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Carbon Reserved Measurement as a Sustainability Strategy for Land Rehabilitation Program in Menoreh Hill Watershed, Central Java, Indonesia

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ABSTRACT

Watershed land rehabilitation is an important strategy to restore degraded land and improve ecosystem services, including carbon sequestration. However, increasing carbon reserves through watershed rehabilitation faces several challenges that need to be addressed. This study aims to measure the carbon reserve of land rehabilitation plants in the Bukit Menoreh watershed in order to make a strategic analysis of sustainable rehabilitation management. Quantitative research with experimental and descriptive approaches. Sampling using stratified random sampling. Primary data collection through field surveys. Durian and mangosteen plant species have the highest carbon reserves, with durian at 127.27 tons C and emission uptake of 467.07 tons CO_2eq. Stand density and plant age significantly affected carbon reserves. The assumption of 100% plant survival results in an emission uptake of 640,960.73 tons CO_2eq in 2040, higher than the 70% assumption of only 403,805.26 tons CO_2eq. The results have important implications for future forest management and land rehabilitation policies, focusing on plant species selection, increasing stand density, and continuous monitoring of carbon reserves. The Menoreh watershed rehabilitation program can be an effective model for climate change mitigation and achieving sustainable development.

1. INTRODUCTION

The restoration of wetlands and floodplains not only improves water quality but also plays a crucial role in reducing flood risks. These natural infrastructures help manage water flow and mitigate the impacts of extreme weather events, which are becoming more frequent due to climate change [1]. Additionally, river basin rehabilitation is an important environmental strategy aimed at restoring degraded land and enhancing ecosystem services, including carbon sequestration. Rehabilitation efforts, such as reforestation and revegetation, significantly increase soil organic carbon reserves [2, 3]. Floodplains and wetlands are crucial for carbon storage compared to their surface area, meaning these areas store substantial amounts of organic carbon, making them a key target for restoration efforts [4-6]. Restoring these areas can significantly enhance carbon sequestration. Land rehabilitation can reduce carbon emissions and increase carbon absorption by promoting plant growth [4]. This process is vital for boosting plant carbon reserves, which play a critical role in climate change mitigation [1-3, 7-10]. Previous study found that the potential economic value of carbon sequestration from watershed rehabilitation efforts has been highlighted [11], with restored sites showing trends of increasing carbon permanence in the soil, and the current carbon price per ton generating significant economic benefits. Previous study suggested that carbon reserves might become an increasingly attractive incentive to restore severely degraded forests [12], with management scenarios involving “logging without cutting” or “low-intensity logging” offering the greatest incentives.

Increasing carbon reserves through river basin rehabilitation presents several challenges that need to be addressed to ensure success. Effective watershed rehabilitation requires comprehensive planning that considers the entire ecosystem. Often, projects lack a holistic approach, leading to less optimal outcomes [13]. Previous studies state that the techniques used in restoration also determine the significance of carbon sequestration [14, 15]. Watershed ecosystems are dynamic, with changes occurring on daily, seasonal, and annual timescales. This variability makes it difficult to predict and manage carbon sequestration outcomes [14]. Proper land and vegetation management is crucial to enhancing carbon reserves. For example, selecting specific plant species can significantly increase soil carbon reserves and plant biomass [16]. Previous study also revealed that afforestation with different tree species can influence carbon sequestration differently [17]. For example, afforestation with longleaf pines can increase evapotranspiration and reduce river flow but also enhance carbon sequestration. Several factors can influence carbon sequestration, including the type of vegetation, which has a significant impact. Shrubs and grasslands, for instance, can increase carbon reserves more than other types of vegetation such as tropical forests or coniferous forests [2, 18]. Furthermore, the age of the vegetation plays a crucial role in carbon sequestration. Younger forests typically show rapid increases in carbon reserves in the early stages, but after reaching maturity, carbon sequestration becomes more stable [2, 19, 20]. Another factor affecting carbon reserves is soil erosion and deposition. Soil erosion tends to decrease carbon reserves due to the loss of organic-rich soil layers, while soil deposition can increase carbon reserves by adding humus and new organic material [19, 21]. Soil texture and stability also play an important role, where soils with stable aggregates improve the accumulation of carbon reserves more efficiently [21].

Water management is equally important. Effective soil moisture management through water conservation techniques can support healthy vegetation growth, which in turn increases carbon reserves in the soil [18, 22]. Meanwhile, floodplain restoration also has a significant impact on carbon reserve storage. Floodplains play a key role in absorbing and storing carbon from water flows and sedimentation [6]. External factors such as climate change also influence the carbon cycle, both directly and indirectly. Changes in temperature, rainfall, and weather patterns affect the ecosystem's ability to absorb and store carbon, ultimately impacting the existing carbon reserves [23]. Ecological techniques used in forest restoration and management can have a positive impact on carbon reserves, such as through the improvement of vegetation and soil quality, which can increase carbon storage capacity [19, 24]. In addition to technical and ecological factors, community participation is also highly influential in enhancing ecosystem services and carbon reserves. Communities involved in rehabilitation and conservation activities can play a role in preserving natural resources and supporting sustainable management practices [25, 26]. Furthermore, the role of appropriate policies and management, including an integrated approach involving various sectors, is crucial to achieving optimal results in carbon reserve storage. Policies that support environmental rehabilitation and conservation can accelerate ecosystem recovery and increase overall carbon storage capacity [27, 28].

This is in line with the mandate outlined in Government Regulation (GR) No. 24/2010 in conjunction with GR No. 61/2012 in conjunction with GR No. 105/2015 concerning the Use of Forest Areas and Minister of Environment and Forestry Regulation No. 27/2018 concerning Guidelines for the Borrowing and Use of Forest Areas. The regulations specify that holders of Forest Area Borrowing and Use Permits (IPPKH) are required to carry out reclamation within their IPPKH concession areas. Additionally, they are also required to rehabilitate river basins (DAS) outside of their IPPKH areas and reforest designated compensation lands as a form of compensation for the land being utilized. The River Basin Rehabilitation Program (DAS) has become one of the priorities for the Indonesian government to address environmental degradation, improve water quality, and reduce the risks of natural disasters such as erosion and landslides, particularly in hilly areas. One example of a program that has already been implemented is the planting of trees and fruit plants in Bukit Menoreh, Purworejo, Central Java, covering an area of approximately 596.92 hectares, carried out by PT. Borneo Indobara. This program involves various types of fruit plants such as durian, Stink Bean, Lanzones, Avocado, and others, and has the potential to create significant social, economic, and environmental impacts for local communities. Active community involvement in the planting and care of the plants shows a high sense of ownership, contributing to social cohesion and increased income through harvests. Thus, this program can improve local food security and create new job opportunities, which in turn enhances community welfare [29-32]. This River Basin Rehabilitation Program involves four subdistricts in the Bukit Menoreh area, Purworejo, Central Java. The program has been implemented since 2021, and by 2024, it will be in its third year, focusing on rehabilitating vegetation with an emphasis on fruit plants. Below is the distribution data for the fruit plant seedlings used in this program (Table 1):

Table 1. Seedling distribution per sub-district

Seedling	Subdistrict				Total	%
	Bagelen	Bener	Kaligesing	Loano		
Avocado	7.118	8.175	23.469	9.751	48.513	23.30%
Sugar Palm	322	67	36	57	482	0.23%
Other Seedling	46	93	65	184	388	0.19%
Lanzones	1.504	47	1.651	8.664	11.866	5.70%
Durian	7.695	25.843	20.600	19.823	73.961	35.52%
Gayam	168	4	18	2	192	0.09%
Guava	302	13	1.877	10	2.202	1.06%
Dog Fruit	65	31	49	5	150	0.07%
Orange	155	6	44	1	206	0.10%
Longan	4.594	2	21	992	5.609	2.69%
Coffee	1.122	109	898	337	2.466	1.18%
Mango	3.018	30	46	14	3.108	1.49%
Mangosteen	7.986	5.424	3.029	14.540	30.979	14.88%
Nutmeg	13	41	65	577	696	0.33%
Stink Bean	2.363	7.887	11.895	4.620	26.765	12.85%
Black Nut	181	18	38	3	240	0.12%
Sapodilla	393	2	19	1	415	0.20%
Total	**37.045**	**47.792**	**63.820**	**59.581**	**208.238**	**100.00%**

Based on the rehabilitation program conducted by PT Borneo Indobara, carbon reserve measurement is an important step to assess the success of the effort [33]. Continuous monitoring of carbon reserves not only enables evaluation of the long-term impacts of restoration activities, but also provides a clearer picture of the effectiveness of the rehabilitation methods applied [34]. In addition, carbon reserve accounting also serves to provide data that can be used to formulate better management practices to optimize carbon sequestration in ecosystems [35]. By understanding carbon reserves, we can also map the spatial distribution of carbon across watersheds, which is influenced by factors such as vegetation type, soil structure and topography [36]. This research will also take into account the projection of potential carbon reserves within 20 years, in contrast to previous studies which only discuss carbon stock policies [27, 28, 35] and which only formulate and simulate carbon stock calculations using Mean Annual Incremant (MAI carbon) [37-39]. This understanding is critical as it can help generate more accurate estimates and support more effective carbon reserve management. Therefore, this study specifically aims to measure the carbon reserve of Menoreh hill watershed land rehabilitation plants in order to make a strategic analysis of sustainable rehabilitation management.

2. RESEARCH METHOD

This study employs a quantitative approach using experimental and descriptive methods. This study aims to measure the carbon reserves stored in the rehabilitation plants of the Bukit Menoreh River Basin (DAS) rehabilitated by PT. Borneo Indobara. This research is also experimental because it will use controlled measurement methods to obtain accurate and valid data on the carbon reserves of rehabilitation plants from various species planted in the area. Additionally, a descriptive design will be used to detail the existing carbon reserve conditions and identify changes in carbon reserves in the rehabilitated land during the course of the program. The research design used will be observational and longitudinal, which allows for continuous measurement of carbon reserves year by year throughout the rehabilitation program. This study calculates the total forest carbon reserves based on the biomass and organic matter content in five carbon pools (aboveground biomass, belowground biomass, dead wood, litter, and soil organic matter) according to the national carbon measurement standards outlined in the SNI 7724:2019 document on Carbon Reserve Measurement and Calculation – Field Measurements for Ground-Based Forest Carbon Accounting. Referring to the guidelines of SNI 7724:2019, carbon measurement uncertainty is identified to come from several sources, including sample variability, tool calibration, and analysis methods. To reduce uncertainty, measurements were taken three times (triplicate), and the results were analyzed using standard deviation. Uncertainties are reported as mean ± standard deviation, with a 95% confidence level.

The sampling technique used was stratified sampling with simple random sampling, with a maximum sampling error of 20%. Stratification of carbon potential based on sub-district area and type of soil map unit at the Menoreh watershed rehabilitation site. There are 4 sub-districts were sampled with varying carbon potential, namely Bagelan (4,079.17 m^2), Bener (8,335.34 m^2), Kaligesing (7,699.32 m^2) and Loano (4,595.39 m^2). The shape of the sample plot used is nested according to field conditions. Each plot is divided into several subplots based on the level of vegetation growth, which includes:

a. Subplot 4 m^2 (2×2 m)

Seedling, woody growth level < 2 cm in diameter and ≤ 1.5 m in height. In this subplot, destructive sampling of understory and litter species was also carried out on an area of 0.25 m^2 (0.5×0.5 m).

b. Subplot 25 m^2 (5×5 m)

Sapling, woody growth stage with diameter ≥ 2 cm and < 10 cm, height ≥ 1.5 m.

c. Subplot 100 m^2 (10×10 m)

Pole, woody growth stage with diameter ≥ 10 cm and < 20 cm, height ≥ 1.5 m.

d. Subplot 400 m^2 (20×20 m)

Tree, woody growth stage with diameter ≥ 20 cm, height ≥ 1.5 m.

The shape and size of the square plot can be seen in Figure 1:

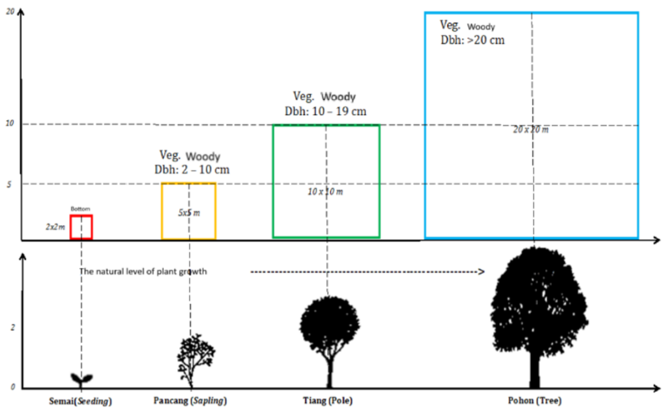


Figure 1. The shape and size of the square plot

Primary data collection was conducted through field surveys to identify the actual conditions in the field as reference material for further analysis. The object of assessment is related to the parameters used for carbon reserve analysis. Survey activities are equipped with a working map which is a map of satellite image interpretation results that have been equipped with data on land map units, regional administration and road networks. Carbon reserve sampling technique by selecting representatives of land map units that have considered the ease of access to the sample location with measuring plot points of Carbon and Soil Reserve Sample Plots. Carbon sequestration assessment of rehabilitation plants was carried out through simplified stages, as seen in Figure 2.

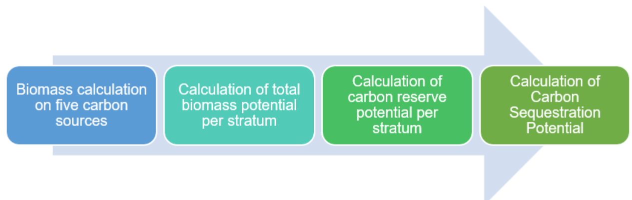


Figure 2. Stages of calculation of potential carbon reserves and sequestration in Menoreh watershed area

The following formulas are used to measure carbon reserves:

a. Calculation of carbon reserves per hectare for above ground biomass can be done using the following equation:

$$C_n = \frac{C_x}{1000} \times \frac{10000}{l_{plot}}$$

Description:

C_n is the carbon content per hectare in each carbon pool in each plot, expressed in tons per hectare (tons/ha).

C_x is the carbon content of each carbon pool in each plot, expressed in kilograms (kg).

l_{plot} is the plot area in each pool, in square meters (m^2).

b. Calculation of total carbon reserve in the measurement plot using the following equation:

$$\mathbf{Cplot = (Cbap + Cbbp + Cseresah + Ckm + Cpm + Cland)}$$

Description:

Cplot is the total carbon content of the plot, expressed in tons per hectare (tons/ha);

Cbap is the total carbon content of aboveground biomass per hectare in the plot, expressed in tons per hectare (tons/ha);

Cbbp is the total carbon content of subsurface biomass per hectare in the plot, expressed in tons per hectare (tons/ha);

Cseresah is the total carbon content of litter biomass per hectare in the plot, expressed in tons per hectare (tons/ha);

Ckm is the total dead wood carbon content per hectare of the plot, expressed in tons per hectare (tons/ha);

Cpm is the total carbon content of dead trees per hectare in the plot, expressed in tons per hectare (tons/ha);

Cland is the total soil carbon content per hectare in the plot, expressed in tons per hectare (tons/ha).

c. Calculation of carbon reserves in a forest stratum uses the following equation:

$$C_{stratum} = \left(\frac{\sum C_{plot}}{n_{plot}}\right) \times \text{stratum area}$$

Description:

$C_{stratum}$ is the total carbon reserve in the stratum, expressed in tons;

n_{plot} is the number of plots in the stratum;

C_{plot} is the total carbon content per hectare of plots in the stratum.

d. Carbon uptake analysis: The amount of carbon reserve obtained was then converted into a carbon dioxide (CO_2) uptake value using the Morikawa equation referenced in [40]:

$$\mathbf{CO_2 = 44/12\ C}$$

Description:

CO_2 = Amount of CO_2 gas absorbed (ton/ha).

3. RESULT

3.1 Characteristics of rehabilitation crops

Forest and Land Rehabilitation (RHL) is an effort to restore, maintain and improve the function of forests and land so that their carrying capacity, productivity and role in supporting life supporting systems are maintained. On the other hand, Forest and Land Rehabilitation (RHL) activities are also an effort to increase carbon dioxide (CO_2) absorption on degraded land. Based on previous research [41], it is stated that one hectare of green leaves can absorb 8 kg CO_2 / hour or 0.8 g / m / hour, equivalent to CO_2 exhaled by 200 people in the same time. Previous research also showed that one hectare of primary dryland forest in Central Kalimantan can store 229.33 tons of carbon [42]. This shows that the potential of forests in absorbing carbon dioxide (CO_2) is very high, so efforts are needed to minimize degraded lands through forest and land rehabilitation programs.

In the Menoreh watershed land rehabilitation program, various types of fruit trees which are Multipurpose Tree Species (MPTs), are selected to support the improvement of forest and land functions. MPTS plants are currently widely used as plants for rehabilitation activities because they have the advantages of being able to quickly adapt to the environment, preserving biodiversity and financially having high economic value and are favored by the community. Multipurpose Tree Species (MPTS) is a land management system where various types of wood are planted and managed, not only to produce wood, but also leaves and fruits that can be used as food or animal feed [43]. Multiple-benefit tree species (MPTS) have several advantages over single-benefit tree species, both endemic and exotic, so these tree species would be more prospective for the success of critical land rehabilitation activities if offered as tree species used for rehabilitation [44].

The Menoreh watershed land and forest rehabilitation program covers four sub-districts. Each sub-district on average received the same type of plants but in different amounts. Kaligesing sub-district is among the sub-districts that received the highest number of seedlings, which amounted to 63,820 MPTs seedlings. Meanwhile, the sub-district with the smallest number of seedlings is Bagelan sub-district. The types of plants with the highest number are Durian and avocado, 73,961 seedlings and 48,479 seedlings, respectively. Meanwhile, the least number of seedlings are Gayam and oranges, totaling 192 and 206 seedlings respectively. In Table 2, it can be seen that the types of plants planted in the Menoreh watershed forest and land rehabilitation program are MPTs (Multipurpose Tree Species). These types of plants were chosen in addition to being expected to improve the physical, biochemical, and morphological quality of the soil, they are also expected to increase forest carbon reserves and sequestration so as to provide environmental services for the community. On the other hand, the types of MPTs plants in the Menoreh watershed area are expected to provide economic value to the community, especially in the type of fruit plants that can be harvested in certain seasons. Some types of MPTs plants and their distribution in various sub-districts are described in Table 1.

Table 2. Weight list of forest and land rehabilitation plants of Menoreh watershed

No.	Seedling	Scientific Name	Weight
1	Avocado	*Persea sp.*	0.52
2	Palm Sugar	*Arenga pinnata (Wurmb) Merr.*	0.9
3	Lanzones	*Lansium domesticum Corr var duku Hasskl.*	0.85
4	Durian	*Durio sp.*	0.57
5	Gayam	*Inocarpus fagifer*	0.71
6	Guava	*Psidium guajava L*	0.75
7	Dog Fruit	*Archidendron pauciflorum*	0.47
8	Orange	*Citrus sinensis Osbeck*	0.78
9	Longan	*Dimocarpus longan Lour.*	0.83
10	Coffee	*Coffea L*	0.62
11	Mango	*Mangifera sp*	0.54
12	Mangosteen	*Garcinia mangostana L*	1
13	Nutmeg	*Myristica fragrans Houtt*	0.52
14	Stinky bean	*Parkia spesiosa Hassk.*	0.45
15	Black Nut	*Pangium edule Reinw. ex Blume*	0.66
16	Sapodilla	*Manilkara zapota (L.) P. Royen*	0.81

In addition to having a high economy, the selected MPTs plants also have the potential to absorb Carbon Dioxide (CO_2) emissions. To find out the potential of carbon reserves and absorption of CO_2 emissions, it is necessary to identify the specific gravity of each type of fruit planted. The scientific name and specific gravity of the plants in the Menoreh watershed rehabilitation program are described in Table 2.

Based on Table 2, it can be seen that each type of fruit tree has a different specific gravity. This difference affects the growth of the tree and its ability to absorb equivalent CO_2 emissions. At the same diameter, trees with higher specific gravity will have a greater carbon reserve or equivalent CO_2 emission sequestration capacity than trees with lower specific gravity.

3.2 Carbon reserve survey results of Menoreh watershed land rehabilitation crops

3.2.1 Carbon emissions reserves and uptake by type

The total carbon stored, especially in RHL plants in the Menoreh watershed, is strongly influenced by the density of the stands. This stand density is very important because it is related to the forest management system applied by the community on their land. The calculation of total carbon reserves in Menoreh watershed rehabilitation plants is based on monitoring/inventory of plant growth in 2023 from February to November. Based on the calculation of the carbon reserve value of 3-year-old Menoreh watershed rehabilitation plants, the species with the highest value is mangosteen with a carbon reserve value of 3.02 kg C or 0.0030 tons C. While the species with the lowest carbon reserve value is Stink Bean with a carbon reserve value of 1.36 kg C or 0.0014 tons.

In the aspect of the number of seedlings planted through the Menoreh watershed rehabilitation program has a fairly high variation, the seedlings with the highest number are durian seedlings with a total number in all sub-districts of 73,961 seedlings. While the lowest number of seedlings in all sub-districts is the type of Dog Fruit with a total of 150 seedlings. The number of seedlings greatly affects the value of total carbon reserves and sequestration in the entire Menoreh Watershed Land and Forest rehabilitation area. It is proven that the Durian species with the highest number of seedlings also has the highest carbon reserves and sequestration, which are 127.27 tons C and 467.07 tons CO_2eq, respectively. While the species with the lowest carbon reserve and sequestration is the Dog Fruit species with a value of 0.21 tons C and 0.78 tons CO_2eq, respectively. The total carbon reserve of forest and land rehabilitation plants in Menoreh watershed is presented in Table 3.

Table 3. Carbon reserve of rehabilitated plants

Seedling	Carbon Value (kg)	Carbon Value (ton)	Total Number of RHL Plants	Carbon Reserve (ton C)	Carbon Uptake (CO_2eq)
Avocado	1.57	0.0016	48.513	76.15	279.49
Palm Sugar	2.72	0.0027	482	1.31	4.81
Lanzones	2.57	0.0026	11.866	30.45	111.74
Durian	1.72	0.0017	73.961	127.27	467.07
Gayam	2.14	0.0021	192	0.41	1.51
Guava	2.26	0.0023	2.202	4.99	18.3
Dog Fruit	1.42	0.0014	150	0.21	0.78
Orange	2.35	0.0024	206	0.49	1.78
Longan	2.51	0.0025	5.609	14.05	51.58
Coffee	1.87	0.0019	2.466	4.62	16.94
Mango	1.63	0.0016	3.108	5.07	18.59
Mangosteen	3.02	0.003	30.979	93.52	343.22
Nutmeg	1.57	0.0016	696	1.09	4.01
Stinky bean	1.36	0.0014	26.765	36.36	133.44
Black Nut	1.99	0.002	240	0.48	1.75
Sapodilla	2.45	0.0024	415	1.01	3.72

Table 4. Carbon reserves of 3-year-old Menoreh watershed land and forest rehabilitation plants in various sub-districts

Plant Type	Total Carbon Reserve per Sub-district				Total
	Bagelan	Bener	Kaligesing	Loano	
Avocado	11.17	12.83	36.84	15.31	**76.15**
Palm Sugar	0.87	0.18	0.1	0.15	**1.31**
Lanzones	3.86	0.12	4.24	22.23	**30.45**
Durian	13.24	44.47	35.45	34.11	**127.27**
Gayam	0.36	0.01	0.04	0	**0.41**
Guava	0.68	0.03	4.25	0.02	**4.99**
Dog Fruit	0.09	0.04	0.07	0.01	**0.21**
Orange	0.36	0.01	0.1	0	**0.49**
Longan	11.51	0.01	0.05	2.49	**14.05**
Coffee	2.1	0.2	1.68	0.63	**4.62**
Mango	4.92	0.05	0.07	0.02	**5.07**
Mangosteen	24.11	16.37	9.14	43.89	**93.52**
Nutmeg	0.02	0.06	0.1	0.91	**1.09**
Stinky bean	3.21	10.71	16.16	6.28	**36.36**
Black Nut	0.36	0.04	0.08	0.01	**0.48**
Sapodilla	0.96	0	0.05	0	**1.01**

3.2.2 Carbon emissions reserves and uptake per subdistrict

Based on the monitoring of 3-year-old Menoreh Watershed Land and Forest Rehabilitation plants, there are three categories of plants based on growth, namely plants with growth >60 cm, 60-100cm, and >100 cm in each sub-district. The total carbon reserves of the three categories of plant growth were then calculated as the carbon potential in each sub-district. The total carbon reserve of forest and land rehabilitation plants in Menoreh watershed is presented in Table 4.

The sub-district with the largest total carbon reserve is Loano with a total carbon reserve of 126.06 tons C. The sub-district with the lowest carbon reserve is Bagelan sub-district with a total carbon reserve of 77.84 tons C. The types of plants that contribute to storing the highest carbon are Durian and Mangosteen with carbon reserves of 127.27 tons C and 93.52 tons C, respectively. While the lowest value is in the type of dog fruit with a total carbon reserve of 0.21 tons C. So that from 208,204 total young plants of the Menoreh watershed land and forest rehabilitation program resulted in a stored carbon reserve of 397.47 tons C.

Rehabilitation activities can periodically increase the ability of a land to absorb and store carbon reserves. The amount of CO_2 sequestration is influenced by the amount of biomass and its carbon content, as well as the density of the stand at that location. Study [45] mentioned that carbon sequestration is strongly influenced by biomass, therefore, anything that causes an increase or decrease in biomass potential will also affect carbon sequestration. Based on the results of the calculation of the potential absorption of CO_2eq emissions in the Menoreh watershed land and forest rehabilitation program, the sub-district with the largest total carbon sequestration is Loano with a total carbon sequestration of 462.65 tons of CO_2eq. Meanwhile, the sub-district with the lowest carbon reserve is Bagelan sub-district with a total carbon sequestration of 285.68 tons CO_2eq.

Table 5. Carbon sequestration of forest and land rehabilitation plants in Menoreh watershed at 3 years old

Seedling	Total Carbon Sequestration per Sub-District				Total
	Bagelan	Bener	Kaligesing	Loano	
Avocado	41.01	47.1	135.21	56.18	**279.49**
Palm Sugar	3.21	0.67	0.36	0.57	**4.81**
Lanzones	14.16	0.44	15.55	81.59	**111.74**
Durian	48.59	163.2	130.09	125.18	**467.07**
Gayam	1.32	0.03	0.14	0.02	**1.51**
Guava	2.51	0.11	15.6	0.08	**18.3**
Dog Fruit	0.34	0.16	0.26	0.03	**0.78**
Orange	1.34	0.05	0.38	0.01	**1.78**
Longan	42.24	0.02	0.19	9.12	**51.58**
Coffee	7.71	0.75	6.17	2.31	**16.94**
Mango	18.06	0.18	0.28	0.08	**18.59**
Mangosteen	88.48	60.09	33.56	161.09	**343.22**
Nutmeg	0.07	0.24	0.37	3.32	**4.01**
Stinky bean	11.78	39.32	59.3	23.03	**133.44**
Black Nut	1.32	0.13	0.28	0.02	**1.75**
Sapodilla	3.53	0.02	0.17	0.01	**3.72**
Total	**285.68**	**312.51**	**397.9**	**462.65**	**1458.73**

Refer to Table 5, plant species that contribute to absorbing the highest carbon are Durian and Avocado with carbon uptake of 467.07 tons CO_2eq and 279.49 tons CO_2eq, respectively. While the lowest value is in the type of jengkol with a total carbon emission absorption of 0.78 tons CO_2eq. So that from 208,204 total young plants of the Menoreh watershed land and forest rehabilitation program resulted in carbon sequestration of 1,458.73 tons of CO_2eq.

3.2.3 Carbon emissions reserves and sequestration up to 2040

The value of carbon reserves calculated at the age of three years can be projected in the next few years by calculating plant growth using the Mean Annual Incremant (MAI carbon) calculation method [37-39]. Every year, the diameter of the tree will increase so that the potential for emission absorption will also increase. Calculation of carbon reserves was carried out in the third year after planting the Menoreh watershed land and forest rehabilitation program. The results obtained are calculations if during the 2040 plantation there is no death or maintenance so that the success of plant life reaches 100% and diameter growth reaches 1.5 cm - 2 cm per year. The data shows that the largest carbon reserve in 2024 is in Loano sub-district with a carbon reserve of 126.06 tons C and in 2040 the carbon reserve in Loano sub-district can reach 55,391.48 tons C. While the lowest carbon reserve is in Bagelan sub-district, which in 2024 plants have a carbon reserve of 77.84 tons C and in 12-year-old plants the carbon reserve can reach 34,202.72 tons C. The average increase in carbon reserves each year in each sub-district varies, the most dominant factor is influenced by plant growth. The potential carbon reserve of forest and land rehabilitation plants until 2040 is presented in the following Figure 3.

In years 3-5, the increase in carbon reserves was relatively high with an increase of 2 to 3 times. In years 6 to 12, the increase in carbon reserves is relatively the same, which is 2 times. The total carbon reserve in all sub-districts in 2024 was 397.47 tons C and increased until 2040; the total carbon reserve in the forest and land rehabilitation area of Menoreh watershed was 174,648.70 tons C.

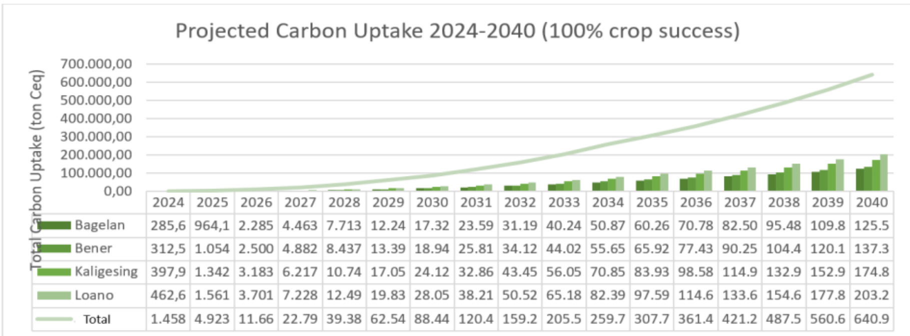
Based on information on the development of carbon reserves per year in each sub-district, the development of annual emission absorption for each sub-district can be calculated. Carbon emission absorption for all sub-districts in 2024 amounted to 1,458.73 tons CO_2eq with the largest carbon emission absorption in Loano sub-district at 462.65 tons CO_2eq and the lowest in Bagelan sub-district at 285.68 tons CO_2eq. In the 2040 crop with 100% crop success, the highest carbon emission uptake in Loana sub-district reached 203,286.74 tons of CO_2eq while the lowest carbon emission uptake was in Bagelan sub-district, reaching 125,524.67 tons of CO_2eq. Thus, the carbon emission absorption of the four sub-districts in the land and forest rehabilitation area of the Menoreh watershed can reach 640,960.73 tons of CO_2eq. The carbon emission absorption potential of land and forest rehabilitation plants up to 2040 is presented in Figure 4.

The calculation of carbon reserves and emissions when compared with the assumption of 70% and 100% life has changed significantly. The assumption of 70% life if in the projection until 2024 no maintenance or replacement of dead plants is carried out so that the number of plants decreases every year. At the age of 2024, the success of the plant is still 100%, then decreases in 2025 to 90%, in 2026 to 80% and in 2027 until 2040 70%. While the assumption of 100% survival if during the 2040 crop there is no death or treatment so that the success of plant life reaches 100%.

In 2024, after planting the emission absorption in 4 sub-districts amounted to 1,458.73 tons CO_2eq. In 2025, after planting, the percent of survival decreased to 90% with carbon sequestration of 4,430.90 tons CO_2eq, so that there was a difference in carbon emission absorption of 492.32 tons CO_2eq compared to when there was no death with carbon emission absorption of 4,923.22 tons CO_2eq. In 2026, after planting, the percent of survival decreased to 80% with carbon uptake of 9,335.88 tons CO_2eq, resulting in a difference in carbon emission uptake of 2,333.97 tons CO_2eq compared to when there was no mortality with carbon emission uptake of 11,669.86 tons CO_2eq. In 2027, after planting, the percent of survival decreased to 70% with carbon emission absorption of 14,359.39 tons of CO_2eq, resulting in a difference in carbon emission absorption of 8,433.29 tons of CO_2eq compared to when there is no death with carbon emission absorption of 22,792.69 tons of CO_2eq. Plants are assumed to grow with 70% success until 2040 after planting, with a total carbon emission uptake of 403,805.26 tons CO_2eq, if without mortality the emission uptake can reach 640,960.73 tons CO2e. So there is a difference in carbon emission uptake of 237,155.47 tons CO_2eq. Comparison of total carbon emissions sequestration per year in 4 sub-districts, assuming 70% and 100% life can be seen in Figure 5.

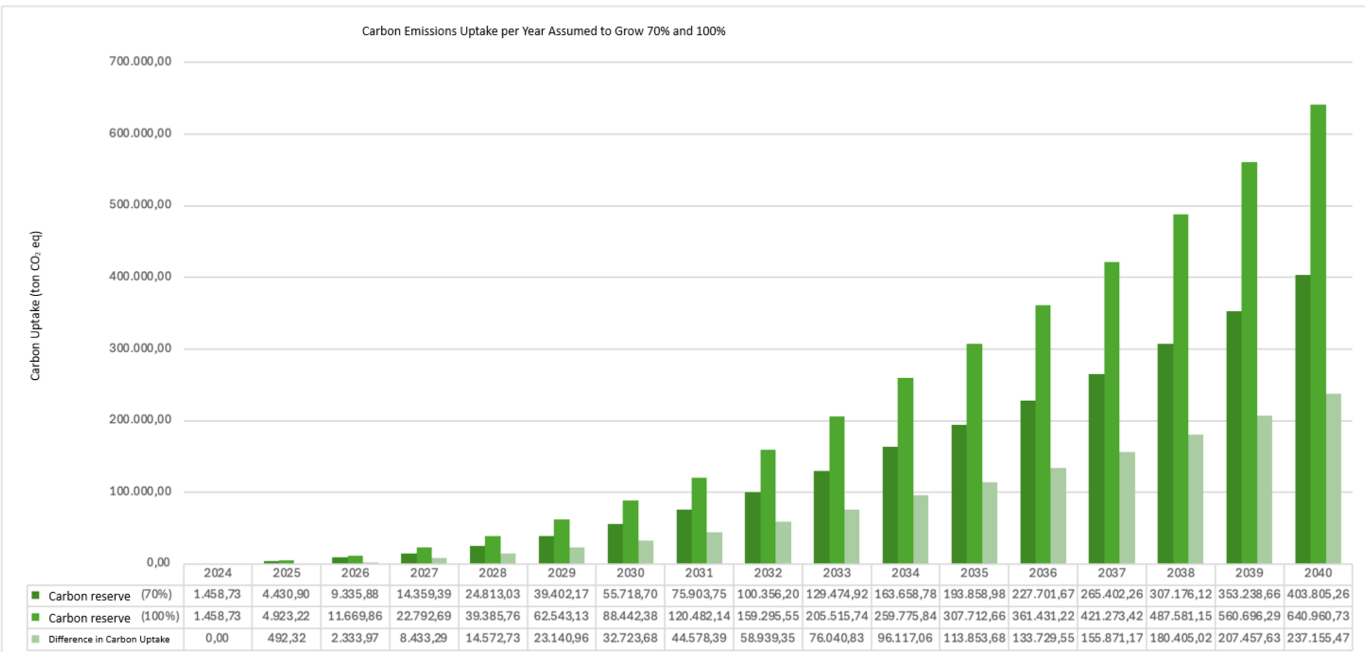
	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Bagelan	77,84	262,7	622,7	1.216	2.101	3.337	4.719	6.429	8.500	10.96	13.86	16.42	19.28	22.47	26.01	29.91	34.20
Bener	85,15	287,3	681,2	1.330	2.299	3.650	5.162	7.033	9.298	11.99	15.16	17.96	21.09	24.59	28.46	32.72	37.41
Kaligesing	108,4	365,9	867,3	1.694	2.927	4.648	6.573	8.954	11.83	15.27	19.30	22.87	26.86	31.31	36.23	41.67	47.63
Loano	126,0	425,4	1.008	1.969	3.403	5.404	7.643	10.41	13.76	17.76	22.44	26.59	31.23	36.40	42.13	48.45	55.39
Total	397,4	1.341	3.179	6.210	10.73	17.04	24.09	32.82	43.40	55.99	70.78	83.84	98.48	114.7	132.8	152.7	174.6

Figure 3. Total carbon reserves in four sub-districts in forest and land rehabilitation sites of Menoreh watershed until 2040 with 100% plant survival success



	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Bagelan	285,6	964,1	2.285	4.463	7.713	12.24	17.32	23.59	31.19	40.24	50.87	60.26	70.78	82.50	95.48	109.8	125.5
Bener	312,5	1.054	2.500	4.882	8.437	13.39	18.94	25.81	34.12	44.02	55.65	65.92	77.43	90.25	104.4	120.1	137.3
Kaligesing	397,9	1.342	3.183	6.217	10.74	17.05	24.12	32.86	43.45	56.05	70.85	83.93	98.58	114.9	132.9	152.9	174.8
Loano	462,6	1.561	3.701	7.228	12.49	19.83	28.05	38.21	50.52	65.18	82.39	97.59	114.6	133.6	154.6	177.8	203.2
Total	1.458	4.923	11.66	22.79	39.38	62.54	88.44	120.4	159.2	205.5	259.7	307.7	361.4	421.2	487.5	560.6	640.9

Figure 4. Total carbon emission uptake in four sub-districts in forest and land rehabilitation sites of Menoreh watershed until 2040 with 100% success of plant survival



	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Carbon reserve (70%)	1.458,73	4.430,90	9.335,88	14.359,39	24.813,03	39.402,17	55.718,70	75.903,75	100.356,20	129.474,92	163.658,78	193.858,98	227.701,67	265.402,26	307.176,12	353.238,66	403.805,26
Carbon reserve (100%)	1.458,73	4.923,22	11.669,86	22.792,69	39.385,76	62.543,13	88.442,38	120.482,14	159.295,55	205.515,74	259.775,84	307.712,66	361.431,22	421.273,42	487.581,15	560.696,29	640.960,73
Difference in Carbon Uptake	0,00	492,32	2.333,97	8.433,29	14.572,73	23.140,96	32.723,68	44.578,39	58.939,35	76.040,83	96.117,06	113.853,68	133.729,55	155.871,17	180.405,02	207.457,63	237.155,47

Figure 5. Comparison of total carbon emissions sequestration per year in 4 sub-districts, assuming 70% and 100% life

4. DISCUSSION

The results of carbon reserve measurements on land rehabilitation plants in the Menoreh watershed show the important contribution of the rehabilitation program in increasing carbon reserves and absorbing carbon emissions in the region. Based on the data obtained, plant species such as durian and mangosteen have the highest carbon reserves, with durian producing carbon reserves of 127.27 tons C and carbon emission absorption of 467.07 tons CO_2eq. In contrast, plant species such as dog fruit showed the lowest carbon reserves and sequestration, at 0.21 tons C and 0.78 tons CO_2eq, respectively. These findings underscore the importance of plant species selection in forest rehabilitation efforts to maximize carbon sequestration potential. Stand density and vegetation growth have a very significant impact on carbon reserves. Previous studies have shown that higher stand density increases the ability of plants to sequester carbon, as more plants will produce more carbon-binding biomass [2]. The Menoreh watershed rehabilitation program showed a clear relationship between the number of seedlings planted and the carbon reserves produced, confirming the finding that more biomass directly increases carbon sequestration capacity. Plant age is also an important factor in the calculation of carbon reserves. As described by Liu et al. [2], young plants usually have a faster growth rate and thus fix more carbon in their early growth phase. However, after reaching a certain age, the rate of carbon sequestration tends to stabilize. Therefore, although younger plants have lower carbon reserves, long-term carbon sequestration rates can be obtained by maintaining sustainable plant growth and maintenance.

A comparison between the assumption of 100% and 70% plant success shows the huge impact on carbon emission uptake. When plants grow with 70% success, carbon sequestration in 2040 is projected to reach 403,805.26 tons of CO_2eq, while if plant survival is 100%, carbon sequestration could reach 640,960.73 tons of CO_2eq. This difference in carbon sequestration of 237,155.47 tons CO_2eq reflects the importance of plant maintenance and replacement of dead plants in ensuring the full potential of rehabilitation efforts. A decrease in plant numbers due to the death of plants that are not replaced can significantly reduce carbon sequestration efficiency, as found by Al-Traboulsi et al. [46], who showed that plant survival greatly affects total carbon sequestration in the long term. Optimal soil moisture and adequate nutrient availability can increase photosynthetic efficiency and biomass growth, thereby increasing carbon sequestration capacity [38, 47]. Conversely, poor soil conditions or drought can limit tree growth and reduce carbon sequestration rates [48].

The results of this carbon reserve measurement have important implications in designing future forest management and land rehabilitation policies. Forest management based on appropriate plant species, such as durian and mangosteen, which are proven to be more effective in increasing carbon reserves, needs to be integrated in watershed rehabilitation policies in other regions. In addition, managing species diversity and increasing stand density will be very important aspects of rehabilitation programs, as these two factors play an important role in maximizing carbon sequestration [2, 18]. The results also reinforce the importance of continuous monitoring of carbon reserves and carbon emission removals in rehabilitated areas. With regular monitoring, adjustments can be made in rehabilitation strategies, including water management techniques and selection of more appropriate plant species. Therefore, the Menoreh watershed land and forest rehabilitation program demonstrates that effective rehabilitation efforts can be a solution for climate change mitigation, ecosystem restoration, and achieving sustainable development goals, with a substantial contribution to global carbon sequestration [33, 49-51].

The socio-economic benefits of the watershed rehabilitation seedling assistance program are not only felt directly by local communities but also create long-term positive impacts for the wider community. The program improves economic welfare, strengthens social solidarity, increases environmental awareness, and reduces natural resource-related conflicts. Other economic benefits of watershed rehabilitation assistance during the initial phase (2021-2024) include (1) empowerment of the surrounding community as direct labor for the process of planting seeds, fertilizing, maintenance, supervision, mentoring and so on. This benefit is in the form of salaries or wages earned by the surrounding community for service activities that have been carried out. (2) Utilization of local product fertilizer purchases, as fertilizing materials. This means that there are income benefits received by the surrounding population for the fertilizer purchase activity. (3) Other supporting needs for the smooth running of activities, such as the purchase of planting tools, plastic, consumption, accommodation, or other support. In addition, other benefits can be realized through the carbon credit market. For example, the projected carbon sequestration of 640,960.73 tons of CO_2eq (with 100% crop success) has significant economic potential if converted into carbon credits. The price of carbon credits varies, but based on current market prices (around 10-10-50 per ton CO_2eq), potential revenue from carbon credits could reach 6.4 million to 6.4 million to 32 million [52]. These revenues can be used to finance further rehabilitation programs, provide incentives to local communities, and support sustainable development. In addition, participation in carbon markets can also increase the attractiveness of green investment in the region, promoting environmentally-based economic growth [33].

The Menoreh watershed rehabilitation program showed significant results in increasing carbon reserves and carbon sequestration in the region, with durian and mangosteen as the two main crops that contributed greatly to carbon reserves. However, these results also highlight the importance of proper plant selection, growth sustainability, and plant maintenance to maximize carbon sequestration potential. The success of this rehabilitation program can serve as a model for other rehabilitation projects that aim to increase carbon sequestration and mitigate climate change.

5. CONCLUSION

The Menoreh Watershed land rehabilitation program has yielded significant results in increasing carbon emission storage and sequestration in the region. Research findings show that plant species such as durian and mangosteen have very high carbon storage potential. Durian was able to generate carbon reserves of 127.27 tons C and absorb carbon emissions of 467.07 tons CO_2eq, while mangosteen recorded carbon reserves of 93.52 tons C. In contrast, dog fruit plant species showed lower carbon storage and sequestration capabilities. Key factors affecting carbon sequestration potential are stand density and vegetation growth. The higher the plant density, the greater the biomass formed, so the ability to sequester carbon also increases. Plant age is also an important consideration, with young plants generally having faster growth and carbon sequestration rates in the early stages, but over time, sequestration rates tend to stabilize. These findings have important implications for the development of future forest management and land rehabilitation policies. The results of this study suggest that the selection of appropriate plant species, such as durian and mangosteen, which are proven to have the highest carbon reserves and carbon emission uptake, should be a priority in rehabilitation programs. In addition, increasing stand density has also been shown to significantly increase the ability of plants to sequester carbon. Equally important, continuous monitoring of carbon reserves and carbon emission uptake in rehabilitated areas should be conducted to evaluate the effectiveness of the program and make necessary adjustments. By applying a comprehensive approach in plant selection, stand density management, and continuous monitoring, the Menoreh watershed rehabilitation program can be an effective model for climate change mitigation efforts through increased carbon sequestration in the ecosystem. The sustainability and success of this program will contribute significantly to the achievement of sustainable development goals, especially in the aspects of environmental management and adaptation to the increasing impacts of climate change.

REFERENCES

[1] Suttles, K.M., Eagle, A.J., McLellan, E.L. (2021). Upstream solutions to downstream problems: Investing in rural natural infrastructure for water quality improvement and flood risk mitigation. Water, 13(24): 3579. https://doi.org/10.3390/w13243579

[2] Liu, Q., Wang, P., Xue, Z., Zhou, Z., Liu, J.E., An, S. (2021). Is the change of soil carbon capacity persistence rising or remain stable with maturity of vegetation restoration? Frontiers in Soil Science, 1: 663910. https://doi.org/10.3389/fsoil.2021.663910

[3] Xue, Z., Fang, X., Wang, W., An, S. (2014). Soil organic carbon distribution under different land uses and landscape positions in two typical watersheds of the loess plateau, China. Nature Environment and Pollution Technology, 13(4): 693.

[4] Limpert, K.E., Carnell, P.E., Trevathan-Tackett, S.M., Macreadie, P.I. (2020). Reducing emissions from degraded floodplain wetlands. Frontiers in Environmental Science, 8: 8. https://doi.org/10.3389/fenvs.2020.00008

[5] Treby, S., Carnell, P.E., Trevathan-Tackett, S.M., Bonetti, G., Macreadie, P.I. (2020). Assessing passive rehabilitation for carbon gains in rain-filled agricultural wetlands. Journal of Environmental Management, 256: 109971. https://doi.org/10.1016/j.jenvman.2019.109971

[6] Wohl, E., Knox, R.L. (2022). A first-order approximation of floodplain soil organic carbon reserves in a river network: The South Platte River, Colorado, USA as a case study. Science of the Total Environment, 852: 158507. https://doi.org/10.1016/j.scitotenv.2022.158507

[7] Basuki, T.M., Pramono, I.B., Auliyani, D. (2020). Biomass carbon reserve and water yield of teak catchments. Journal of Degraded and Mining Lands Management, 8(1): 2481. https://doi.org/10.15243/jdmlm.2020.081.2481

[8] Li, Y., Jiao, J., Wang, Z., Cao, B., Wei, Y., Hu, S. (2016). Effects of revegetation on soil organic carbon storage and erosion-induced carbon loss under extreme rainstorms in the hill and gully region of the Loess Plateau. International Journal of Environmental Research and Public Health, 13(5): 456. https://doi.org/10.3390/ijerph13050456

[9] Nie, X., Li, Z., Huang, J., Huang, B., Xiao, H., Zeng, G. (2017). Soil organic carbon fractions and reserves respond to restoration measures in degraded lands by water erosion. Environmental Management, 59: 816-825. https://doi.org/10.1007/s00267-016-0817-9

[10] Yuan, Y., Gao, X., Huang, K., Wang, J., Zhao, X., Gao, X., Zhao, X. (2023). Evolution of the water–carbon relationship at basin scale under the background of a vegetation restoration program. Land Degradation & Development, 34(10): 2975-2989. https://doi.org/10.1002/ldr.4661

[11] Matzek, V., Lewis, D., O'Geen, A., Lennox, M., Hogan, S.D., Feirer, S.T., Tate, K.W. (2020). Increases in soil and woody biomass carbon reserves as a result of rangeland riparian restoration. Carbon Balance and Management, 15: 1-15. https://doi.org/10.1186/s13021-020-00150-7

[12] Russell-Roy, E.T., Keeton, W.S., Pontius, J.A., Kerchner, C.D. (2014). Rehabilitation forestry and carbon market access on high-graded northern hardwood forests. Canadian Journal of Forest Research, 44(6): 614-627. https://doi.org/10.1139/cjfr-2013-0437

[13] Kroll, S.A., Horwitz, R.J., Keller, D.H., Sweeney, B.W., Jackson, J.K., Perez, L.B. (2019). Large-scale protection and restoration programs aimed at protecting stream ecosystem integrity: The role of science-based goal-setting, monitoring, and data management. Freshwater Science, 38(1): 23-39. https://doi.org/10.1086/701756

[14] Lininger, K.B., Lave, R. (2024). River restoration can increase carbon storage but is not yet a suitable basis for carbon credits. BioScience, 74(10): 717-724. https://doi.org/10.1093/biosci/biae083

[15] Tian, D., Xiang, Y., Seabloom, E., Wang, J., Jia, X., Li, T., Niu, S. (2023). Soil carbon sequestration benefits of active versus natural restoration vary with initial carbon content and soil layer. Communications Earth & Environment, 4(1): 83. https://doi.org/10.1038/s43247-023-00737-1

[16] Srivastava, P., Singh, N. (2022). Effects of microbial inoculants on soil carbon reserve, enzymatic activity, and above ground and belowground biomass in marginal lands of Northern India. Land Degradation & Development, 33(2): 308-323. https://doi.org/10.1002/ldr.4153

[17] Haas, H., Kalin, L., Sun, G., Kumar, S. (2024). Understanding the effects of afforestation on water quantity and quality at watershed scale by considering the influences of tree species and local moisture recycling. Journal of Hydrology, 640: 131739. https://doi.org/10.1016/j.jhydrol.2024.131739

[18] Vijayakumar, S., Bazrgar, A.B., Coleman, B., Gordon, A., Voroney, P., Thevathasan, N. (2020). Carbon reserves in riparian buffer systems at sites differing in soil texture, vegetation type and age compared to adjacent agricultural fields in southern Ontario, Canada.

Agriculture, Ecosystems & Environment, 304: 107149. https://doi.org/10.1016/j.agee.2020.107149
[19] Wang, Y., Fu, B., Lü, Y., Chen, L. (2011). Effects of vegetation restoration on soil organic carbon sequestration at multiple scales in semi-arid Loess Plateau, China. Catena, 85(1): 58-66. https://doi.org/10.1016/j.catena.2010.12.003
[20] Zhao, D., Bi, H., Wang, N., Liu, Z., Hou, G., Huang, J., Song, Y. (2024). Does increasing forest age lead to greater trade-offs in ecosystem services? A study of a Robinia pseudoacacia artificial forest on the Loess Plateau, China. Science of the Total Environment, 926: 171737. https://doi.org/10.1016/j.scitotenv.2024.171737
[21] Tang, X., Liu, S., Liu, J., Zhou, G. (2010). Effects of vegetation restoration and slope positions on soil aggregation and soil carbon accumulation on heavily eroded tropical land of Southern China. Journal of Soils and Sediments, 10: 505-513. https://doi.org/10.1007/s11368-009-0122-9
[22] Xu, J., Jiao, A., Deng, M., Ling, H. (2024). Changes in ecosystem carbon sequestration and influencing factors from a ‘Past-Future’ perspective: A case study of the Tarim River. Ecological Indicators, 169: 112861. https://doi.org/10.1016/j.ecolind.2024.112861
[23] Gao, Y., Jia, J., Lu, Y., Yang, T., Lyu, S., Shi, K., Yu, G. (2021). Determining dominating control mechanisms of inland water carbon cycling processes and associated gross primary productivity on regional and global scales. Earth-Science Reviews, 213: 103497. https://doi.org/10.1016/j.earscirev.2020.103497
[24] Xu, Y., Yang, D., Tang, L., Qiao, Z., Ma, L., Chen, M. (2023). Exploring the impact of grain-for-green program on trade-offs and synergies among ecosystem services in West Liao River Basin, China. Remote Sensing, 15(10): 2490. https://doi.org/10.3390/rs15102490
[25] Addisie, M.B., Molla, G. (2021). Trends of community-based interventions on sustainable watershed development in the Ethiopian highlands, the Gumara watershed. Sustainable Water Resources Management, 7(6): 87. https://doi.org/10.1007/s40899-021-00567-1
[26] Meena, D.C., Pal, S., Chand, P. (2022). Assessment of watershed management ecosystem services in India: A meta-analysis. Current Science, 123(11): 1352-1358. https://doi.org/10.18520/cs/v123/i11/1352-1358
[27] Rodriguez, B.C., Palma-Torres, V.M., Castañeda, T.J., Codtiyeng, S.K., Castillo, J.F., Sasi, A.P.V., Andrada, R.T. (2023). Drivers and impacts of land use and land cover changes on ecosystem services provided by the watersheds in the Philippines: A systematic literature review. International Forestry Review, 25(4): 473-490. https://doi.org/10.1505/146554823838028201
[28] Sumalatha, I.P.P.A., Sugunan, R., Thethi, H.P., Pratap, B., Fallah, M.H., Maan, P. (2024). Integrating forest management and Watershed health for Sustainable Water sources. In International Conference on Sustainable Goals in Materials, Energy and Environment (ICSMEE’24), Kerala, India, p. 03015. https://doi.org/10.1051/e3sconf/202452903015
[29] Amri, K., Latuconsina, H., Triyanti, R., Setyanto, A., Prayogo, C., Wiadnya, D.G.R., Ramlan, A. (2023). Pengelolaan Sumber Daya Perikanan Laut Berkelanjutan. Penerbit BRIN.
[30] Basuki, T.M., Nugroho, H.Y.S.H., Indrajaya, Y., Pramono, I.B., Nugroho, N.P., Supangat, A.B., Simarmata, D.P. (2022). Improvement of integrated watershed management in Indonesia for mitigation and adaptation to climate change: A review. Sustainability, 14(16): 9997. https://doi.org/10.3390/su14169997
[31] Supangat, A.B., Basuki, T.M., Indrajaya, Y., Setiawan, O., Wahyuningrum, N., Purwanto, Anggraeni, I. (2023). Sustainable management for healthy and productive watersheds in Indonesia. Land, 12(11): 1963. https://doi.org/10.3390/land12111963
[32] Takele, A., Birhanu, A.A., Wondimagegnhu, B.A., Ebistu, T.A. (2023). The impact of watershed development on food security status of farm households: Evidence from Northwest Ethiopia. Cogent Economics & Finance, 11(2): 2288466. https://doi.org/10.1080/23322039.2023.2288466
[33] Mante, K.M.B., Cadiz, N.M. (2024). Above-ground carbon reserve in rehabilitated and unrehabilitated mined areas in Mogpog, Marinduque, Philippines. Journal of Degraded & Mining Lands Management, 11(4): 6379-6385. https://doi.org/10.15243/jdmlm.2024.114.6379
[34] Mokria, M., Mekuria, W., Gebrekirstos, A., Aynekulu, E., Belay, B., Gashaw, T., Bräuning, A. (2018). Mixed-species allometric equations and estimation of aboveground biomass and carbon reserves in restoring degraded landscape in northern Ethiopia. Environmental Research Letters, 13(2), 024022. https://doi.org/10.1088/1748-9326/aaa1e3
[35] Van Rooyen, M.W., Van Rooyen, N., Stoffberg, G.H. (2013). Carbon sequestration potential of post-mining reforestation activities on the KwaZulu-Natal coast, South Africa. Forestry, 86(2): 211-223. https://doi.org/10.1093/forestry/cps070
[36] Yu, H., Zha, T., Zhang, X., Nie, L., Ma, L., Pan, Y. (2020). Spatial distribution of soil organic carbon may be predominantly regulated by topography in a small revegetated watershed. Catena, 188: 104459. https://doi.org/10.1016/j.catena.2020.104459
[37] Brown, S., Lugo, A.E. (1984). Biomass of tropical forests: A new estimate based on forest volumes. Science, 223(4642): 1290-1293. https://doi.org/10.1126/science.223.4642.1290
[38] Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia, 145(1): 87-99. https://doi.org/10.1007/s00442-005-0100-x
[39] Zianis, D., Mencuccini, M. (2004). On simplifying allometric analyses of forest biomass. Forest Ecology and Management, 187(2-3): 311-332. https://doi.org/10.1016/j.foreco.2003.07.007
[40] Hardjana, A.K. (2010). Potensi biomassa dan karbon pada hutan tanaman Acacia mangium di HTI PT. Surya Hutani Jaya, Kalimantan Timur. Jurnal Penelitian Sosial dan Ekonomi Kehutanan, 7(4): 237-249. https://doi.org/10.20886/jpsek.2010.7.4.%p
[41] Kurdi, S.Z. (2008). Pengaruh emisi CO_2 dari sektor perumahan perkotaan terhadap kualitas lingkungan global. Jurnal Permukiman, 3(2): 137-150. https://doi.org/10.31815/jp.2008.3.137-150
[42] Junaedi, A. (2007). Dampak pemanenan kayu dan perlakuan silvikultur tebang pilih tanam jalur (TPTJ) terhadap potensi kandungan karbon dalam vegetasi hutan alam tropika: Studi kasus di areal IUPHHK PT Sari Bumi Kusuma, Kalimantan Tengah. Bogor: Institut Pertanian

Bogor.
[43] Minarningsih, M. (2022). Komposisi, Keragaman dan Profil Tanaman Agroforestri di Taman Hutan Raya Wan Abdul Rachman (Composition, Diversity, and Profile of Agroforestry Plants in Wan Abdul Rachman Grand Forest Park). Jurnal Penelitian Hutan Tanaman, 19(2): 91-110.
[44] Irwanto, I., Hatulesila, J.W., Talaohu, M., Ely, A.S. (2022). Kombinasi jenis tanaman pola Dusung pada berbagai ketinggian tempat di Negeri Luhu Seram Barat. Jurnal Hutan Pulau-Pulau Kecil, 6(1): 94-108. https://doi.org/10.30598/jhppk.v6i1.5796
[45] Natalia, M., Sudhakar, Y.N., Selvakumar, M. (2013). Activated carbon derived from natural sources and electrochemical capacitance of double layer capacitor. Indian Journal of Chemical Technology, 20: 392-399.
[46] Al-Traboulsi, M., Sjögersten, S., Colls, J., Steven, M., Black, C. (2013). Potential impact of CO_2 leakage from Carbon Capture and Storage (CCS) systems on growth and yield in maize. Plant and Soil, 365: 267-281. https://doi.org/10.1007/s11104-012-1390-5
[47] Poorter, L., Bongers, F., Aide, T.M., Almeyda Zambrano, A.M., Balvanera, P., Becknell, J.M., Rozendaal, D.M.A. (2016). Biomass resilience of Neotropical secondary forests. Nature, 530(7589): 211-214. https://doi.org/10.1038/nature16512
[48] IPCC. (2006). Guidelines for national greenhouse gas inventories. Prepared by the National Greenhouse Gas Inventories Programme. Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K, editors. Published: IGES, Japan.
[49] Alam, A., Nashiruddin, A., Bafana, F.A., (2024). Implementing waqf forests in Indonesia: A SWOT and internal-external factor evaluation analysis. International Journal of Environmental Impacts, 7(3): 475-483.
[50] Achmad, A., Ramli, I., Sugiarto, S., Irzaidi, I., Izzaty, A. (2024). Assessing and forecasting carbon stock variations in response to land use and land cover changes in Central Aceh, Indonesia. International Journal of Design & Nature and Ecodynamics, 19(2): 465-475. https://doi.org/10.18280/ijdne.190212
[51] Golar, G., Basir-Cyio, M., Isrun, I., Bakri, R., Rusydi, M., Bohari, B., Pratama, M.F. (2021). Recovery of agricultural areas affected by traditional gold mining: Sustainable food supply stability. International Journal of Design & Nature and Ecodynamics, 16(2): 177-184. https://doi.org/10.18280/ijdne.160207
[52] World Bank. (2022). State and Trends of Carbon Pricing 2022. State and Trends of Carbon Pricing. Washington, DC: World Bank.