonly utilized tree that thrives in various soil types, including volcanic, laterite, rocky, sandy and sand.

Durian (*D. zibethinus*) is a tropical fruit found in Southeast Asia and is renowned as the king of the fruit. Durian comes in various variations, each with its own physical characteristics. Durian is an Indonesian native plant [61]. There are approximately 31 types of durian worldwide, 19 of which are found in Kalimantan. In comparison, seven other types of durian are dispersed across Sumatra, with the majority still growing wild in the jungle [62]. The durian spread extends to various countries, including Indonesia, Thailand, Myanmar, India and Pakistan. In Indonesia, durian is an important export commodity due to rising demand. As one of the riparian vegetation, Durian is also well-known as a plant species that considerably reduces lake pollution in the form of N and P components, which typically come from rice fields and river flows through plant physiological mechanisms [63], [64].

The nutmeg tree (*M. fragrans*) is a high-value spice-producing tree [65]. Since ancient times, the commodity of nutmeg has been well-known to foreign countries. The part of this commodity utilized is the fruit, which consists of pulp, seed coat, and seeds. Indonesia is the world market's largest exporter of nutmeg seeds (around 60%). Nutmeg is an export commodity with good prospects because it will always be continuously needed in the food, beverage, medicine, and other industries. Before the rapid development of floating net cages (FNA), the area around Lake Maninjau was one of the nutmeg-producing areas. Nutmeg is considered an economically valuable plant that could contribute to community welfare, where efforts to plant and utilize nutmeg optimally are considered potential and alternative economic activity opportunities that can replace income from FNA.

In addition, nutmeg productivity is closely connected with soil moisture, minerals, drainage, lack of flooding, yearly rainfall, maximum temperature, and humidity index (Basir et al. 2018). Nutmeg was classified as Data Deficient (DD) [58] (Tables 1 and 2). As a result, information on population, growth patterns, dangers, use and commerce, and conservation activities is scarce but desperately needed. Future studies may demonstrate that its threatened status is correct. Compiling available data is critical for informing future species management.

T. sureni (suren) is a forestry plant with numerous uses. Suren trees are medium to large in stature, growing up to 40 (60) m tall and 100 cm in diameter (300 cm in mountainous places), with a dark brown juvenile branch. Suren is a forestry commodity with good woody qualities and a high economic value [66]. Suren trees are suitable for timber and non-wood items [67]. Suren leaves contain bioactive chemical compounds that are useful as antioxidants [68]. The roots are a relatively woody, solid root system that can stabilize hillslopes and riparian areas and reduce the risk of landslides [69]. Therefore, one of the efforts to maintain and protect the riparian zone in the Lake Maninjau area is through replanting plant species that are not only highly beneficial socio-economically but also environmentally, especially the species *C. lucifera L., D. zibhetinus, M. fragrans,* and *T. Sureni*. An essential ecological engineering technique for managing riparian zones is vegetation suit maintenance. In this regard, an eco-restoration model and a reconstruction strategy for the vegetation community have been established to assist in developing future lake management plans [70].

Species diversity is a prominent element in finding forest ecosystems and will be a significant tool to improve the ability to maximize biodiversity conservation [71]. The tree and pole category's highest species diversity index (H') was in S1 (1.62 and 1.78, respectively). Meanwhile, for the sapling category, the highest H' was found in S3 (1.83) and the seedling category was also in S1 (2.41). Overall, the H' at all research sites and growth stages was categorized as low class (1.34) (Fig. 4). This indicates that the riparian vegetation community might be unstable or distressed, requiring sustainable management and a conservation effort. The value for the H' of riparian vegetation in Maninjau Lake is relatively higher than that of mangrove forest in Sarawak, Malaysia (1.18) [72] and protected areas in Muara Kubu, West Kalimantan (0.23) [73].

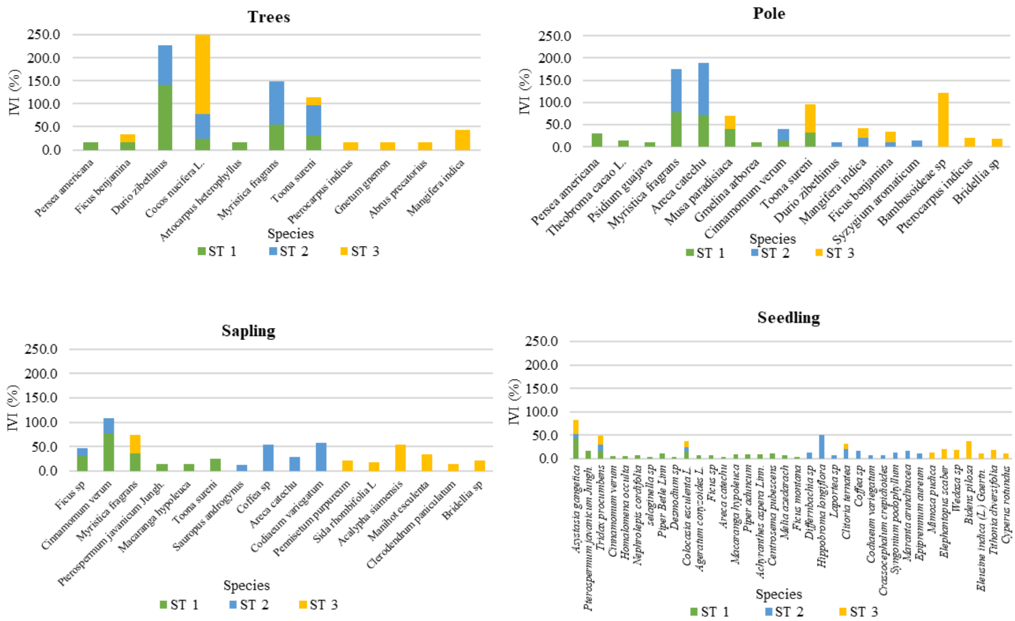

Fig. 3. IVI (%) of riparian vegetation at each in Maninjau Lake for trees, poles, saplings and seedlings categories

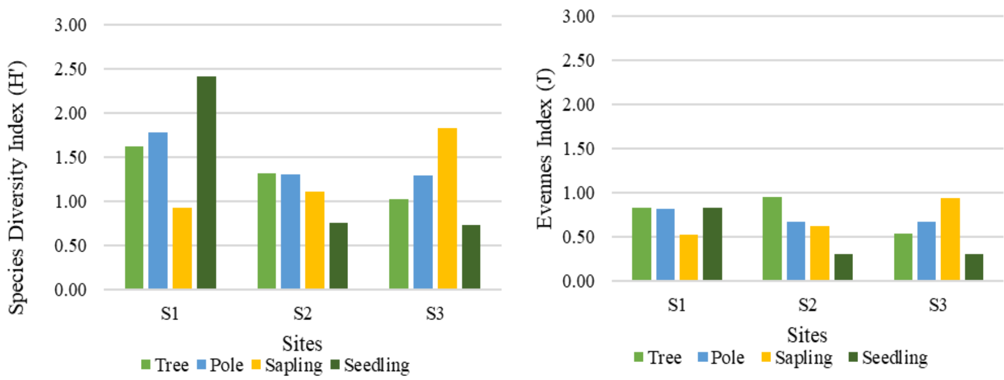

Fig. 4. The species diversity index (H') and Evenness Index (J) at each research site and growth-stage

In contrast, all research sites' Evenness Index (J) was categorized as moderate to high. The highest value of J was found in the seedling category at S3 (0.31), while the highest value was found in the tree category at S2 (0.95). From tree research sites, the J value has an average of 0.67 or a high score (Fig. 4), indicating that the research site's riparian vegetation species were evenly distributed [74]. In this regard, the composition and diversity of riparian vegetation in Maninjau Lake reflect the features of riparian vegetation in the tropical Sumatra region. Geographical differences, habitat types and significant disturbances by natural and anthropogenic factors are some of the causes of differences in vegetation diversity and evenness in different landscapes [75].

Natural factors that cause disturbances in riparian areas include wind, fire and water activities. In contrast, anthropogenic factors include deforestation, construction of settlements and dams, animal grazing and land conversion into agriculture and plantations. These two disturbance factors significantly impact forest vegetation structure, causing compositional and structural changes in lake riparian vegetation communities, reducing flora and fauna diversity and evenness and changing soil characteristics [76, 77]. Regarding this, the low average value of the diversity index (H' = 1.34) recorded in the riparian zone of Lake Maninjau indicates that anthropogenic factors, such as the expansion of agricultural land, plantations, settlements, fisheries and logging activities, have reduced the diversity of riparian vegetation (Fig. 5).

Fig. 5. Fisheries activities and agricultural land in the riparian zone of Lake Mainjau

This result is similar to those of [78], who studied the composition and diversity of tree species in riparian forests at Lake Barombi Kotto, Cameroon, where the study results also indicated that the low diversity of tree species at one of the research sites was caused by severe land conversion and logging activities. Another survey by [79] They also noted that human-caused disturbance parameters, such as trash, riparian forest logging, and other disturbance activities, can be used to demonstrate the relationship between these variables and species richness and composition. Their study's findings revealed that sites close to urban areas typically have low vegetation diversity due to high land use change activities.

The differences between riparian vegetation density in each research site (Tables 1 and 2) also demonstrate that anthropogenic activities significantly influence the structure and composition of trees in the riparian lake. The highest density of trees and poles is found in S2. This forest area is minimally disturbed by human activities, followed by S1 and S3, riparian forest areas vulnerable to plantation and agricultural activities. Hence, to overcome this problem, logging prohibitions both by community traditions and regional regulations could be an effort to protect the diversity and population of vegetation in riparian areas [78].

DBH distribution and AGC stock of riparian vegetation in Maninjau Lake

Riparian vegetation in Maninjau Lake was dominated by small-size trees, ranging from 10 – 15cm (25.12%) and 15 – 20cm (34.98%) (Fig. 6). The distribution of diameter classes showed the differences in reproduction and regeneration potential of the forest [80]. Generally, the diameter class of riparian vegetation in Maninjau Lake had an inverted J-shaped distribution. In this regard, the J-shaped distribution represents healthy regeneration. A few patterns emerged among the species with positively skewed distributions (inverted J-curve). They frequently had the maximum density in the smaller DBH classes, and their density gradually decreased as they moved up into the larger classes. It demonstrated a strong capability for regeneration and reproduction. All woody species' seedling and sapling composition and densities could be utilized to calculate renewal [36].

The distribution of tree density in the shape of an inverted J curve in the riparian zone of Lake Maninjau also shows that the location is disturbed and is in the succession stage, so most of the species identified are species that regenerate in secondary forests [76]. The low density of large-diameter trees might be due to the logging of large commercial and non-commercial tree species and increased tree mortality immediately following logging activities. Numerous studies demonstrate that stem density, species abundance and richness are inversely correlated with logging intensity [81, 82]. Siltation and the construction of trails in riparian zones also significantly affect the structure and composition of riparian vegetation [76]. It is crucial to comprehend the factors that influence the regeneration of riparian vegetation and the decline in the density of large woody trees, particularly before creating management plans and conservation strategies [83, 84]. Predictive models could be established to identify high-risk areas and support decisions for management, local communities and government across riparian landscapes [85].

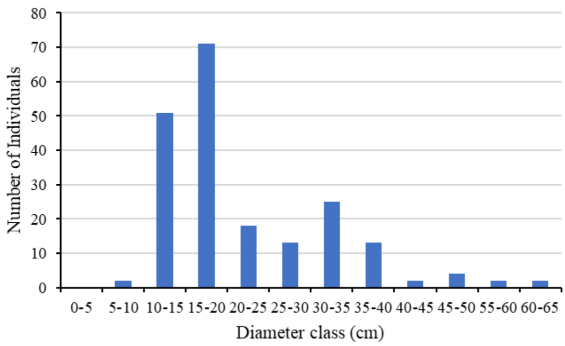

Fig. 6. Distribution of diameter class for pole and tree of riparian vegetation

The large trees contained a significant portion of the biomass and carbon supply (Meragiaw et al. 2021). Twenty riparian vegetation species categorized as pole and adult trees with DBH > 10cm were considered when estimating AGC stock. The highest AGC stock (28.65%) was recorded in *D. zibethinus* with an average of AGB of 296.39Mg ha^{-1} or equivalent to AGC stock of 137.94Mg C ha^{-1}, followed by *C. Lucifera L* (261.25Mg ha^{-1} and 73.17Mg C ha^{-1}) and *M. Indica* (139.68Mg ha^{-1} and 69.84Mg C ha^{-1}) (Table 3). This result indicated that, on average, *D. zibethinus* sequestered the highest amount of CO_2 per tree. The mean of AGB and AGC stock of the twenty species of riparian vegetation categorized as a pole and adult tree accounted for 53.45 ± 81.41Mg ha^{-1} and 23.52 ± 33.06 Mg C ha^{-1}, respectively (Table 3).

The results of this study show that in the riparian zone of Lake Maninjau, the highest AGC were recorded in the three sizeable woody tree species with the largest population averages, including *D. zibethinus, C. Lucifera L.* and *Mangifera indica* (Table 3), which indicates that the dominant species tend to have higher basal areas and carbon stocks. This result is in line with [86], who studied carbon stocks in the Gerba-Dima moist Afromontane forest in South-western Ethiopia and [15], who examined above-ground carbon stocks in Kibate Forest around Wonchi Crater Lake, Central Highland of Ethiopia, where the findings in both studies indicated that tree species represented by the number of individuals with greater DBH would contribute significantly to carbon stocks. The remaining forests containing large-trunk tree species need to be restored and conserved, meaning an environment that has experienced anthropogenic intervention needs additional attention [87].

Table 3. Summary of the number of individuals, DBH average, AGB and AGC stock of riparian vegetation in Maninjau Lake

Name of species	Number of individuals	DBH Average (cm)	AGB ($Mg\ ha^{-1}$)	AGC ($Mg\ C\ ha^{-1}$)
Persea americana	3	15.92	9.62	4.81
Ficus benjamina	4	20.70	23.85	11.92
Durio zibethinus	16	41.16	296.39	137.94
Cocos nucifera L.	31	29.78	261.25	73.17
Artocarpus heterophyllus	3	24.20	25.34	12.67
Myristica fragrans	35	18.66	55.08	29.41
Toona sureni	11	17.50	23.64	13.56
Theobroma cacao L.	2	26.50	5.85	2.93
Psidium guajava	1	11.15	3.40	1.70
Areca catechu	38	16.21	76.34	38.17
Musa paradisiaca	12	10.96	10.86	5.43
Gmelina arborea	1	10.19	2.70	1.35
Cinnamomum verum	11	13.00	18.79	9.39
Mangifera indica	5	24.68	139.68	69.84
Syzygium aromaticum	2	19.11	27.54	13.77
Pterocarpus indicus	2	15.76	10.03	5.01
Gnetum gnemon	1	23.89	24.49	12.24
Abrus precatorius	1	23.89	24.49	12.24
Bambusa sp.	6	19.11	27.30	13.65
Bridellia sp	1	9.55	2.28	1.14
Mean		**19.60 ± 7.50**	**53.45 ± 81.41**	**23.52 ± 33.06**

The highest mean of AGC stock and CO_2 sequestered with 414.14 ± 64.97Mg C ha^{-1} with 1519.88 ± 238.46Mg CO_2e was recorded in site two (S2) that located in the forest area with minimal anthropogenic activity, then followed by site one (S1) that found in a forest area affected by plantation activities (317.16 ± 38.13Mg C ha^{-1} and 1163.98 ± 139.94Mg CO_2e) and site three (S3) that located near of rice field and settlements (307.08 ± 83.34Mg C ha^{-1} and 1126.98 ± 305.86Mg CO_2e). The result demonstrated the significant difference between AGC stock in each site, where the AGC stock in S2 was significantly higher than S1 and S3 (Tukey HSD; $p < 0.05$, $p = 0.009$ and $p = 0.039$).

The average AGC stock and CO_2 sequestered in all research sites is 346.13 ± 62.15Mg C ha^{-1} and 1,270.28 ± 228.09 Mg CO_2e. The average AGC in the riparian vegetation of Lake Maninjau (346.13 ± 62.15Mg C ha^{-1}) was significantly greater than in Kibate Forest around Wonchi Crater Lake, Ethiopia (38.3 ± 4.31Mg C ha^{-1}) [15], global average carbon stock in tree biomass in riparian forests (68 - 158 Mg C ha^{-1}) [9], total AGC of living trees in riparian forests of boreal lakes in northeastern Ontario (29.29 - 296,137Mg C ha^{-1}) [88] and mean carbon densities of Canadian boreal forest ecosystems (208 Mg C ha^{-1}) [89], but still lower than total carbon stocks of semi-natural beech-dominated, Suserup forest, Denmark (395 Mg C ha^{-1}) [90] and Mature hardwood, cottonwood and softwood forests on Danubian floodplains (474, 403 and 356Mg C ha^{-1}, respectively) [91]. The AGC stock and CO_2 sequestered in each site are shown in Figure 7.

The research results also revealed that the AGC stock in the sampling plots was relatively varied, ranging from 141.02 (plot 1, S3) to 534.29 Mg C ha^{-1} (plot 3, S2). Differences in the distribution of large-stemmed riparian vegetation species may cause variations in the AGC stock in the sampling plot. Therefore, research sites with abundant tree species with large trunks tend to have more extensive AGC stocks than areas with fewer large-diameter trees, possibly due to high levels of disturbance from anthropogenic activities. The high values of AGC stock and CO_2 sequestered in S2 compared to low values in S1 and S3 revealed that forest structures such as DBH distribution and the density of trees might influence AGC stocks [93, 94]. The species richness (taxonomic attribute) also increases the value of AGC stocks [95]. Research by [96] shows that the ecosystem areas with a composition of 5 species have carbon stocks 70 – 90% higher than monotype ecosystems. This is also in line with research by [97], which states that locations with high tree species richness have higher total carbon stocks than those with low tree species richness. In this case, 20 different riparian vegetation species are included in the pole and tree categories, considered in estimating the AGC stock, so the value is relatively high. Therefore, it is crucial to comprehend how AGC stocks are impacted by ecosystem structure, composition and species diversity, particularly in ecosystems prone to human interference.

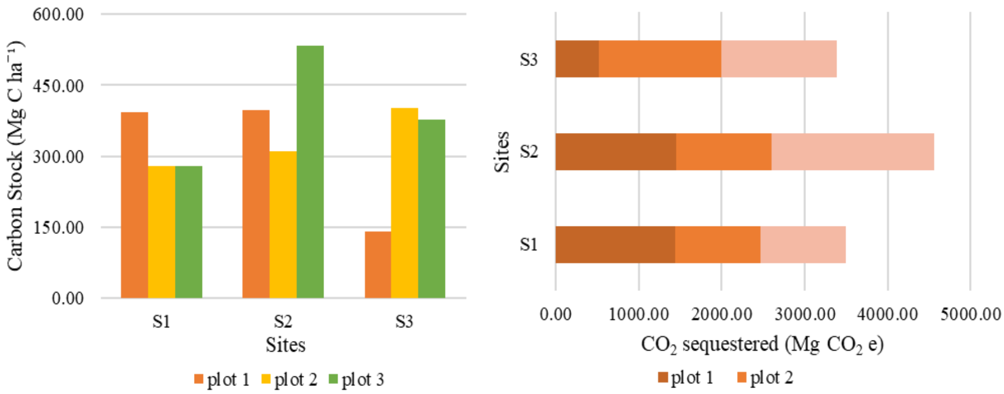

Fig. 7. The AGC stock and CO_2 are sequestered at each site in Maninjau Lake

Management of Lake Riparian Zone

The present condition of the Lake Maninjau riparian zone is greatly influenced by pressure from both natural and anthropogenic factors. The expansion of aquaculture, agriculture, plantations, logging and tourism has significantly affected land areas and the quality of lake waters [98]. Environmental degradation in the riparian zone dramatically affects the water quality of Lake Maninjau, which is categorised as heavily eutrophic [26]. The findings of this research indicate that anthropogenic activities are a significant driving factor of environmental degradation in the riparian zone, which could have a long-term impact on the composition, structure and diversity of tree species in the Lake Maninjau riparian zone. Furthermore, significant changes in tree species' structure, design and diversity could significantly influence the distribution of AGC stocks and CO_2 absorption in riparian vegetation [15]. In this regard, the highest AGC stock and CO_2 sequestration values were reported in forests with minimal human disturbance (S2) and tended to be lower at locations with a plantation (S1) and agricultural (S3) impact. This result indicates the importance of sustainable management efforts, one of which is through riparian zone restoration and conservation efforts.

Restoration of riparian forests will provide various advantages, especially in capturing land erosion flows, filtering unused nutrients and toxic waste, and providing habitat for terrestrial and aquatic organisms [99] and numerous valuable ecosystem services for enhancing community health and welfare [100]. However, investment in riparian forest restoration has not received much attention, partly because the area is relatively small [9]. Despite the comparatively small size, riparian forests typically have better growth circumstances, one of which is due to optimal soil moisture. They can also acquire carbon reserves at a higher level than terrestrial forests, which considerably aids in rapid carbon sequestration [101] and supports climate change mitigation [102]. This study's findings also showed that riparian vegetation has considerable potential for contributing to carbon sequestration, which can be an additional advantage of restoring riparian forests. Therefore, this study suggests that riparian forest restoration and conservation could provide rapid carbon sequestration advantages and long-term benefits for ecosystem services.

The primary objective of riparian restoration is to promote ecological processes and long-term connections between terrestrial, riparian and aquatic ecosystems [103]. This process is focused on returning riparian conditions to pre-disturbed conditions and rehabilitating and recovering diversity as well as ecological functions and services [104]. Restoration efforts in degraded riparian areas can be carried out through passive (natural regeneration) and active intervention strategies [16]. Functional restoration aims to remove sources of disturbance and implement strategies for accelerating recovery and overcoming barriers to that recovery. In contrast, passive restoration seeks to eliminate factors that cause disorder by humans, livestock and other disturbing agents and allow natural regeneration [105].

Research by [106] has proven that active restoration strategies are more effective than passive restoration in restoring forest composition and structure, such as increasing basal area, tree density, trunk size and height. Active restoration requires better site management efforts, which include land preparation, selecting the suitable species for planting, good drainage and chemical weed control over approximately three years before an active restoration approach is implemented [107]. Selection of native perennial plant species that have economic value and strong stem and root structures, such as *D. zibethinus* (Durian), *A. heterophyllus* (Jackfruit), *F. benjamina* (Beringin) and *M. fragrans* (Nutmeg) could be an alternative species used in active restoration efforts that can benefit not only the environment but also community livelihoods. Understanding and considering the cultural perceptions and acceptability of the species employed in restoration projects is crucial. Regarding this, the success of restoration initiatives depends on the involvement of local stakeholders and potential species for use in these initiatives must be evaluated using standards that consider both social benefits and technical limitations, such as the requirement for germination and propagation under nursery conditions and their ecological properties [108]

Conclusions

A total of 57 species from 27 families of riparian vegetation were identified around Maninjau Lake, out of which 20 were adult tree forms. Eighteen out of 87 riparian vegetation species around Maninjau Lake are identified in the IUCN Red List of threatened species. Coconut (*C. nucifera L.*), Durian (*D. zibethinus*), nutmeg (*M. fragrans), Suren (T. sureni), bettle nut (Areca catechu), cinnamon (Cinnamon verum) and coromandel (Asystasia gangetica)* are the most essential riparian vegetation around Mninjau Lake. The results showed that AGC stock distribution varied between sites, which was related to the abundance of large trunk tree distribution, mainly due to anthropogenic pressures. Anthropogenic factors, particularly the expansion of agricultural land, aquaculture, and logging, significantly affected the AGC stocks of riparian vegetation around Maninjau Lake. This research showed that riparian vegetation around Maninjau Lake significantly contributes to CO_2 sequestration in the region and can support climate change mitigation efforts in Indonesia. The findings of this research indicate that the average AGC stock and CO_2 sequestration of riparian vegetation around Lake Maninjau is 346.13 ± 62.15 Mg C ha^{-1} and $1,270.28 \pm 228.09$ Mg CO_2e, so it has a significant contribution to CO_2 absorption. Therefore, this research emphasizes the importance of conservation and restoration in protecting and recovering the structural vegetation composition in the riparian zone and maintaining its function as a carbon-sequestering ecosystem that can support climate change mitigation efforts.

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