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ORIGINAL RESEARCH PAPER

Land use changes, green house gas emissions, and rehabilitation model of native tree species towards sustainable management

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ABSTRACT

BACKGROUND AND OBJECTIVES: Tropical peatlands play a crucial role in the global ecosystem. These distinctive ecosystems are frequently regarded as peripheral areas that are not suitable for agricultural purposes. Peatlands serve as efficient carbon storage systems in a consistent climate, however, they are vulnerable to alterations. This study focuses on analyzing the dynamic of peatland use land cover changes, its driver and impact on green house gas emission, and rehabilitating degraded peatlands in Jambi province, Indonesia, specifically in the Bram Itam and Londerang peat forest reserves. This study was depicted into 3 objectives consisted of 1) Utilize spatial analysis to examine the dynamics of peatland use change and the trajectory of peatland use, as well as to identify the drivers behind these changes; 2) describe the effects of altering peatland utilization; and 3) describe seedling performance planted on the peatland forest of Jambi province, as Tanjung Jabung Barat and Tanjung Jabung Timur.

METHODS: Land-use and land-cover change analysis was carried out utilizing various map resources. Cellular Automata-Markov is employed to forecast forthcoming land cover alterations by evaluating the likelihood of land cover transitions throughout a given period. Planting trials using native peatland tree species were conducted at 2 locations with 2 different rehabilitation models following social typology of the sites.

FINDINGS: Key findings indicate that peatland conversion to non forest use significantly increases greenhouse gas emissions, while rehabilitation with native tree species shows promising results in carbon sequestration. Peatland use land cover alteration in anthropogenically disturbed peat areas significantly contributes to emissions through peat decomposition and fires. Biophysical analysis reveals variations in peat depth, water table levels, and precipitation between these sites. The two locations exhibit notable disparities in terms of peat soil attributes, such as potential of hydrogen, nutrient composition, and exchangeable cations. This study examines the growth performance of several native tree species that were planted on degraded peatlands. Native peatland tree species like Shorea balangeran, Ilex cymosa, and Fagraea crenulata show promising survival and growth rates. Areca nut (Areca catechu), a non native peatland species, was planted for non-timber forest product purposes. This study delivers significant insights for policymakers looking to strike a balance between economic priorities and environmental conservation.

CONCLUSION: Land use change that results in the degradation of peatlands must be avoided because it will be a source of greenhouse gas emissionsThe selection of suitable indigenous tree species holds significant importance in the restoration of peatlands, taking into account ecological, social, and economic considerations. The findings support potential for wet agroforestry and paludiculture to restore peatlands, mitigate carbón dioxide emissions, and enhance livelihoods while emphasizing the need for inclusive governance and technical capacity.

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76	7	3

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INTRODUCTION

The tropical peatlands ecosystem holds significant importance within the climate system due to its unique characteristics and functions (Minasny *et al*., 2023). Peatland comprises undecomposed or partly decomposed organic materials, such as leaves, trunks, and wood. The organic matter was submerged in the basin on a yearly basis, leading to the formation of anaerobic conditions and a significantly reduced rate of decomposition. Peat formation is a time-consuming process, as highlighted by Takada *et al.* (2016), with its initiation dating back to the Holocene period (Hapsari *et al.,* 2021). Tropical peatlands are characterized by a low potential of hydrogen (pH), high water content, elevated humic acid content, extremely low bulk density, and limited nutrient content (Sutejo *et al.,* 2017). Variations in peat's hydrological properties, chemistry, and organic matter will have a direct impact on vegetation changes (Garsetiasih *et al.,* 2022). Peatlands play important roles in ecosystem services: as carbon preservation on the below- and above-ground (Murdiyarso *et al.,* 2019), in protection functions of water regulation, carbon storage (Leng *et al.,* 2019), biodiversity conservation (Husson *et al.,* 2018), cultivation functions of support on land productivity and multiple products, hydrological functions of water storage and distribute it to the environments (Harrison *et al.,* 2020). Natural tropical peatlands are considered marginal lands (Wichtmann *et al.,* 2016), which are unsuitable for agriculture. While numerous plant species have the ability to thrive in challenging environments, only a restricted selection of plant species that naturally inhabit peatlands are recognized for their capacity to offer sustenance, specifically in the form of carbohydrates and fruits (Uda *et al.,* 2020). A recent publication reported that Indonesia covers 13.4 million hectare (Mha) of peatlands (Anda *et al.,* 2021). The tropical peatlands of Indonesia face the threat of rapid land-use/land-cover change and subsidence owing to massive canalization. The drivers of peatland cover change in Indonesia consisted of deforestation, land cover change to agriculture, and estate plantation (Miettinen *et al.,* 2016), and fire (Taufik *et al*., 2022). The increasing population impacted the increasing need for agricultural land. Peatlands, being classified as marginal lands, offer less competitive conditions for cultivation compared to mineral soils. In order to reduce costs and expedite land clearing, certain individuals resort to the practice of slashing and burning peatlands (Purnomo *et al*., 2017). Peatland management has received less attention three decades ago and peatland regulations are not sufficiently known to many peatland users (Uda *et al*., 2020). The increasing occurrence of fire disasters and concerns regarding global climate change have caused a shift in the approach to managing peatlands in Indonesia (Krisnawati *et al*., 2021). Peatland use change dynamic analysis is important as it helps estimate the future role of global peatlands (Leifeld *et al.,* 2019). Land use and land cover change on peatlands may have significant environmental implications. It is imperative to comprehend the patterns and factors that contribute to these alterations in order to ensure the long-term viability of land management and conservation efforts. Due to drainage and changes in land use, peatlands are now a source of greenhouse gases; but, by restoring drained regions, they may become carbon neutral (Leifeld *et al*., 2019). The transformation of land use and vegetation cover in tropical peatlands, originally designated for forest vegetation, necessitates their rehabilitation. This will make an important contribution to achieving the government's commitment to reduce emissions and sustainable development goals (Basuki *et al*., 2019). Some obstacles to peatland rehabilitation in Indonesia generally include changes in peat topography, drainage, invasive ferns and shrub species, repeated fires, and the risk of flooding. It also includes climate change, inconsistent land use policies, and a lack of alternative livelihood options (Dohong *et al.,* 2018). The peatland of Jambi province is one of the essential ecosystem in the tropics, particularly in their contribution to global climate change. Native peatland tree species has been used as peatland rehabilitation in Jambi province, particularly in two districts of Tanjung Jabung Barat (TJB) and Tanjung Jabung Timur (TJT). Nevertheless, the study did not concentrate on forest regions but rather solely on a specific indigenous peatland species (Wulandari *et al*., 2021). The primary emphasis of numerous studies lies in analyzing the short-term outcomes of reforestation, while the long-term effects on greenhouse gas (GHG) emissions remain largely unexplored (Smith *et al*., 2014). Limited research on the specific roles and efficiency of different native tree species in carbon sequestration (Jones *et al*., 2017). A recent study reported peat forest rehabilitation in

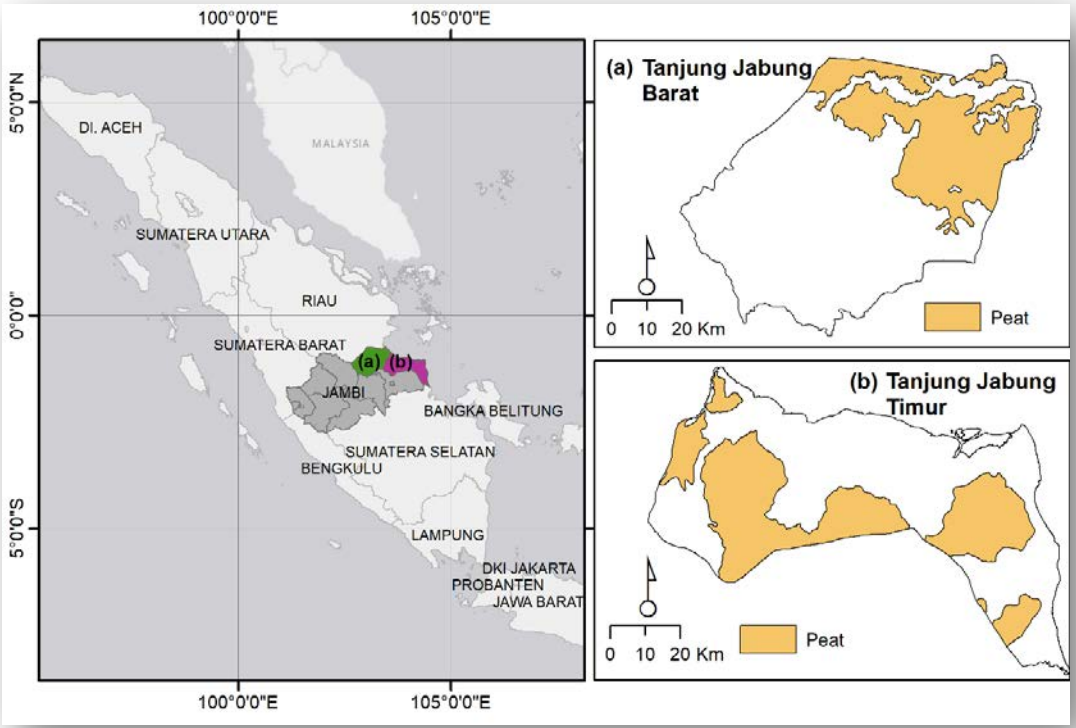


Fig. 1: Geographic location of the study area in the districts of TJB ~~peatlands~~ and TJT of Jambi Province, Indonesia

Kepau Jaya of Riau province using combination of native and non-native peatland tree species (*Shorea balangeran* and *Coffea liberica*) (Frianto *et al.,* 2024). To date, there is no documented evidence of utilizing a combination of various native peatland species in the rehabilitation of peat forests in Jambi. Therefore, study actions on peatland rehabilitation using native and beneficial peatland tree species are important to be conducted in Jambi to restore degraded peatlands, which are prone to fire during the dry season, and inundated during the rainy season (Lampela *et al.*, 2017). The study aimed to 1) describe peatland use change dynamics and peatland use trajectory and drivers using spatial analysis; 2) describe impact of peatland use change; and 3) describe seedling performance planted on the peatland forest of TJB and TJT by developing demonstration plots. The creation of these two demonstration plots involved the application of experimental research. The hypothesis of this research was consisted of i) drivers and land use change trajectory between TJB and TJT were different, and ii) each plant species has different growth response. This study has been carried out in Jambi province, Indonesia. The planting of native peatland tree species as peatland rehabilitation model was carried out in 2017-2018, and data analysis was conducted in 2023 by combining with spatial data up to 2022.

MATERIALS AND METHODS

Study area

Jambi province covers an area of 4.9 Mha, comprising 621,000 hectare (ha) of peatland or 12.6 percent (%) of the total area) (Fig. 1). In order to address the degradation of peatlands, a rehabilitation initiative was carried out, focusing on the development of demonstration plots within two districts. The sites were selected based on the map of analysis land use change, followed by consultation with local actors, such as Forest Management Units (FMUs) of TJB and TJT, and migrant farmers around the location of TJB.

The demonstration plot in TJT was established on the Londerang Forest Reserve area, which is geographically located at 103°46'37.42"–103°47'18.19" east (E) and 1°18'0.97"–1°19'7.59" south (S). The Londerang Forest Reserve was encompassed by smallholder oil palm plantations and a plantation forest dedicated to pulp and paper production. Many canals have been established since the development of the plantation. Recurrent fires often occur in this area (Prasetyo *et al.,* 2016). The planting site was a post-fire forest 2015, where many burnt trees remain standing. The land covers were shrubs and understory plants. Some vegetation grows by natural succession, such as *Melastoma malabathricum, Nephrolepis hirsutula,* and *Stenochlaena palustris*. In TJB, the demonstration plot was established in the Bram Itam Forest Reserve area (103°20'39.98" E – 0°58'12.90' S). The last forest fire in the location was in 2015 (Tata *et al.,* 2016a). The main objective of the peatland restoration efforts was to rehabilitate two peat forest reserves, namely Hutan Lindung Gambut (HLG) situated along the Bram Itam river in the TJB district, and the peat forest reserve of Londerang in the TJT district. The two forest reserves are laid on different peatland hydrological units (PHU), namely PHU of Batara – Mendahara River in TJB and PHU of Mendahara – Batanghari River in TJT district. The Bram Itam River peat forest reserve encompasses a total area of 15,050 hectares (ha) dedicated to peatland conservation. About 5,000 ha of the utilization block of HLG Bram Itam has a peat depth of less than 2 meters (m). While in the TJT district, the peatland restoration was located in the protected peat-swamp forest (PSF) of Londerang River, which covers an area of 12,484 ha.

Prior informed consent (PIC) and selection of local participating farmers

Migrant people have occupied some areas of peat forest reserve of TJB since the 1990s (Nugroho *et al.,* 2021). The collaborative forest rehabilitation method with residents was utilized in creating the demonstration site. Some villagers of Mekar Jaya were organized in a Suren Jaya Farmer Group and were involved in the implementation of demonstration plot. The farmer group selection was based on recommendation of the TJB's FMU. To conform with the indigenous people's rights of Convention No. 169 (ILO, 1989), prior informed consent was obtained from the villagers of Mekar Jaya, TJB. In TJT, none of the villagers were included in the research activities, which was attributed to the diverse social conditions present. The necessary permits to conduct research in TJB and TJT were secured from the Forest Management Units (FMUs) of TJB and TJT, along with the Forestry Services Office of Jambi Province.

Data collection

Several map sources were used for analyses of land-use land-cover change. Land use maps of Jambi province based on Landsat interpretation in 1990, 2000, 2011, and 2022, from the Ministry of Environment and Forestry (MoEF) of Indonesia. Furthermore, other maps that were utilized encompassed the administrative map of Jambi Province and the district of TJB and TJT, the forest area map, PHU map, the ecosystem function of PHU map, and peatland map.

Drivers of land-use and land-cover changes

Identifying the multitude of factors that influence changes in the utilization and coverage of peatlands is essential in identifying the drivers of peatland use and land-cover change. To identify these drivers, a combination of spatial analysis, field surveys, stakeholder interviews, and data on land use policies and regulations were used.

Impact land-use land-cover change

The biophysical evaluation included measuring the depth of peat and groundwater levels in the field, along with conducting soil analysis in the laboratory. Peat depth was measured once at the plot's core using peat auger Eijkelkamp at every demonstration plot in TJB and TJT districts. The demonstration plots of HLG Bram Itam TJB and the secondary forest of TJB exhibited peat depths of 0.60 m and 1.25 m, respectively. At the same time, peat depth in the demonstration plot of HLG Londerang TJT ranged from 2.90 to 3.70 m. The groundwater table (GWT) measurement was carried out at a monitoring well 100 m from the edge of the plot. In TJB, GWT monitoring was conducted manually using a meter stick every day from 1 December 2017 to 28 February 2018. Secondary data of GWT and rainfall measurements obtained from the peat water level monitoring system (Sistem Pemantauan Air Lahan Gambut/SIPALAGA), which is a water level monitoring system) were collected from the neighboring stations of Parit Culum II of TJT and

Bram Itam Kanan of TJB between December 1, 2018, and December 31, 2019. In addition, the annual temperature and precipitation of TJB and TJT were analyzed using secondary data and the WorldClim2 method described by Fick and Hijmans (2017). Peat samples were obtained from each experimental site utilizing the peat auger Eijkelkamp. In TJT, peat soil samples were collected from peat depth 0–0.50 m from six replicates. In TJB, peat soil samples were collected per layer sequentially from 0–0.25 m and 0.25–0.50 m in the demonstration plot and secondary forest. The mineral soil substratum was not taken into consideration during the analysis. The peat soil samples were brought to the soil laboratory service of Southeast Asian Regional Centre for Tropical Biology (SEAMEO BIOTROP) for analysis of their chemical properties, such as pH (glass electrode), macronutrients of nitrogen (N) total (Kjeldahl), phosphor (P) total (hydrochloric acid 25%) and P available (Bray I), kalium (K)-exchangeable, calcium (Ca)-exchangeable, magnesium (Mg)-exchangeable, carbon (C)-organic according to Mebius method (Sato *et al.,* 2014), cation exchange capacity (CEC) (extract method–ammonium acetate 1.0 N pH 7, base saturation (BS), aluminum cation (Al^{3+}), hydrogen cation (H^{+}), and ash content (Loss on Ignition method) (Farmer *et al.,* 2014). The sulphur content of TJB was determined through using a spectrophotometer at a wavelength of 420 nanometer (nm) (Horwitz, 2000). The analysis also encompassed the examination of the physical attributes of peat soils, including density, fiber, ash, and water content. Bulk Density (BD) and water content were analyzed in the laboratory using the gravimetric method. The laboratory utilized the sieving method to ascertain the peat fiber content (Soil Research Institute, 2005). The peat soil samples underwent wet sieving with a 100-mesh sieve at a particle size of 0.149 millimeters (mm), both with and without

Plant species selection for rehabilitation

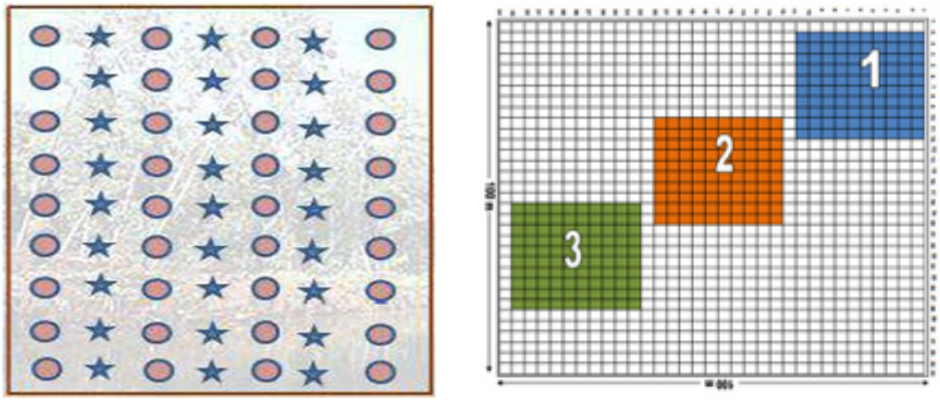
The selection of species for restoring degraded peatlands in the two locations was determined by factors specific to the area, including the type of peatland, historical land use, ease of access, and the characteristics of the local community. Eight woody tree species, namely *Dyera polyphylla, Ilex cymosa, Litsea cassiaefolia, Litsea robusta, Shorea balangeran, Syzygium acuminatum, Syzygium campanulatum,* and *Vitex pinnata*, and one species non-timber forest product of areca nut (*Areca catechu*) were selected for the rehabilitation. The absence of land tenure conflicts in TJT facilitated the selection of tree species based on their ability to thrive in fluctuating inundation conditions. Four indigenous peatland species were deliberately chosen for cultivation in this particular environment; *Alstonia pneumatophora, D. polyphylla, Fagraea crenulata,* and *S. balangeran*. Native tree species were selected based on their adaptability to local peatland conditions, their role in enhancing biodiversity, and their ability to improve soil structure and hydrology. The source of all seedlings can be traced back to the Jambi province.

Rehabilitation of peat-swamp forests

In TJB, the woody tree species arranged in strip planting, with each row consisting of 75 seedlings of one species. *A. catechu* was planted in between two woody species. A single block comprised of eight rows of eight woody tree species and eight rows of areca nut seedlings. The planting distance was 3 m x 3 m (Fig. 2a). A total of 225 seedlings per woody tree species were grown, while 1,800 seedlings of woody tree species and 1,800 areca nuts were planted. All the seedlings that were planted were carefully observed and measured over the course of one year. In TJT, the experiment was also designed as a randomized block design. Four woody plant species have been selected; each was planted in a block of 1 ha, with a planting distance of 3 m x 3 m. In total, 4,400 seedlings of 4 woody-tree species were planted. Three sub-plots of 30 m x 30 m were positioned diagonally to capture the variation of micro-topography of the peatlands (Fig. 2b). The observation and growth measurement were conducted in 3 sub-plots of 30 m x 30 m, totaling 361 seedlings.

Data analysis

In the analysis, the land use map from the MoEF of Indonesia was classified into 6 land cover classes, which are forest, shrub, agriculture, water body, settlement, and others. The land-use or land-cover map underwent overlay with additional maps before proceeding to further analysis. The analysis was conducted using geographic information system (GIS) software ArcGIS 10.5, IDRISI 17.0 the Selva edition, and microsoft office. The land cover projection for peatland ecosystems of TJB and TJT districts



(a) (b)

Fig. 2: Rehabilitation model of degraded peatlands in Jambi. (a) Line planting model design in TJB, (b) Block planting model design in TJT. Remarks of 2a: Red circle = woody-tree species; blue star = areca nuts. Remarks of 2b: Blue, orange, and green squares are sub-plots of 30 m x 30 m, nested in a 100 m x 100 m plot

was conducted through the utilization of a cellular automata (CA)-Markov model with image processing tools in the terrset software (IDRISI) 17.0 software, specifically the selva edition. This approach was employed to forecast future changes in land cover by assessing the likelihood of land cover transformation over different time periods. The Cellular Automata model is based on grid and cell, where the cell core interacts with neighbour cell cores. Information from the years 2000, 2009, and 2018 was utilized to project alterations in land use or land cover by the year 2036. Peatlands are highly vulnerable ecosystems, and alterations in land utilization can result in substantial environmental consequences, such as greenhouse gas emissions. The GHG emission were calculated based on data on activities that occurred in the Jambi peat area with emission factors from the 2nd Forest Reference Emission Level (FREL) of Indonesia document that has been reported to the United Nations Framework Convention on Climate Change (UNFCCC) (Republic of Indonesia, 2022). The seedlings' growth was assessed by recording both stem diameter and total height. Each seedling underwent measurement and observation over the course of a year. The areca nut seedlings were observed for their survival. The plant growth from the two sites was analyzed separately using variance analysis. Tukey's test was used to detect the significance of the differences between mean values. Soil characteristics of the two sites were compared and analyzed using T-student analysis. Statistical analysis was performed using SPSS Statistics 16 (IBM Corporation, USA).

RESULTS AND DISCUSSION

Peatlands characteristics of TJB and TJT districts

Peatlands in Jambi has wide range of typology from low to very deep peat. Peat depth of TJB district is ranging from 0.50–3 m, while peat depth of TJT district is ranging from 1–3 m. Typically, the peat composition in two districts is primarily characterized by a peat depth ranging from 2 to 3 meters. The peatland soil in TJB and TJT is classified as Histosol, a type of soil associated with organic matter accumulation. Within the Bram Itam Forest Reserve of TJB, the upper layer of peat soil, specifically in the 0 to 0.25 meter depth, commonly consists of sapric peat, which is peat that has undergone decomposition. Hemic peat (half-decomposed peat) was found in the 0.25–0.50 m layer. The undecomposed or fibric peat was found in the layer deeper than 0.50 m. A clay-textured soil substrate was discovered at a depth exceeding 0.60 m. The degree of peat decomposition in TJB ranges from sapric at the uppermost layer to fibric at the lowermost layer. The water level in the study demonstration plot from 1 December 2017 to 28 February 2018 ranged from -0.50 to 0.11 m. Based on the annual rainfall data provided by The Agency of Meteorology Climatology and Geophysics, there exists a slight disparity in precipitation between the

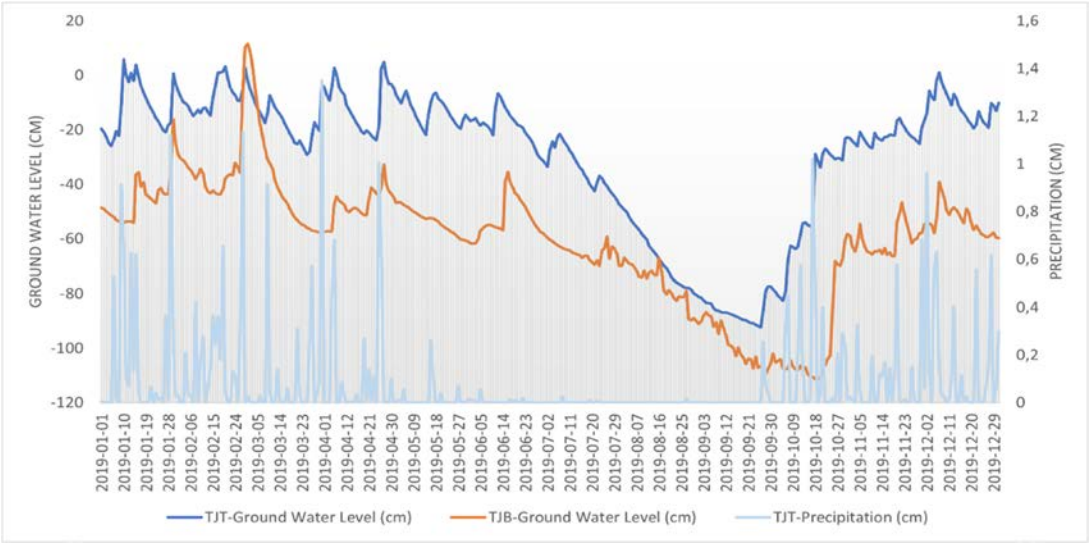


Fig. 3: Ground water table (GWT), precipitation in the Parit Culum station TJT district, and Bram Itam Kanan station TJB district, from 1 January 2019–31 December 2019 (SIPALAGA, 2019)

districts of TJB and TJT. The mean annual rainfall of TJB was higher than TJT's, which was 2,918 and 1,830 mm, respectively (BPS, 2016). According to SIPALAGA (one year observation) at the station of Parit Culum of TJT, rainfall has a direct impact on GWT (Fig. 3).

On the site of TJT and TJB, the fluctuation of GWT was high. During the rainy season at TJT, which spans from January to March and October to December, the groundwater table (GWT) experienced an elevation of up to 0.06 m above the surface. Conversely, in the dry season from April to September, the GWT exhibited a decline of 0.92 m below the surface. SIPALAGA data showed that the GWT of TJB was deeper than TJT. Based on direct measurement at one pole measurement, during the observation (from December 2017 to February 2018) GWT ranged from -0.60 to 0.11 m. Flooding occurred for a short duration. During 2019, there was a period of drought caused by decreased precipitation levels. The annual temperature in TJB is slightly cooler than that of TJT. The annual temperature of TJB ranged from 296.45–300.15 °K and in TJT ranged from 299.85–300.25 °K. The maximum temperature of TJB ranged from 301.65–304.95 °K, while TJT ranged from 304.65–305.05 °K. Temperature minimum TJB ranged from 291.65–295.65 °K, whereas TJT was 295.15–295.85 °K. The spatial distribution of temperature of TJB and TJT is shown in Fig. 4.

The comparison of annual rainfall in TJB closely resembled that of TJT. Precipitation levels in TJB and TJT varied between 2313 and 2539 mm annually. Precipitation of the wettest month of TJB occurred in January (270–313 mm), while TJT happened in December (258–321 mm). In July, the driest month of TJB experienced a precipitation range of 96-114 mm, whereas TJT received rainfall ranging from 96-140 mm during the same month. The spatial distribution of precipitation for both TJB and TJT can be observed in Fig. 5.

The HLG Londerang in TJT has experienced repeated fire (Fig. 6). According to Prasetyo *et al.* (2016), the fire occurred several times between 2001 and 2015. Peatland fires are a common occurrence annually, typically happening either during the El Nino or La Nina period. The majority of the fire took place within the boundaries of the community's land. After the use of fire for land preparation was banned in 2016 by the Governor of Jambi province, severe fire still occurred both in TJB and TJT. The GWT in TJB and TJT revealed that the peatlands had been dried severely due to massive canal constructions in Londerang and Bram Itam (Giesen and Sari, 2018).

Proper management of water resources and understanding peatland hydrology are essential

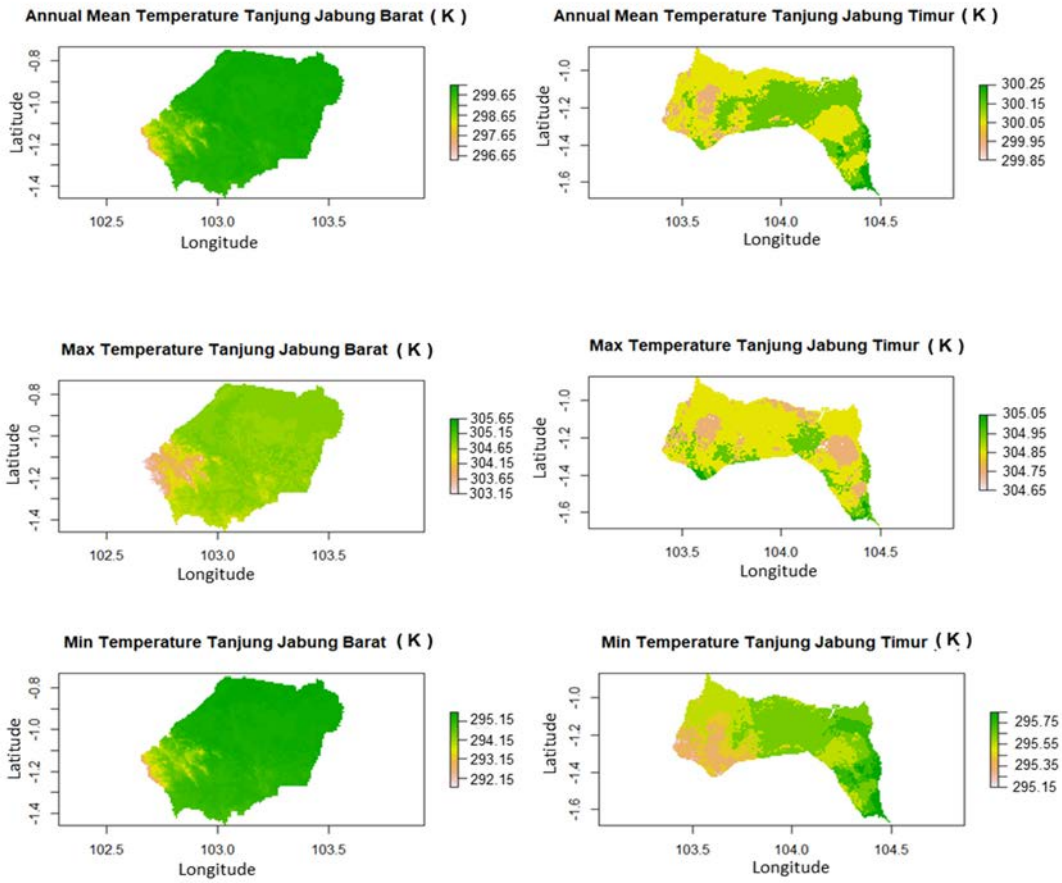


Fig. 4: Spatial distribution of temperature in TJB and TJT districts, Jambi province

factors in the effective utilization of peatlands (Tiemeyer *et al.,* 2024). GWT measurement is crucial as GWT can be used as an early warning system of fire on peatlands (Taufik *et al.,* 2019), and it positively relates to carbon dioxide (CO_2) emissions (Cooper *et al.,* 2020). According to Government Regulation No. 54/2016, the cultivation function of the PHU has a maximum GWT limit of 0.40 m below the surface, to avoid land subsidence and fires in the dry season. Despite the implementation of canal blocking in the vicinity of the demonstration plot at Londerang TJT and Bram Itam TJB, the process did not effectively restore the degraded peatlands and resulted in a rise in GWT. The GWTs at both sites were low; and peatlands are prone to fire in the dry season. Even though precipitation distribution in TJT and TJB is almost similar, the annual temperature of TJT was hotter than that of TJB (Figs. 4 and 5). The fire susceptibility of TJT was heightened due to the temperature disparity. The primary stressors that tropical forests face are heat and drying (Saatchi *et al*., 2021). During the rainy season, the plot of rehabilitation in TJT and TJB experienced flooding. It was only occurred occasionally and only for a short duration; several hollows in TJT were temporarily saturated. Peatland rehabilitation is often hindered by the presence of a high water table or flooding (Yuwati *et al*., 2021).

Characteristics of peat soils

The physical and chemical characteristics of tropical peat soils undergo significant changes due to stabilized land uses, resulting in distinct features observed in open and forested areas (Könönen *et al.,*

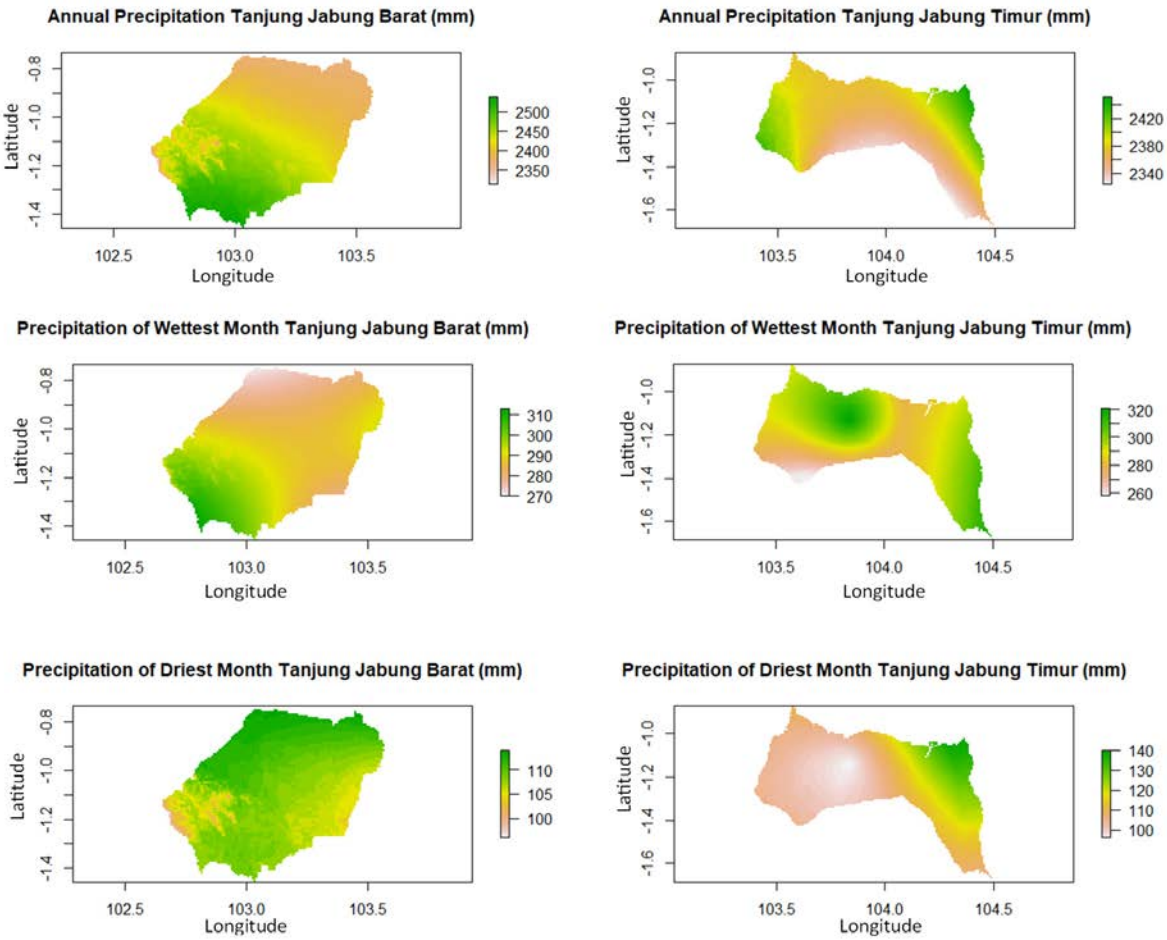


Fig. 5: Spatial distribution of precipitation in TJB and TJT districts, Jambi Province

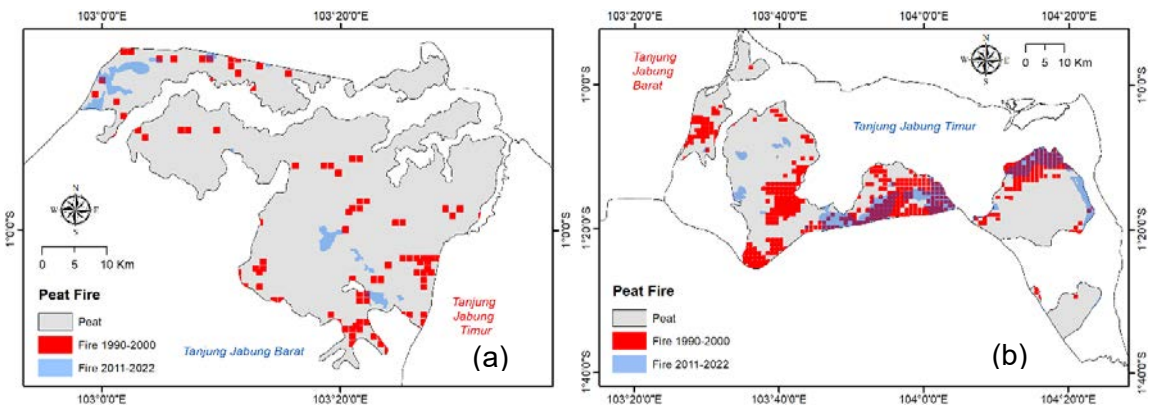


Fig. 6: Peat fires in 1990–2000 and 2011–2022 (a) TJB, (b) TJT

Table 1: Chemical properties of peat soils from rehabilitation site from TJB compared to TJT

No.	Parameter	Rehabilitation site TJT	Rehabilitation site of TJB at peat layer of				Secondary forest of TJB at peat layer of			
		Peat depth 0–25 cm Mean ± SD	0–25 cm		25–50 cm		0–25 cm		25–50 cm	
1	pH (H_2O)	4.25 ± 0.58	3.40	*	3.40	*	3.90	ns	4.00	ns
2	pH (KCl)	3.42 ± 0.60	2.50	*	2.40	**	2.80	ns	3.10	ns
3	Corg (%)	54.41 ± 2.46	47.27	**	45.31	**	46.31	**	42.49	**
4	Ntotal (%)	1.82 ± 0.37	0.78	**	0.74	**	0.81	**	0.76	**
5	C/N	31.17 ± 7.16	60.60	**	61.20	**	57.17	**	55.91	**
6	Pavailable (ppm)	25.37 ± 3.56	21.10	*	20.80	*	14.60	**	13.70	**
7	K (meq/100g)	1.45 ± 0.60	0.52	*	0.50	*	0.51	*	0.50	*
8	Ca (meq/100g)	12.01 ± 4.73	7.34	*	6.77	*	6.03	*	6.11	*
9	Mg (meq/100g)	3.44 ± 1.22	11.14	**	11.23	**	13.62	**	13.54	**
10	Na (meq/100g)	1.43 ± 0.39	0.17	**	0.16	**	0.27	**	0.26	**
11	CEC (meq/100g)	139.68 ± 17.10	56.69	**	57.35	**	58.78	**	56.54	**
12	BS (%)	13.63 ± 5.00	33.40	**	32.50	**	34.80	**	36.10	**
13	Al^{3+} (meq/100g)	2.15 ± 1.25	3.02	ns	3.05	ns	3.62	*	3.55	*
14	H^+ (meq/100g)	1.12 ± 0.25	2.53	**	2.49	**	3.04	**	2.71	**

Remarks: TJT = Tanjung Jabung Timur, TJB = Tanjung Jabung Barat. Numbers in the same row followed by asterisk(s) show significantly different result (T-student test: * = at 5%, ** = at 1%, ns = not significant).

2015). The soil properties were affected by a recurring fire that occurred in the rehabilitation areas of TJT and TJB. The characteristics of peat soil from TJT are significantly different from those with TJB (Table 1). The recurrent fire, which usually occurs in TJT and TJB, affects the soil properties in the upper layer. The combustion process typically leads to a decrease in C-organic content, macronutrient content, and pH levels (Nusantara *et al*., 2020). The cultivated and drained peatlands of TJB have significantly different soil chemical characteristics compared with TJT, as shown in Table 1. TJB has low pH, ranging from 3.4–3.6. The exchangeable Al^{3+} and H^+ content in research demonstration plots and secondary natural forests was higher in all layers than in TJT peat soils. The macro-nutrient contents of C-organic, N-total, P-available, K, Ca, and Na of TJT were higher than those of TJB. In TJB, the macro-nutrient contents, except for Mg, declined along with deeper peat layers. The CEC of TJT is significantly higher than that of TJB.

The C-organic content of TJT soil is significantly higher than that of TJB both at sites of the demonstration plot and secondary PSF. N-total of peat soils of Londerang TJT were categorized as high to very high according to the criteria of Balai Penelitian Tanah (Soil Research Institute, 2005), with a C/N ratio of 31.74. However, the pH, CEC, and majority of macronutrients present in TJT surpass those found in TJB. The ash content in TJB is higher than that in TJT. It implies that the peat soil of TJB is more fertile than TJT's. The ash content measurement serves as a reliable gauge for assessing the fertility of peat soil (Zusevica *et al*., 2023). The soil acidity (pH H_2O and pH KCl) of TJT is significantly higher than that of TJB. The pH value in secondary PSF tends to be higher than that of the study demonstration plot in TJB. The susceptibility of sulfate-based soil is contingent upon its positioning on the soil surface and the level of canal intensity associated with land use, making it prone to oxidation (Fahmi *et al*., 2014). The decrease of pH in the shallower or upper layers may be caused by oxidized sulphur content and increased organic matter (Nystrand *et al*., 2021). In TJB, sulphur content ranged from 0.84–0.85%; P-total ranged from 60.4–61.3 parts per million (ppm). The ash content of TJB is higher than that of TJT. The Al^{3+} content in the soil of the secondary forest of TJB was higher than that of the rehabilitation site. The release of minerals containing aluminum may occur as a result of the elevated acidity level caused by the oxidation sulphur materials (Nystrand *et al*., 2021). It is stated that oxidation of pyrite materials may occur if drainage is carried out. The exchangeable cations of Ca, Mg, K, Na, and CEC of TJB are relatively the same at the layers of 0–0.25 and 0.25–0.50 m. The CEC value is

high in peat soil of TJT, which relates to high C-organic content. The Base saturation of TJT and TJB's research sites is low and relate to low pH, implying less fertile soil, ultimately impacting the success of rehabilitation planting efforts. The content of P-available and P-total in the study demonstration plot of TJB in the upper layer is high, but low content in the lower layer. The availability of phosphorus in soil, diminishing with depth, exhibits a similar pattern to the nitrogen content, which also declines with increasing depth. This decrease is caused by the relatively reduced weathering in deeper layers. The application of biochar and organic fertilizer derived from chicken manure and pineapple leaf fiber has the potential to enhance the availability of phosphorus in peat soils (Ch'ng *et al.,* 2014). Peat soils that have the potential for sulphate are suggested not to be disturbed (Fahmi *et al.,* 2014). If these soils are to be utilized for agricultural purposes, a thorough assessment of the peat layer's potential must be conducted to ensure that the GWT remains above the sulphate horizon, and liming is needed in the horizon. Burning peat soil resulted in a decrease in organic acids and their ability to bind metal ions, compromised soil structure, diminished water retention capacity, and lowered soil fertility (Yustiawati *et al.,* 2015). The peatlands around the study location were in a category of relatively easy to rehabilitate.

Peatland-uses changes in Jambi

In contrast to broader regional studies, this research delves into a localized and detailed analysis of changes in peatland cover. By concentrating on the micro-scale, valuable information is obtained regarding the mechanisms involved in the decline and regeneration of peatlands, crucial for focused conservation endeavors. The peatland landscape covers various land uses or land covers, such as PSF, monoculture, mixed garden, agriculture, and bushes. The analysis of changes in land use or land cover is employed to recognize current land uses within the framework of a holistic landscape management strategy. Agriculture is a key contributor to global GHG emissions (Kamyab *et al.*, 2024). A comprehensive assessment of greenhouse gas emissions and sequestration in agriculture was conducted to support sustainability (SaberiKamarposhti *et al.*, 2024). Peatland-use change from PSF to a drained agriculture reduced methane emission (Cooper *et al.*, 2020). The reduction of methane emissions is not proportionately offset by the rise in carbon emissions, primarily due to decomposition processes and alterations in land utilization (Somer *et al.*, 2023). Land use change also reduced peatland productivity (Basuki *et al.,* 2019). Moreover, land-use change projection is important to be analysed as an early warning indicator in the peatland landscape management. Approximately 52% of the peatlands within Jambi province can be found specifically in the TJB and TJT districts. Peatlands of TJB district were positioned at two PHUs, namely PHU of Batanghari River–Tungkal River, and PHU of Tungkal – Mendahara River. Peatlands in TJT district were located in 4 PHUs, namely PHU of Air Hitam Laut – Buntu Kecil River, Batanghari – Mendahara River, Batanghari – Niur River, and Tungkal – Mendahara River. Most peatland areas in TJB and TJT districts were designated as 'other use' based on the 'area functions' criteria established by Indonesia. The 'other use' is not a forest area, which has the potential to be developed into agricultural land and developed land. The PSF reserve is only 10-11% of total peatlands of TJB, and the conservation PSF was located in TJT district. About 20-35% of peatlands were classified as peat-forest production areas. The analysis reveals that peatlands in Jambi, Indonesia, have been utilized since the 1990s for purposes such as timber exploitation, agricultural land, and as a transmigration area from Java. They have different land use compositions since the 1990s and land use changes in the following year periods (Fig. 7a–b). In 1990s, the two districts were dominated by PSFs, both undisturbed and disturbed forests. Forest plantations presented in TJT only. Agricultural land has developed widely in TJB district up to 45% of peatland area. In comparison to the TJT district, the proportion of agricultural land in the peatland area was merely 16%. The agricultural lands consisted of annual and perennial crops. Peatland areas in TJB and TJT were almost equal, e.g., 141,000 ha and 181,000 ha, respectively. The land-use composition of the two districts has been different since 1990s. In 2019, PSF covers decreased fast. Over half of the peatlands in TJB district were utilized for agricultural purposes, whereas in TJT district, the proportion of agricultural land rose to 24%. The expansion of shrub-lands showed a notable increase in both TJB and TJT districts, with an annual growth rate of 596

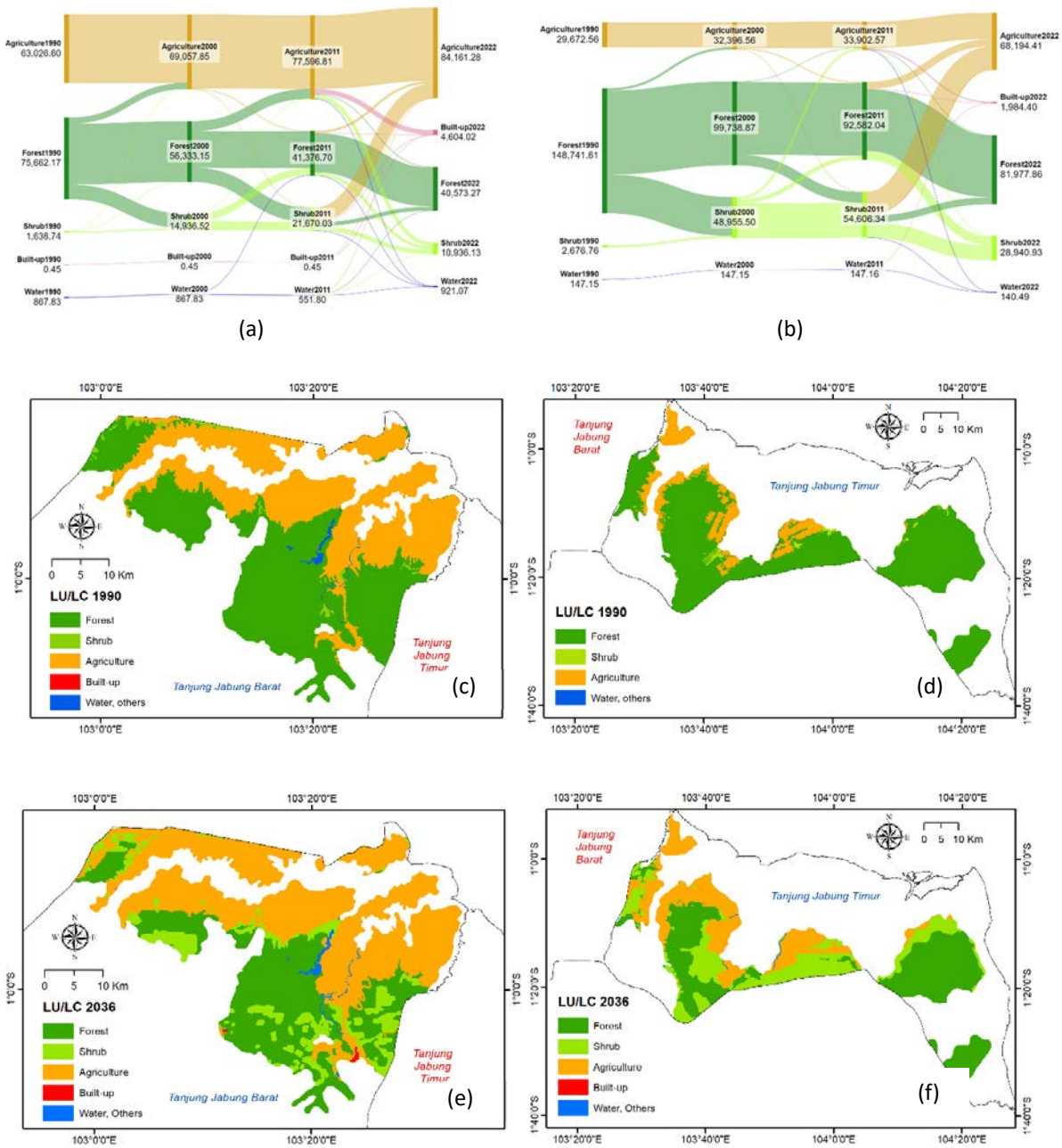


Fig. 7: Land-use or land-cover change from 1990 to 2022 in (a) TJB; (b) TJT; (c–d) Distribution of peatland-use or land-cover in 1990 in TJB and TJT districts; (e–f) Projection of peatland-use or land-cover in 2036

and 1885 hectares per year (ha/y), respectively. The land-use change projection based on historical data can be used to improve people's awareness to protect this unique ecosystem for better management and interventions. Fig. 7c–f illustrate the distribution and projection of land-use/land-cover in the TJB and TJT districts. The examination of historical and continuous utilization of peatlands offers

valuable insights into comprehending the present circumstances, the factors that led to its formation, and the potential guidance it can offer for future endeavors (Widyatmanti *et al.,* 2022). In 1990s, PSFs as undisturbed and disturbed PSFs, were dominated peatland ecosystems in TJB district. Meanwhile in TJT district, there was already a forest plantation on peatland ecosystem. Since the 1990s, agriculture has been implemented within the peatland ecosystem of the two districts. The TJT district possesses a smaller proportion of agricultural land, accounting for only 16% of the total peatland areas. In contrast, the TJB district boasts a larger expanse of agricultural land on peatlands, constituting 45% of the total area. Jambi has a long history on rubber (*Hevea brasiliensis*) agroforest, which was started in the early 20th century (Akiefnawati *et al.,* 2021). Rubber agroforests have been gradually substituted by monoculture rubber and oil palm plantations since the 1950s, as these plantations have proven to be more financially lucrative than rubber agroforests (Akiefnawati *et al.,* 2021). Shrubs in the two districts were just small area, around 2–5%, and there were few settlements in the peatland landscape of TJB.

The Cellular Automata-Markov (CA-Markov) model predicts an increase in developed lands within the TJB and TJT districts by 2036, as indicated by the land-use projection. The projection illustrates a rise in peat-forest coverage in both districts due to the decrease in shrubs on peatlands (Fig. 7 e–f). Compared to the others algorithm, Asadi *et al.* (2022) showed that the CA-Markov is most successful in predicting the future. CA-Markov modelling is a powerful tool for predicting land cover change due to its ability to handle spatial and temporal dynamics effectively, making it widely used. The utilization of CA-Markov chains has proven to be highly effective in various geographic and spatial fields, leading to its widespread recognition. Notably, the application of this modeling technique has yielded remarkably precise outcomes in studies related to land use classification and urban growth modeling (Ghosh *et al*., 2017). These models also possess constraints. The CA-Markov model presupposes that the transition probabilities remain constant over time, indicating that they do not change throughout the projection period (Asif *et al*., 2023). This assumption may not always hold true in real-world scenarios where land use policies, economic factors, and environmental conditions can change, potentially altering transition probabilities. The model further postulates a static boundary for the study area, disregarding any potential external factors that may extend beyond this demarcation (Rimal *et al*., 2017). The CA-Markov model simplifies the complex processes governing land cover changes by reducing them to a set of transition probabilities. This approach does not capture the full complexity of human-environment interactions, socio-economic drivers, and policy impacts that can influence land use changes. Consequently, certain intricacies of the dynamics of land cover may go unnoticed (Ozturk, 2015). A comprehensive strategy is necessary to tackle the rising levels of greenhouse gas emissions on peatlands resulting from alterations in land use and land cover. It is essential to use sustainable land management techniques to lessen the impact on peat ecosystems. It is imperative to implement interventions that promote eco-friendly peatland management, including the adoption of paludiculture practices within agroforestry systems (Uda *et al.,* 2020). Rewetting drained peatlands, implementing controlled drainage systems, and utilising agroforestry practices are few strategies that can assist in preserving the wet conditions essential for sequestering carbon. As a fragile ecosystem, peatlands are unresistant to change, even though they perform as efficient carbon sinks in an unaltered environment. The growing demand for land in peatland utilization and the risk of disruptions like wildfires have led to alterations in land management. Fire outbreaks in the years 1997-1999, 2015, and 2019 have been observed in multiple peat areas in TJB and TJT. The figure of peatland land-use change in districts of TJB and TJT since 1990s until 2022 was similar to peatland degradation and sequence of forest conversion reported by Miettinen *et al.* (2016). The increasing percentage of converted and managed peatlands has brought attention to the importance of effective management practices in ensuring sustainable peatland management of TJB and TJT districts.

GHG emission from land-use land-cover change on peat

Peatlands are renowned for their carbon storage capacity, however they are resistant to change. This study aims to measure the extent of carbon loss that

Table 2: Land-use or land-cover changes area on peatlands and the GHG emissions or emission due to land-use or land-cover change in TJB and TJT in the periods of 1990-2000, 2000-2011, and 2011-2022.

Period	Category	TJB	TJT
	a. Land-use or land-cover changes area on peatlands (ha)		
		(ha)	
1990-2000	Deforestation-forest Degradation	28,060.05	50,198.37
	Forest enhancement	79.09	-
	Non forest degradation	376.65	-
	Non forest enhancement	94.83	-
	No change	112,585.15	131,039.72
2000-2011	Deforestation-Forest Degradation	32,790.03	26,338.11
	Forest Enhancement	7,748.45	6,126.11
	Non forest degradation	1,602.05	278.37
	Non forest enhancement	815.06	7,023.64
	No change	98,240.18	141,471.84
2011-2022	Deforestation-forest Degradation	4,229.54	17,633.70
	Forest enhancement	5,401.25	8,618.83
	Non forest degradation	9,429.86	16,242.48
	Non forest enhancement	77,762.48	47,240.75
	No change	44,372.65	91,502.32
	b. GHG emissions or emission due to land-use or land-cover change		
		(tCO_2e/y)	
1990-2000	Biomass loss	775,372	1,750,526
	Peat decomposition	1,291,336	1,881,385
	Non CO_2 from fire	14,328	536,032
	Peat Fire	145,215	5,814,594
	Total 1990-2000	2,226,251	9,982,538
2000-2011	Biomass loss	(187,954)	376,436
	Peat decomposition	629,843	1,316,868
	Non CO_2 from fire	-	-
	Peat fFir	-	-
	Total 2000-2011	441,889	1,693,305
2011-2022	Biomass loss	28,735	(361,117)
	Peat decomposition	154,663	372,579
	Non CO_2 from fire	2,456	126,973
	Peat fire	25,134	1,555,806
	Total 2011-2022	210,988	1,694,240

Note: - denotes no data available. Values in the parentheses have negative values

can be attributed to alterations in land cover. The empirical evidence enhances the comprehension of the carbon sequestration potential of peatlands and the consequences of their degradation on climate change. Human activities that are driven by agricultural expansion, forest plantation, peat drainage, and fire, have led to widespread land-use and land-cover changes on peatlands. There is an increasing trend in the area of land-use and land-cover change from 1990-2000, 2000-2011, and 2011-2022 in the TJB and TJT regions. Forest cover change in the TJB peatland region exhibits a declining trend leading up to the period 2011-2022, with a higher percentage of area undergoing change (69%) compared to the TJT region (50%) (Table 2a). Peatland have sensitivity to land use changes, particularly due to agricultural expansion and drainage (Evans *et al.*, 2016). Land-use and land-cover changes on peatlands have resulted in decreased carbon stock from deforestation and forest degradation, increased carbon stocks from changes non-forest to forest, and decreased and increased carbon stocks in non-forest areas. The emission of greenhouse gases (CO_2, CH_4, and N_2O) into the atmosphere has been triggered by various activities, including biomass loss, emissions from peat decomposition, and emissions from peat fires. Emissions from peat decomposition are the largest contributor to emissions compared to biomass loss,

e.g. >65% in TJB, and >78% in TJT district. There is a downward trend in average emissions from 1990-2000 to 2011-2022. The average emission level in TJB reached 2.2 million ton CO_2 equivalen per year (tCO_2e/y) in 1990-2000 and decreased to 0.2 million tCO_2e/y in 2011-2022; as well as in TJT which reached 10 million tCO_2e/y in 1990-2000 and decreased to 1.7 million tCO_2e/y in 2011-2022 (Table 2b).

Drivers of land-use land-cover change on peat

The peatlands of TJB and TJT face a critical dilemma between development and conservation due to the rising demand for infrastructure, timber, and agricultural products. The intricate balance between progress and conservation is particularly highlighted in the relationships among building infrastructure, promoting agricultural expansion, and addressing the interconnected issues of drainage and wildfires. Anthropogenic activities have the potential to disturb the natural processes of carbon sequestration and decomposition that take place in peatlands, which are essential to their ecological equilibrium. Peat disturbances, such as peat decomposition and peat fires, are the primary sources of emissions in peat areas within TJB and TJT regions (Table 2b). Anaerobic bacteria assist in the slow breakdown process of organic matter that builds up in wet circumstances, transforming peatlands into carbon storage. The equilibrium of peatlands may be disrupted as a result of alterations caused by human interventions, such as the construction of canals for agricultural purposes, deforestation for timber extraction, and peat fire. Peat decomposes more quickly when peatlands are drained because it exposes the organic matter that was previously submerged in water. The GHGs, mostly CO_2 and methane (CH_4), are released into the environment because of this process. Methane, in particular, possesses a considerably higher warming potential than CO_2 when considering shorter timeframes, making it a potent GHG. Waterlogged peatlands normally have anaerobic conditions that prevent methane emissions, but changes in land use can produce disruptions that release large amounts of this powerful gas. Consequently, the alteration of peatlands not only endangers their ability to retain carbon but also contributes significantly to the accumulation of greenhouse gases that intensify the phenomenon of global warming. Managing GWT depth in degraded peatlands is crucial for achieving Indonesia's emission reduction target by 2030, with plantation forests showing the highest CO_2 emissions (Novita *et al.*, 2021). The plantation forest concessions have been legally managing some PSF areas in TJB and TJT districts since 2004; and in TJT, some plantation forest concessions have been established since 1997. The 1997–1999 fires occurred in several peat areas in TJB and were more massive in TJT district. During the time frame of 2000 to 2011, no instances of fires were detected. However, in the subsequent period of 2011 to 2022, fires once again affected numerous peat areas in TJB and TJT, with notable occurrences in TJB and TJT, especially in 2015 and 2019 (Fig. 6).

Growth performance of several plant species for peatland rehabilitation

This study findings provide solution to increase forest cover, which is an actionable rehabilitation models and strategies for the successful establishment of native tree species in degraded peatland areas. Native trees are highly adapted to adapt to the specific environmental conditions of their local habitats, rendering them exceptionally efficient in the process of capturing and sequestering CO_2 (He *et al.*, 2020). Native species are inherently more resilient to local climate conditions, making them better suited to with stand the impacts of climate change (Yaakobi *et al.*, 2023). This resilience exhibited by land management practices plays a crucial role in ensuring their long-term sustainability amidst evolving environmental conditions. Eight native peatland tree species and areca palm plants grow well on the degraded peatlands of TJB. The analysis of variance indicate that plant type had a significant impact on height growth, while its effect on survival and stem diameter was not found to be statistically significant. The survival percentage of the eight types of forestry plants at 1 year was between 55.6–82.7% (Table 3). The highest survival percentage is *I. cymosa*, and the lowest is *L. cassiaefolia* (white medang). Five plant species with the best height growth are *S. balangeran, L. cassiaefolia, L. robusta, I. cymosa,* and *S. campanulatum*. Five species of native tree species were planted in TJT; plant species influenced the stem diameter, plant height, and survival significantly, while the block did not affect the growth. The results of the seedlings' performance in the TJT can be observed in

Table 3: Survival, stem diameter, and plant height of plant species after 1 year planted at of TJB and TJT, Jambi Province

No	Plant species (local name)	Survival (%)	Stem diameter (cm)	Plant height (cm)
		TJB		
1.	*Dyera polyphylla* (jelutung rawa)	(60.0 ± 10.5) a	(2.00 ± 0.35) a	(103.0 ± 6.8) c
2.	*Shorea balangeran* (balangeran)	(62.7 ± 10.0) a	(2.93 ± 0.55) a	(244.6 ± 21.5) a
3.	*Litsea cassiaefolia* (white medang)	(55.6 ± 13.5) a	(1.55 ± 0.76) a	(159.0 ± 32.5) abc
4.	*Litsea robusta (*medang mangga)	(66.3 ± 18.9) a	(2.31 ± 0.57) a	(186.4 ± 63.3) abc
5.	*Vitex pinnata* (laban)	(64.1 ± 5.6) a	(3.11 ± 1.01) a	(136.4 ± 30.6) bc
6.	*Ilex cymosa* (kayu telak)	(82.7 ± 18.0) a	(2.37 ± 0.32) a	(190.9 ± 10.8) ab
7.	*Syzygium campanulatum* (kelat)	(67.2 ± 26.7) a	(2.85 ± 0.26) a	(173.4 ± 27.0) abc
8.	*Syzygium accuminatum* (jambu-jambu)	(71.0 ± 25.8) a	(2.42 ± 0.06) a	(147.8 ± 13.6) bc
9.	*Areca catechu* (areca nut)	(63.3 ± 3.3) a	-	-
		TJT		
1.	*Shorea balangeran* (balangeran)	(84.5 ± 5.9) a	(0.71 ± 0.01) b	(102.3 ± 3.2) a
2.	*Fagraea crenulata* (bira-bira)	(63.5 ± 4.0) ab	(1.12 ± 0.09) a	(44.0 ± 1.0) d
3.	*Dyera polyphylla* (jelutung rawa)	(48.4 ± 19.6) b	(0.87 ± 0.08) b	(61.7 ± 5.1) bc
4.	*Stemonurus scorpioides* (pasir-pasir)	(86.2 ± 6.0) a	(0.51 ± 0.02) c	(56.0 ± 2.7) cd
5.	*Alstonia pneumatophora* (pulai)	(86.2 ± 13.1) a	(0.72 ± 0.13) b	(75.7 ± 10.7) b

Note: Values followed by the same letter in the same column are not significantly different at 5% significance level based on Tukey test

Table 3. The results showed that the stem diameter and seedling height of *F. crenulata* were significantly different from other species. S. balangeran proved to be the most adaptable plant species among the five types found in TJT, Jambi province, specifically on peatlands. Seedlings with more than 60% survival are considered the most suitable species for degraded peatland rehabilitation.

Eleven tree species (excluding areca nut) planted in the rehabilitation plots of TJB and TJT are native peatland tree species; all trees grow well in saturated areas. These eleven tree species show great potential in restoring the deteriorated peatlands area of TJT and TJB, making them well-suited for paludiculture endeavors. Three native peatland tree species planted in the demonstration plot of rehabilitation were also reported as dominant tree species and genera at TJB and TJT, such as *D. polyphylla, Litsea* sp. and *Syzigium* spp. (Siregar *et al.,* 2015). In TJB, where the forest area has been occupied by communities, *A. catechu* (areca nut) seedlings were planted to provide non-timber forest products for the community living around the peat forest reserve. While in TJT, the absence of any tenurial conflict facilitated the implementation of a strategy to restore the deteriorated peatlands by introducing woody tree species. Using native species is more likely to gain local community support, as these species are often culturally and economically significant. Rehabilitation of degraded peat forests in TJB and TJT using native peatland tree species reveals that *I. cymosa* and *A. pneumatophora* have the best survival at TJB and TJT. The best height growth survival performance was *I. cymosa* (TJB) and *A. pneumatophora* (TJT). The best stem diameter growth was shown in *S. balangeran* (TJB) and *F. crenulata* (TJT). *S. balangeran* showed the best height growth both in TJB and TJT. *S. balangeran* also has the best performance as reported in Central Kalimantan (Lampela *et al.*, 2017). Within the tenth indigenous peatland tree species introduced in TJT and TJB, S. balangeran is recognized for its high-quality logwood (Indriani *et al.,* 2019). Timber of *F. crenulata* is also used as light construction (Wong and Sugumaran, 2012). Current reports showed that leaves and twigs of *S. balangeran* contained high antioxidant and antidiabetic activity (Ramadhan *et al.,* 2022). Leaves of *I. cymosa* also has been used as traditional medicine for allergies in Bangka regency (Swandi *et al*., 2021). Developing non-timber forest products from native peatland tree species in peatland rehabilitation poses a significant challenge due to the potential use of other tree species planted as traditional medicine in TJT and TJB. The mixture of woody tree species and non-timber forest products in an agroforestry system is an approach for forest rehabilitation and minimizing social conflict with the community who occupied the forest area. Areca nut is not a native peatland species; it needs low water-table and does not survive in saturated conditions (Tata, 2019). During the period of 2017-2018, the activities carried out in Jambi province revealed that

the areca nut possessed significant economic worth and enjoyed a favorable market (Fendria *et al.*, 2020). The local communities cultivated areca nut years ago, as areca nut is known as 'jambé,' which is also the province's name (Fendria *et al.,* 2020). In the Minister Forestry regulation no. 35 (2007), areca nut is categorized as non-timber forest product (NTFP). Nevertheless, it has not been incorporated into the roster of suggested plant species for the restoration of peatland forests as outlined in The Minister Environment and Forestry Regulation no. 16/2017, which provides technical guidance for the rehabilitation of peat ecosystem functions. Apart from areca nuts, swamp jelutong (*D. polyphylla*) trees can be tapped for latex, whereas jelutong sap has economic value (Tata *et al.*, 2016b). According to an ex-tapper of jelutong latex in TJB, before 1997, the price of jelutong latex was twice that of rubber latex. Jelutong trees and areca palms are potential commodities to improve communities' welfare around peatland forests in Jambi province (Fendria *et al.,* 2020). Nevertheless, the cultivation of areca nut necessitates proper drainage, making it unsuitable for enhancing GWT levels and mitigating the risk of fire (Tata, 2019). In the longer term, planting areca nut trees on peatlands would increase CO_2 emissions. The agroforestry system has been reported to accommodate degraded landscapes' ecological, social, and economic functions (Harun *et al*., 2022). The Food and Agriculture Organization for the United Nations (FAO) recommends the implementation of wet agroforestry in cases where the peatlands cannot be completely rehabilitated to their original state as a wetland or PSF (Tan *et al.,* 2021). Wet agroforestry and paludiculture can restore the peatlands, minimizing CO_2 emissions and improving livelihoods and food security (Lupascu *et al.,* 2023). The effectiveness of rehabilitation initiatives frequently hinges on the backing and engagement of indigenous populations. Socio-economic factors such as land tenure issues, competing land uses, and local livelihoods can pose significant challenges. Achieving community support and ensuring that rehabilitation efforts are in sync with local needs and priorities can be a complicated task. Resistance to change can arise, particularly if rehabilitation activities are seen as conflicting with traditional land use practices or economic interests. Adequate hydrological conditions are crucial for the survival and growth of native tree species in peatlands. Water levels need to be carefully managed to prevent both waterlogging and excessive drainage. Establishing and maintaining the ideal hydrological balance can be technically challenging and resource-intensiveContinuous monitoring and management are essential, but can pose challenges in remote or resource-constrained regions. Implementing an adaptive vegetation model can be challenging due to the need for large quantities of improved seedlings, land preparation and plant maintenance. Ferns and weeds in degraded peat areas can also suppress the growth of adaptive vegetation. Controlling the ferns and weeds is necessary for the rehabilitation plants to grow optimally, but this may come at a higher cost. In order to ensure the effectiveness of peatland restoration efforts, it is essential to incorporate the practice of obtaining free, prior, and informed consent (FPIC) is necessary. FPIC refers to the right of the local community to give or withhold their consent for any actions that would affect their lands, territories, or rights. In Jambi Province, peatland restoration was implemented while taking into account a variety of factors, such as the state of the burned peat ecosystem, hydrological conditions, rehabilitation techniques, species selection, and community social factors (Suharti *et al.*, 2022). Conflicts arising from divergent interests between business concessions, communities, municipal governments, and other stakeholders are a common occurrence in peatland restoration efforts, as they involve navigating the trade-offs between environmental and socio-economic considerations. Peatland restoration will be successful if those competing agendas can be combined and resolved and if governance and technical capacity are strengthened (Harun *et al.,* 2022).

CONCLUSION

The importance of adopting sustainable practices for the preservation and rehabilitation of degraded peatlands is emphasized by the intricate interplay between land use changes, greenhouse gas emissions, and peat ecosystems. This study contributes valuable insights into plant species selection and design of the planting systems aimed at rehabilitating degraded peatlands. Peatlands of TJT and TJB have been degraded since years ago, leading to significant alterations in peat soil

properties. The deterioration has been intensified by human activities, specifically the drainage for agricultural purposes and the repeated occurrence of peat fires. The findings of our study have direct implications for policy and management. The detailed quantification of GHG emissions can inform climate change mitigation policies, while the proposed rehabilitation strategies provide a blueprint for on-the-ground restoration projects. Wet agroforestry, incorporating beneficial tree species, offers a viable approach to enhance the ecological functions of degraded and burned peatlands while also offering alternative livelihood opportunities. Tree species selection is important, as it determines the technical rehabilitation procedures. Native tree species that are adapted to peatland environments thrive in saturated conditions, in contrast to non-native tree species. Based on this study, *S. balangeran, I. cymosa*, and *F. crenulata* are the most promising tree species for peatland rehabilitation. Those three species have potential use as nutraceuticals. It is essential to consider the potential use of planted trees as nutraceuticals to ensure that they can serve as a sustainable source of non-timber forest products for the communities near Londerang TJT and Bram Itam TJB in the future. By providing tangible benefits to local communities, such as access to valuable non-timber forest products, rehabilitated peatlands can garner increased support and participation from stakeholders, enhancing the sustainability of conservation efforts. The implementation of practical suggestions can significantly improve the effectiveness of reforestation initiatives and guarantee the long-term viability of rehabilitated peatland ecosystems. The preservation of peatlands' delicate equilibrium is crucial for sustaining their ecosystem services and mitigating the impacts of climate change. Undoubtedly, the decisions made today will shape the future of these significant landscapes in the face of a changing climate.

AUTHOR CONTRIBUTIONS

W.C. Adinugroho performed planned the experiments, collected samples/data in the field, data analysis, wrote the original draft preparation, interpreted and discussed the results, and validation and editing. H.L. Tata performed collected samples/data in the field, wrote the original draft preparation, interpreted and discussed the results, and validation and editing. Darwo performed planned the experiments, collected samples/data in the field, data analysis, interpreted and discussed the results, and validation and editing. Y. Lisnawati performed planned the experiments, collected samples/data in the field, data analysis, interpreted and discussed the results, and validation and editing. H.S. Nuroniah performed collected samples/data in the field, data analysis, interpreted and discussed the results, and validation and editing. R. Dewi performed collected samples/data in the field, data analysis, interpreted and discussed the results, and validation and editing. I. Heriansyah performed collected samples/data in the field, data analysis, interpreted and discussed the results. Mawazin performed collected samples/data in the field, data analysis, interpreted and discussed the results.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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ABBREVIATIONS

%	Per cent
Al^{3+}	Aluminum cation
BD	Bulk density
C	Carbon
Ca	Calcium
CA	Cellular Automata
CA-Markov	Cellular Automata-Markov
CEC	cation exchange capacity
CH_4	Methane
cm	centimeter
CO_2	Carbon dioxide
FMUs	Forest management units
FPIC	free, prior, and informed consent
FREL	Forest reference emission level
GHG	Green house gas
GIS	Geographic information system
GWT	Groundwater table
H^+	Hydrogen cation
ha	hectare
HCl	Hydrochloride acid
HLG	Hutan Lindung Gambut
IDRISI	Image processing tools in the terrset software
K	Kalium
^oK	Kelvin degree
m	meter
meq	milliequivalent
mm	millimeter
M ha	Million hectare
Mg	Magnesium
MoEF	Ministry of Environment and Forestry
N	Nitrogen
N_2O	Nitrous oxide
NH_4	Ammonium
Na	Sodium
nm	nanometer
P	Phosphor
pH	Potential of hydrogen
PHU	peatland hydrological units
ppm	Parts per million
PSF	Peat-swamp fores
SIPALAGA	Sistem Pemantauan Air Lahan Gambut
tCO_2e	tonnes of carbon dioxide equivalent
TJB	Tanjung Jabung Barat
TJT	Tanjung Jabung Timur

UNFCCC	United Nations Framework Convention on Climate Change
y	year

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