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Review

Agroforestry as an approach to rehabilitating degraded tropical peatland in Indonesia

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Abstract

Peatland is a unique ecosystem with water saturation; peatland regulates hydrological processes, climate, environmental conditions, and biodiversity. Poor management practises regarding peatlands can lead to land degradation, and peatland degradation typically has negative effects. Recent tropical peatland research in Indonesia has predominantly revolved around the examination of the ecological consequences resulting from various management approaches. There is little study on farmers' agroforestry efforts to preserve and restore degraded peatlands. A comprehensive examination was undertaken to assess a range of facts, information, and scholarly articles pertaining to the practise of agroforestry on peatlands in Indonesia. The primary incentive for farmers to adopt agroforestry systems originates from their recognition of the impending scarcity of trees. By integrating intercrops with cultivated trees, farmers anticipate generating adequate money to fulfil their family's economic requirements. Farmers who choose intensive intercropping practises are motivated by market demand, whereas farmers who do not adopt this approach tend to favour crops that necessitate less rigorous management. The provision of governmental assistance holds significant importance, and there is a pressing need for additional guidance and support. The potential for rehabilitating degraded peatlands by the implementation of agroforestry practises of native tree species is considerable. Their growth patterns contribute to enhanced vegetative coverage, resulting in heightened moisture levels, reduced temperatures, diminished fire hazards, and improved peat soil quality. The relationship between the physiography of the land and the depth of the peat is directly associated with the patterns and components of agroforestry in peatland environments.

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Introduction

Peatland is a unique ecosystem that is always saturated with water and serves multiple purposes, such as regulating hydrology, climate, environment, and biodiversity. Peatlands are comprised of decomposed plant matter that has accumulated over time to produce peat soils (Page and Bairds, 2016). Peat soils are susceptible to change, relatively less fertile, and irreversibly dry. Tropical peatlands, in particular, are composed of plant debris produced by wetland forests, including stems, branches, and roots that retain their original plant characteristics. Firdaus et al. (2011) and Mustamo et al. (2016) have observed that the physical properties of peat soils are determined by the effect of numerous interconnected variables. The physical characteristic of peat soil that is often compared to mineral soil is its high soil water content. According to Agus et al. (2019), the water retention capacity of peat soils varies between 200 and 1,000% by weight or 50-90% by volume. The capacity of peat soils to retain water is influenced by the maturation of peat and the depth of groundwater (Taufik et al., 2019). Fibric peat materials have the capacity to retain water ranging from 500 to 1000% of their weight, but hemic and sapric peat materials exhibit a comparatively lower water retention capability, ranging from 200 to 500%.

In general, peatlands occupy around 3% of the Earth's land area (Blodau, 2002; Yu et al., 2011; Vitt and Short, 2020) and serve as significant ecosystems for the preservation of biodiversity, management of climate (Joosten, 2015), and enhancement of human well-being (Wildyana, 2017). Tropical countries cover a significant amount of global peatland area, estimated to be around 31-46 million hectares, accounting for approximately 10-12% of the total peatland area worldwide (Page et al., 2011; Dargie et al., 2017). These tropical peatlands are distributed across various regions, including Southeast Asia, Africa, South and Central America, the Caribbean, Mainland Asia, Australia, and the Pacific (Rieley and Page, 2016). Indonesia has the greatest extent of tropical peatland, approximately 14.1 million hectares, as documented by several sources (Page et al., 2011; Osaki et al., 2016; Anda et al., 2021). The majority of these peatlands are concentrated on the islands of Sumatra, Kalimantan (Borneo), and Papua (Purnomo et al., 2019; Anda et al., 2021). Peatlands, in their natural condition, offer significant environmental benefits on a global scale, particularly in relation to climate change, owing to their substantial capacity for carbon (C) storage (Page et al., 2011). These peatlands currently store approximately 28 gigatonnes (Gt) of carbon, which is three times the aggregate carbon storage of all forests in Indonesia (Warren et al., 2017).

The primary function of the tropical peatland ecosystem is to serve as a means of subsistence for the local people living inside or in close proximity to peatland regions. Peatlands in Indonesia have been exploited by local communities for traditional agricultural practises for an extended period of time, namely in areas that consist of shallow peat measuring approximately 0.5 m, primarily located alongside major rivers (Najiyati et al., 2005; Osaki et al., 2016). Since the 1970s, extensive peatland areas in Sumatra and Kalimantan have undergone deforestation and drainage to facilitate agricultural expansion (Noor, 2012).

Subagio et al. (2015) reported that the most extensive continuous region earmarked for agricultural transformation, exceeding 1 million hectares, in Central Kalimantan, Indonesia, was deforested in 1995. However, the conversion efforts were ceased in 1999 as a result of environmental problems associated with peat drainage. While the technical aspects of peatland development have been comprehensively studied (Mamat and Noor, 2019), the practical implications of peatland drainage are generally unfavourable in the medium to long term due to the multitude of negative impacts it can entail (Widyati, 2011).

Inappropriate management of peatlands can lead to the degradation of land, and such degradation of peatlands generally has negative impacts. The primary factors contributing to the degradation of tropical peatlands, specifically in Indonesia, encompass the utilisation of fire as a means of land clearance and excessive development of drainage systems, which subsequently lead to land subsidence and an augmented vulnerability to floods (Purnomo et al., 2021a).

According to Page et al. (2009), the occurrence of forest and peatland fires has been on the rise since 1997 due to an extended period of drought. The most severe conditions on record were observed in 2015 (Huijnen et al., 2016; Miettinen et al., 2017) in Central Kalimantan, a province that experiences recurrent instances of intense forest and peatland fires during extended periods of drought. Kiely et al. (2019) have observed that the wildfires under consideration release substantial amounts of trace gases and aerosols, leading to serious levels of regional air pollution. This pollution has negative impacts at both local and national/international scales, including significant economic losses (Tacconi, 2003), health problems among humans, and a contribution to global climate change (Uda et al., 2019).

The conversion of approximately 10 million hectares of peatlands in Southeast Asia leads to carbon emissions ranging from 132 to 159 million metric tonnes per year due to peat oxidation and the subsequent rise in peat fires. These activities not only contribute to the increase in greenhouse gas emissions but also pose a significant threat to human health and livelihoods (Marlier et al., 2013; Miettinen et al., 2017). Furthermore, the loss of peat due to oxidation and fire leads to land subsidence and a heightened vulnerability to flooding (Hooijer et al., 2012; Evers et al., 2016; Evans et al., 2019). Subsidence can occur in drained peatlands as a result of the combined processes of consolidation and decomposition (Hooijer et al., 2010; Hooijer et al., 2012).

Indonesia has undertaken many initiatives to tackle the challenges connected with degraded peatlands. The establishment of the Peat Restoration Agency (BRG) was authorised through Presidential Regulation No. 1 of 2016 with the primary objective of conserving and restoring peatlands that have undergone degradation (Agustiyara et al., 2021; Purnomo et al., 2021b). Within the context of enhancing peat ecosystems, the terminology commonly employed revolves on restoration and rehabilitation. It is evident that the focus of these endeavours predominantly aligns with rehabilitation.

Restoration refers to the systematic efforts undertaken to aid in the recovery of ecosystems that have experienced degradation, damage, or destruction. On the other hand, rehabilitation is a management intervention that seeks to restore the level of ecosystem function in a degraded area, with the goal of renewing and sustaining ecosystem services in a manner that is environmentally sound. It is important to note that rehabilitation does not aim to restore biodiversity and integrity to the same extent as the undegraded reference ecosystem, as outlined by Gerwing et al. (2022).

The BRG has endeavoured to embrace a comprehensive approach to the preservation and rehabilitation of deteriorated peatlands. This approach encompasses hydrological restoration (re-wetting), revegetation, revitalization of livelihoods, and expedited fire protection measures. The re-wetting plan aims to restore the hydrological conditions of peatlands to a state that closely resembles their natural state through the implementation of measures such as blocking and/or filling canals and constructing deep wells (Dohong, 2019; Sutikno et al., 2019). The process of revegetation involves the reintroduction of native plant species in forested regions and peat swamp lands. However, it is worth noting that the effectiveness of propagating and cultivating indigenous species is typically limited, as indicated by Mishra et al. (2021).

The revitalization of local livelihoods seeks to offer alternative means of survival for local communities, serving two primary objectives: first, to enhance income and welfare, and second, to foster greater involvement of local communities in the operation and upkeep of the re-wetting infrastructure established in their vicinity (Dohong, 2019). To fulfil the government's objective of peatland restoration, it is imperative to devise rapid propagation cultivation methodologies that may effectively generate native tree seedlings at a suitable pace.

Community economic empowerment refers to the implementation of strategies aimed at promoting economic activities such as new agriculture practises (e.g. fish farming, and beekeeping). These activities are intended to discourage communities from engaging in forest encroachment, which is known to contribute to the degradation of forests and peatlands. Additionally, community economic empowerment initiatives also seek to foster the protection of forest regions. In relation to this objective, Putiksari et al. (2014) observed that the primary determinant of deforestation was the income of the community. Consequently, it is imperative to offer economic prospects that can sustain the livelihoods of communities engaged in peatland rehabilitation initiatives.

The implementation of revegetation as a restoration activity may be considered as less attractive within the local context due to its prolonged duration and the absence of immediate economic benefits for the community in the short to medium term. According to Kallio et al. (2011), the process of planting trees, particularly for the purpose of timber production, involves a considerable duration until the trees achieve a size suitable for harvesting. Consequently, tree planting can be regarded as a prolonged investment that yields limited returns in the immediate term. Hence, the implementation of an agroforestry system presents itself as a viable option for the restoration of deteriorated peatlands while concurrently offering economic benefits to the local community.

Agroforestry is an approach to agriculture that aims to achieve social, economic, and environmental advantages by including trees with other crops. It has been suggested in many research papers as a potential solution for rehabilitating degraded peatlands (Maftu'ah et al., 2021; Purnomo et al., 2021c). There is evidence suggesting that the practise of agroforestry has a positive impact on soil quality, agricultural productivity, ecosystem sustainability, and revenue generation (Neupane and Thapa, 2001; Jose, 2009).

In the context of non-peatland areas, Yuwariah (2016) asserts that agroforestry exhibits greater productivity and a more equitable distribution of yields throughout the year when compared to monoculture practises. Additionally, the adoption of agroforestry mitigates the risk of crop failure by diversifying plant species, thereby reducing vulnerability. Furthermore, the potential losses resulting from market price fluctuations for a single crop can be compensated by the sale of alternative crops within the agroforestry system. Multiple studies have demonstrated that agroforestry not only plays a crucial role in promoting environmental sustainability and biodiversity (Paembonan et al., 2018) but also offers potential solutions to poverty-related challenges (Namwata et al., 2012; Moriarty et al., 2014; Suharti, 2015; Kholifah et al., 2017).

This article examines the environmental, biophysical, and socio-economic dimensions of agroforestry farming as a potential strategy for rehabilitating degraded tropical peatlands. This study pertains to the practise of agroforestry techniques on peatlands within communities, as well as the underlying factors that drive community engagement in such practises. Do agroforestry practises yield economic advantages and enhance peatland ecosystems, therefore helping to the protection and rehabilitation of ecosystems? Does the implementation of the agroforestry system on peatland lead to enhancements in soil health, including chemical, biological, and climatological dimensions? The primary emphasis of our study is centred around the agroforestry community stakeholders, with the objective of identifying common experiences in carrying out agroforestry practises on peatlands. Additionally, our research aims to address topics such as peatland conservation and rehabilitation, as well as issues related to the implementation of agroforestry methods.

Tropical Peatlands: Characteristics and Land Use

Tropical peatlands are characterised by a consistent and abundant rainfall pattern over the majority of the year, along with elevated levels of humidity. The presence of lowland topography and poor drainage, when combined, has led to the consistent saturation of soil, limited oxygen availability, and decreased rates of plant litter decomposition (Page et al., 2022). Peat accumulates in areas where the input of organic material to the peat surface exceeds the output resulting from the decomposition over a long period of time.

The rapid decomposition of plant litter is facilitated by climatic conditions characterised by consistent moisture and high temperatures. However, the accumulation of peat deposits is attributed to several factors, including the high rates of litter production, the resistant nature of the litter, waterlogging, and the presence of high acidity (pH < 4.5) and limited nutrient availability. These factors collectively impose significant constraints on the soil decomposer communities.

Tropical peats typically exhibit an organic matter concentration above 60% (by dry weight), leading to a substantial carbon content ranging from 45% to 55% (by dry weight of organic matter). Additionally, these peats possess a notable ability to retain water. Tropical peatlands exhibit a prevalence of woody detritus, whereas corresponding areas in temperate and boreal regions primarily consist of moss and herbaceous plant debris.

The peatlands of Southeast Asia are primarily characterised by the presence of large hardwood species (Page et al., 2006). Similarly, in Africa and the Americas, there exist substantial communities of palms alongside hardwood trees, as well as open vegetation that is predominantly composed of grasses, reeds, and sedges (Dargie et al., 2017; Draper et al., 2018). Tropical peatlands are predominantly ombrotrophic ecosystems characterised by their acidic nature, with pH levels ranging from 3.0 to 4.5. These peatlands also exhibit limited nutrient availability, as shown by studies conducted by Weiss et al. (2002) and Page et al. (2011).

Furthermore, the nutrient levels in these peatlands are influenced by the extent of river flood regimes, as indicated by research conducted by Lähteenoja and Page (2011) and Roucoux et al. (2013). The nutrient concentrations found on the surface of peat in forested peatlands in Southeast Asia typically fall between the range of 100-2,400 μg/g for calcium (Ca) and 300-700 μg/g for magnesium (Mg) (Weiss et al., 2002; Lampela et al., 2014). According to Lähteenoja and Page (2011), the concentrations of calcium (Ca) and magnesium (Mg) in the surface peat of minerotrophic Amazonian peatlands that are impacted by rivers can surpass 10,000 μg/g and 2,700 μg/g, respectively.

Peat and its hydrological characteristics

Peatlands, similar to other wetlands, typically exhibit a groundwater table that is either at or slightly below the soil surface in their natural state (Wosten et al., 2006). Nevertheless, drainage is implemented for several objectives, mostly in the context of agriculture, to facilitate the drying out of land, rendering it conducive for the cultivation of agricultural crops. The conversion of land use, particularly when changing from peat forest to agricultural land, requires the implementation of drainage systems. This is due to the fact that peat forests naturally experience inundation, but most cultivated plants are adapted to dry-land conditions.

Peatlands have been artificially drained for centuries, including in tropical areas, and drainage, along with deforestation, is the biggest human disturbance to the tropical peatland ecosystem. The primary objective of drainage in peatlands, in addition to reducing the groundwater level, is to eliminate a portion of the organic acids that have the potential to harm the root system of plants. The process of drainage typically results in an elevation of peat bulk density as a result of the combined impacts of heightened peat oxidation (Waddington and Price, 2000; Anshari et al., 2010) and subsidence (Hooijer et al., 2012). The increasing bulk densities have been found to have a negative impact on hydraulic conductivity, resulting in a reduction in lateral subsurface water losses (Whittington and Price, 2006). Additionally, this phenomenon can potentially contribute to an increase in surface or near-surface runoff. One further consequence of drainage is the observed elevation in peat pH and total nitrogen levels, resulting in a notable reduction in the C/N ratio at oil palm and agricultural areas. However, the water content and total organic carbon remain generally stable, as reported by Anshari et al. (2010).

Alterations in forest cover primarily involve the process of drainage, which subsequently produces a decline in the groundwater level (Wösten et al., 2006; Sumarga et al., 2016; Uda et al., 2017; Cooper et al., 2019). This, in turn, affects various attributes of peat soil, such as decomposition processes and compaction, ultimately leading to a reduction (Sherwood et al., 2013; Evans et al., 2019) that is correlated with an elevation in bulk density (Sinclair et al., 2020). The hydrological characteristics of peatlands are influenced by bulk density, which plays a crucial role in determining the soil's water storage capacity (Rydin et al., 2013). Furthermore, peat hydraulic conductivity could be influenced by its bulk density or the degree of decomposition (Wong et al., 2009; Kurnianto et al., 2019), resulting in reduced water retention and a higher probability of flooding (Hooijer et al., 2012; Könönen et al., 2015; Evers et al., 2016; Evans et al., 2019). Alterations from forests to alternative land uses that result in decreased land coverage also have an impact on hydrological processes by modifying the runoff patterns. According to Holden et al. (2006), the drained upland peat in the UK exhibited significantly higher levels of macropore flow, soil pipe density, and pipe flow compared to the intact peat.

Besides climatic and anthropogenic factors, soil properties are expected to have an impact on peat hydrology. Specifically, humic and sapric peat are prone to drying at a faster rate and require a longer duration, making them more vulnerable to peat fires (Taufik et al., 2019). Consequently, the capacity of peat to retain water during the rainy season and gradually release it during the dry season is likely to diminish. Jaenicke et al. (2010) emphasised the significance of elevating the water level as a crucial component of peatland restoration efforts. However, it should be noted that complete mitigation of degradation is challenging due to the inherent difficulties of achieving optimal water levels near the wetland surface. Furthermore, it is crucial to acknowledge the significance of high biomass production vegetation in mitigating heterotrophic respiration, in addition to its contribution to the increasing of the water table (Jauhiainen et al., 2008).

Tropical peatland carbon stock

According to the findings of Page et al. (2011), it has been determined that peatlands located in Southeast Asia contain the highest carbon density among all tropical peatlands, with an average of 2,775 metric tonnes of carbon per hectare. Based on the results reported by Page et al. (2011) and Dargie et al. (2017), the estimated global tropical peat carbon (C) stock is approximately 105 gigatonnes (Gt C), with a range of 87 to 136 Gt C. Among this total, Southeast Asian peatlands contribute approximately 69 Gt C, with a range of 66 to 70 Gt C. African peatlands, on the other hand, contribute roughly 34 Gt C, with a range of 9 to 52 Gt C. Poulter et al. (2021), stated that the carbon density of vegetation in peatlands in Southeast Asia ranged from 27 to 275 t C/ha before anthropogenic disturbance. While the majority of carbon storage takes place below the surface, the presence of carbon in plants serves a significant purpose in supplying organic material for the creation of peat and sustaining ecosystem functionality, hence safeguarding subsurface carbon reservoirs (Sjögersten et al., 2014).

Southeast Asia's total greenhouse gas (GHG) emissions from managed land covers are predominantly attributed to carbon losses, reaching approximately 78% of the overall emissions (146 Mt C/year) (Miettinen et al., 2017; Cooper et al., 2020). The process of land conversion, sometimes accompanied by drainage, has been shown to cause a decline in the groundwater table, resulting in the deterioration of peatlands. Additionally, this process has been found to significantly increase the release of CO_2 into the atmosphere. According to Wright et al. (2013), in peatlands that have been converted and degraded, the presence of water saturation in dry peat during rainfall inundation can promote increased release of CO_2 from the peat through the stimulation of microbial respiration. Furthermore, the occurrence of peatland fires has assumed significant importance due to the area of land affected, the intensity of the burning, and the magnitude of greenhouse and trace gas emissions, aerosols, and particulate matter released into the atmosphere (Page et al., 2002; Huijnen et al., 2016; Stockwell et al., 2016). The combustion of peatland is primarily characterised by smouldering fires (Hu et al., 2018), which exhibit prolonged durations and can penetrate various depths below the peat surface, ranging from a few centimetres to several tens of centimetres, depending upon the humidity conditions (Page et al., 2002; Ballhorn et al., 2009; Page et al., 2009; Simpson et al., 2016). The adverse effects of air pollution caused by peat fires have significant implications for both livelihoods and the economy across extensive geographical areas, as the smoke generated can disperse over distances reaching tens or even hundreds of kilometres (Marlier et al., 2015). Meteorological drought, characterised by reduced precipitation, leads to hydrological drought, which in turn causes a deficiency in soil moisture and desiccation of the peatland litter. This desiccated litter becomes highly susceptible to combustion and acts as a fuel layer, capable of igniting the underlying peat layer (Taufik et al., 2017). Emissions exhibit an upward trend during years characterised by severe fire incidents. To illustrate, various estimates for the year 2015 indicate emissions ranging from 227 Tg C (Huijnen et al., 2016) to 510 Tg C (Yin et al., 2016). In addition to the production of greenhouse gases, peat fires have significant local environmental consequences, such as alterations in peat chemistry and microbiology.

Land use change and its impacts

Significant alterations in land use have taken place in the peatlands of Southeast Asia. Peatland covered by native forests in peninsular Malaysia, Kalimantan, and Sumatra experienced a decline from 119,000 km^2 in 1990 to 46,000 km^2 in 2015 (Miettinen and Liew, 2016). Logging impacted the majority of this forest, with intact forest occupying less than 10,000 km^2. Conversely, agricultural area increased from 17,000 km^2 to 78,000 km^2. Globally, the magnitude of this transformation and the swift depletion of indigenous peat wetland ecosystems are beyond comparison (Page et al., 2022). Peatlands in Indonesia and Malaysia are converted primarily by industrial plantation companies that manufacture palm oil (39 percent) and pulp and paper (11 to 26 percent) (Miettinen and Liew, 2016; Wijedasa et al., 2018). Small-scale cultivators account for 43-44 percent of peatland conversion. Moreover, substantial regions of exposed peatlands, which are susceptible to fire, remain dormant and devoid of any existing economic advantages (Miettinen and Liew, 2016; Page and Hooijer, 2016). The impacts of this land use modification encompass the hydrological characteristics of peat. Tropical peatlands exhibit elevated hydraulic conductivity when undrained

(Baird et al., 2017). However, peatlands impacted by tidal flood waters have been documented to have lower conductivity (Kelly et al., 2014). When these elements are combined, they produce a low hydraulic gradient, a high water storage capacity at the peat surface, and gradual radial water loss towards the perimeter of the dome. The principal mechanism by which water storage is influenced is by evapotranspiration from vegetation and the peat surface. After peatlands have been drained and deforested, subsurface flow becomes significantly more significant. As a result of a substantial reduction in evapotranspiration losses, deforestation increases discharge and water table fluctuations, according to Dommain (2010) and Baird et al. (2017). As a consequence of this phenomenon, agriculturally converted peatlands may experience water surpluses during the rainy season, potentially leading to flooding, while water scarcity during the dry season heightens the risk of fire and water shortages (Mezbahuddin et al., 2015; Baird et al., 2017).

Peatland conversion exacerbates the hydrological consequences through the induction of additional drainage-induced modifications, specifically peat subsidence, which augments the vulnerability to flooding. Physical and biological processes contribute to subsidence, including peat compaction subsequent to water table reduction and peat oxidation above water table, which promotes microbial decomposition and carbon dioxide release into the atmosphere (Hooijer et al., 2012; Laurén et al., 2021). The configuration of the peat dome undergoes temporal variation due to drainage subsidence, an effect that concurrently diminishes the carbon storage capacity (Cobb et al., 2020). An additional concern associated with peat subsidence is the potential eventual exposure to aerobic conditions of the underlying infertile sand or previously saturated marine clays rich in pyrite (Haraguchi, 2016; Page et al., 2022). Sulfuric acid is created through the oxidation of pyrite (iron sulphide), which severely acidifies drainage and peat water. Metals, including Al, Fe, Mn, and As, are mobilised into the solution when the pH is lowered (to pH 2). This drainage water may have harmful impacts on crop output and be poisonous to plants, aquatic life, and humans.

Agroforestry for Peatlands Conservation and Rehabilitation

Agroforestry practices in peatlands

Indonesia has had an established agroforestry system ever since the transition from hunting and gathering to farming as the primary means of sustaining human livelihoods (Penot, 2004; Penot et al., 2017). Agroforestry is integrated into a shifting cultivation system in Central Kalimantan, Indonesia, whereby communities plant trees on land that is subsequently abandoned, thereby ensuring that the land continues to yield advantages for both individuals and communities. Rubber (*Hevea brasiliensis*), durian (*Durio zibethinus*), rambutan (*Nephelium lappaceum*), and langsat (*Lansium domesticum*) are frequently cultivated species. Communities also traditionally plant trees as fences and to mark the boundaries of their lands. Shifting cultivation is predominantly implemented by the Dayak community in Kalimantan, specifically in wetlands situated on shallow peat or riverbanks (Nopembereni et al., 2018; Silvianingsih et al., 2020). Currently, the inhabitants of riverside villages who formerly laboured on embankments have migrated progressively to the side of the major road and initiated agricultural endeavours in the vicinity of the recently established community, which is predominantly situated on substantial deep peat.

When it comes to soil fertility, farmers who cultivate land with a peat layer greater than three meters-which is considered marginal are generally required to apply substantial amounts of fertiliser inputs to support agricultural development. Farmers are particularly aware of the fact that plant growth will be hampered in the absence of fertilisers, especially manure and NPK fertilisers, at the onset of land clearance. This is due to the fact that peat soil, being ombrotrophic (rain-fed), possesses extremely low fertility and high acidity, both of which are detrimental to plant development (Alwi and Hairani, 2007; Harun et al., 2020). Moreover, base saturation is extremely low despite the extremely high cation exchange capacity (CEC) (Aryanti, et al., 2016; Harun et al., 2020). The utilisation of fertiliser on peat soils elicits contrasting outcomes: while it may promote plant development, it accelerates the decomposition process, consequently leading to a decrease in peat resources and greenhouse gas emissions (Husnain et al., 2017; Khasanah and van Noordwijk, 2019; Anshari et al., 2021).

Farmers' agroforestry practises exhibit variation contingent upon their level of knowledge and expertise. Migrant peatland farmers from Central Kalimantan who were previously accustomed to cultivating on fertile mineral soils and have Javanese backgrounds reported notable disparities in success rates when comparing agroforestry systems that rely on indigenous tree species to those that employ alternative species considered suitable for agroforestry and agro-food production in the Indonesian climate. The farmers were compelled to modify their agricultural selections. For instance, they initially cultivated sengon (*Falcataria moluccana*), a species of a tree commonly utilised in agroforestry in Java, but it did not thrive in the peat soils of Central Kalimantan. Numerous of these Javanese migrant farmers combine commodities and trees through the practise of intercropping. Through the management of trees in this system, sufficient sunlight is supplied to sustain vegetable harvests that are interplanted among them. Conversely, traditional indigenous agricultural communities exclusively combine species of woody plants. For example, jelutung (*Dyera* sp.) or rubber

(*Hevea braziliensis*) is planted with rambutan (*Nephelium lappaceum*), while alternating rows of trees of the same species such as belangiran (*Shorea belangeran*), pulai (*Alstonia* spp.), tumih (*Combretocarpus rotundatus* (Miq.)), mulberry (*Morus alba*), and gemor (*Alseodaphne* sp.) are grown on different fields. In contrast to intercropping with trees, vegetables are cultivated individually in a monoculture cropping system. The primary justification for not intercropping vegetable crops with trees is that, in order to replicate the spacing of trees in the forest and to suit the conditions of the land, trees are planted closer together than on Javanese farms. In accordance with the peat depth, farmers have devised various types of agroforestry, according to Rotinsulu et al. (2022). The majority of them cultivate endemic trees, such as rubber, gelam, and gerunggang (*Cratoxylum arborescens*), in shallow peatlands as intercrops with vegetables and fruit; on medium peatlands, rubber, annual crops, and fruits are produced; and on deep peatlands, fruit, and rubber can be combined as intercrops.

Farmers generally have an understanding and knowledge regarding the application of organic and inorganic fertilisers to peatlands in order to increase their yield. All agree, however, that the most important criterion for selecting trees that survive without extensive fertilisation and maintenance is plant suitability. While farmers initially apply a restricted quantity and variety of fertiliser to trees during the planting process, they adhere to the principle that these trees will subsequently be supplied with a fraction of the fertiliser utilised for intercrops, particularly those cultivated seasonally between trees.

The components of agroforestry in peatland regions exhibit a strong correlation with the topographical features of the terrain and the peat depth. Applegate et al. (2022) and Harun et al. (2022) both state that the pattern of agroforestry close to the river embankment is different from that further onto the deep peat dome. In non-peat areas, which are usually found on river embankments, agrosilvofishery and agrofishery are often practiced. Farmers plant several seasonal plants and tree species around their fish ponds in order in order to fortify the pond embankments; typical timber species are *Shorea balangeran*, sengon (*Falcataria moluccana*), and *Nauclea orientalis* (bengkel), combined with cash crops. Several food crops are suitable for planting on the bunds, including bananas, pineapples, rambutan, soursop, guava, mango, red chillies, katuk (*Sauropus androgynus*), and cassava.

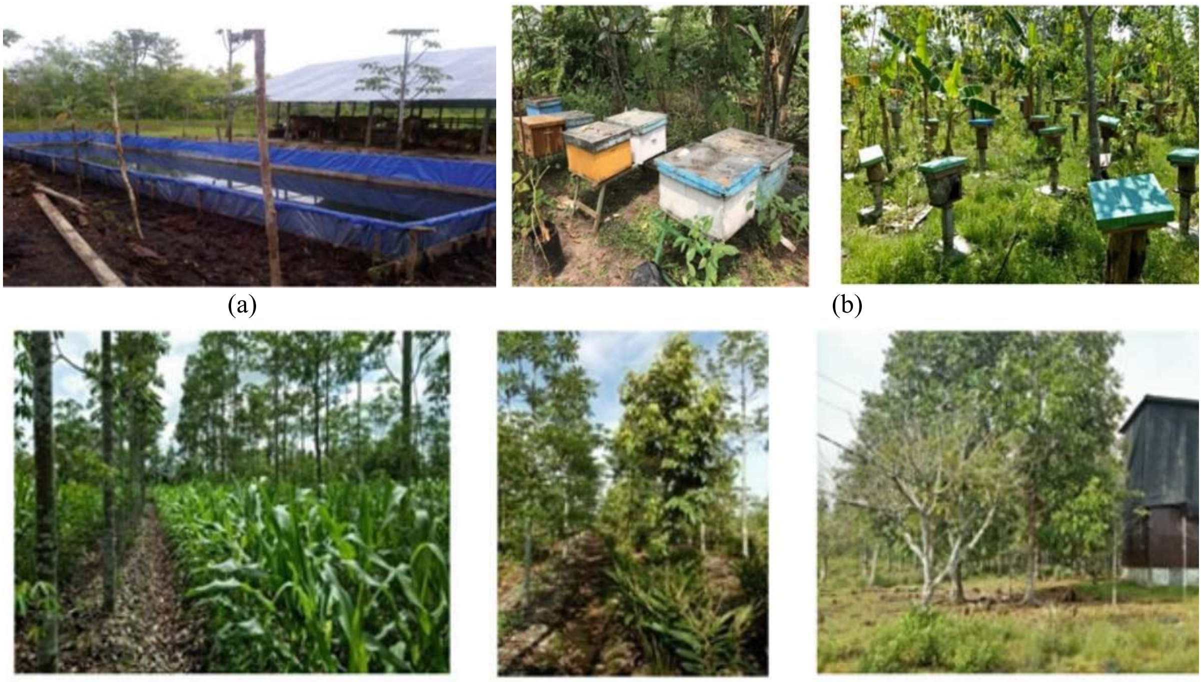
Frequent flooding is identified as the primary constraint for fish farming along river embankments (Harun et al., 2022). However, by expanding livelihood opportunities that combine agroforestry and fish farming in shallow peat areas and non-peat soils, it may be possible to attract community support for the preservation and rehabilitation of forests in deeper peat regions (Applegate et al., 2022). Regarding agroforestry in deeper peat soils (backswamp), Harun et al. (2022) discovered that local communities in Central Kalimantan had devised a number of patterns.

Initially, an agrosilvicultural system comprising four cultivation patterns is described: (a) rice fields bordered by banana trees and timber trees; (b) vegetables grown on the paddy field bunds; and (c) fruit trees, vegetables, and *Paraserianthes falcataria*. (d) alley cropping consists of vegetable plants positioned between the two lanes of trees and deciduous trees spaced at 5x4 m, 6x7 m, and 5x3 m, respectively. *P. falcataria*, *Aquilaria malaccensis, Hevea brasiliensis, Dyera polyphylla*, and *Elaeis guinensis* were among the woody tree species that were incorporated into the soil alongside annual crops including maize, mustard greens, eggplant, kangkung, spinach, spring onions, and chillies, (e) as perimeter fencing, *D. polyphylla* trees were planted, and in the core region, vegetable crops including corn, chilli peppers, mustard greens, kangkung, and eggplant, were planted, (f) the livestock area was partitioned into two sections: one was allocated for annual crops, and the other was planted with woody trees, including *D. polyphylla, Combretocarpus rotundatus*, and *Acacia mangium*. In addition to seasonal crops (such as dragon fruit, corn, chilli, taro, and mustard greens), the latter included pineapple and fruit trees (including rambutan (*Nephelium lappaceum*).

Harun et al. (2022) have identified a second system known as agropasturesilvofishery. This system integrates the cultivation of agricultural crops, livestock rearing, fish cultivation in tarpaulin ponds, and the cultivation of tree crops (specifically, *D. polyphylla*) inside a single land unit. The agricultural practise employed involves the implementation of the alley planting technique, complemented by a split-plot arrangement strategy for land organisation. A plastic pond, measuring 10 m in length, 3 m in width, and 1.5 m in depth, is situated amidst two rows of trees, as depicted in Figure 1a.

The fish species that are cultivated include *Clarias gariepinus*, often known as catfish, and papuyu (*Anabas testudneus*). *D. polyphylla* is commonly cultivated alongside several vegetable crops, including maize (*Zea mays*), chillies (*Capsicum* spp.), and mustard greens (*Brassica juncea*). In addition, farmers engage in the rearing of livestock within the same area. Fodder grass has been cultivated along the perimeter of the land. Honey beekeeping is practised by several farmers in Central Kalimantan (Figure 1b). In addition to its economic significance, beekeeping serves as a valuable practise for facilitating pollination and functioning as a biocontrol mechanism against ants, flies, and other pests that may pose a threat to floral and fruit crops. The agrosilvopasture system, as described by Harun et al. (2022), is the third system under consideration. This combines agricultural crops, trees, and fodder (Figure 1c). In this agricultural practise, annual crops are strategically cultivated in the interstitial spaces between rows of

D. polyphylla, with a specific spacing arrangement of 5x5 m. Additionally, fodder grasses suitable for cattle and goats are intentionally planted along the periphery of the cultivated field. As stated by Applegate et al. (2022), the cultivation of cash crops and honey production, along with trees such as sengon (*Falcataria moluccana*) and cash crops on shallow peat bunds or gelam (*Melaleuca leucadendra*), can create a buffer zone around deep peat areas (i.e., 50 cm to 3 m). Additionally, it is possible for agroforestry systems to be structured as follows: coffee (*Coffea liberica*)-based, fish ponds and productive (timber, fruit) trees, or sago (*Metroxylon sagu*)-based. An approach to agroforestry that utilises endemic peat swamp forest tree species in conjunction with gelam (*Melaleuca leucadendra*) and honey production has been developed for deep peat (>3 m depth) (Applegate et al., 2022).


(a) (b)

(c)

Figure 1. Several agroforestry model on peatland.

Additionally, Harun et al. (2022) reported that numerous types of agroforestry have been established on deep peat domes. Vegetables are planted alongside trees, including *D. polyphylla*, in the first system. This system's segmentation pattern can be classified into three categories: (1) Annual crops, such as durian, rambutan, papaya, soursop, orange, and pineapple, are cultivated in alleyways between trees of *D. polyphylla* or *A. malaccensis*. Additionally, the following annual crops are planted in the same areas: maize, cassava, chilli, eggplant, mustard greens, and *Ceiba pentandra*, which provides shade. (2) The land is divided into two sections, with one section designated for the cultivation of seasonal crops and the other section either designated for tree planting or allowed to naturally regenerate into forest. *Combretocarpus rotundatus* and *D. polyphylla* are incorporated into the planting of fruit trees and annual crops. (3) Gaharu wood (*Aquilaria malaccensis*) and *D. polyphylla* are among the woody trees that encircle the agricultural cultivation area.

The second system is an agrosilvopastoral system, which integrates animal feed, vegetables, and *D. polyphylla*. Perennial crops are planted 5x5 m apart between fields of *D. polyphylla* trees, with fodder grasses lining the sides. Fruits and tubers, including taro, cassava, and rambutan, are also cultivated. Furthermore, the farmers maintain cows as well as goats. In the third system, known as silvopasture, the land that was planted with *D. polyphylla* is converted into grazing land for goats and ducks. This model has the benefit of providing *D. polyphylla* with a weed-free environment, manure fertiliser, and a conducive environment for swallows. After undergoing fermentation, swallow droppings can be utilised as an organic soil ameliorant fertiliser. Tree species (including *D. polyphylla* and *A. malaccensis*), fruit plants (including rambutan and pineapple), seasonal crops (including maize, cassava, chilli, eggplant, and mustard greens), and livestock (including chickens, ducks, swallows, cows, and goats) are the primary constituent crop species in silvopasture.

Additionally, the agrosilvopastoral system may involve the upkeep of colony boxes (hives) housing honey bees (*Apis mellifera*), which are positioned within the yard where various nectar and pollen sources, such as ornamental plants, maize, spinach, and dragon fruit, are cultivated. Within this agrosilvofishery system, the land is utilised for fish farming, tree crops, and vegetable cultivation. Pond effluent has the potential to be utilised as liquid organic fertiliser, whereas processed agricultural waste can be converted into fish feed. One potential agricultural configuration involves the cultivation of woody plants such as coconut, breadfruit, agarwood, *Leucaena leucocephala* and *Pometia pinnata* along the periphery, while a fish pond measuring 2-3 m in width, 10-15 m in length, and 1.5-2 m in depth are positioned in the centre of the land. The periphery of the fish ponds contains carp and papuyu (*Anabas testudineus*) fish, vegetables cultivated alongside. Additionally, perennial crops such as agarwood, hybrid coconut, rambutan, and soursop are planted along the land's edge, with a 1.5-m-wide, 4-m-long plastic pond positioned in the centre to facilitate catfish farming.

Motivation of agroforestry farmers

Motivation is essential in the process of adopting agroforestry. Nevertheless, motivating small-scale farmers proves to be an enormous challenge due to their constrained land resources, expertise, and understanding. As per the author's personal experience, individual motivational courage can differ considerably. One can assess the comparative potency of the motivations that govern an individual in a broad sense by considering the following criteria: (1) a strong will to do something, (2) the duration of time devoted to the activity, (3) a readiness to set aside other responsibilities or obligations, (4) a readiness to pay for costs associated with the action, and (5) unwavering determination in completing the task. To increase their income, farmers will diligently labour and devote the majority of their time to farming.

The acceptance or rejection of available technology may also be influenced by farmer motivation; farmers who are motivated by external influences are more likely to give significant consideration to the technology that is presented to them (Idawati et al., 2018). Agroforestry farmers operating on peatlands in Central Kalimantan were primarily motivated by economic considerations. Farmers who had successfully implemented agroforestry exhibited a determined commitment to its maintenance and a sufficient amount of time devoted to agroforestry-related efforts, similar to how they would manage non-agroforestry crops.

In addition to being receptive to initial guidance from government agencies, farmers were also eager to acquire knowledge through the implementation of agroforestry patterns. Certain farmers successfully expanded their agricultural efforts through the cultivation of kelulut (stingless honey bees) and the rearing of livestock (goats, cows, for instance). Meanwhile, agroforestry farmers aspire to generate revenue from wood, latex, and even non-extractive sources such as tourism activities. Conversely, their immediate source of revenue is generated through intercropping, typically involving the cultivation of short-lived plants in response to market demand. Agroforestry farmers endeavour to optimise the productivity of their intercrops through the establishment of greater interrow spacing between trees, which ensures that the intercrops continue to receive optimum sunlight for growth (Jaya et al., 2022).

In contrast, conventional farmers frequently cite decreased yields of key agricultural crops and uncertainty regarding the system's efficacy as the primary reasons for not adopting agroforestry practises. Another study (Sagastuy and Krause, 2019) identified four primary motivations for which farmers employ agroforestry cultivation patterns: to increase income, to diversify production systems, to improve land quality and productivity, and to increase self-sufficiency.

The main driving force behind the implementation of agroforestry systems on peatlands in Central Kalimantan is the endorsement and assistance from the government, coupled with the economic rationale of establishing a sustainable investment opportunity. Farmers have the belief that there will be a rise in the need for wood in the forthcoming years. Consequently, certain farmers consider standing timber, such as jelutung and rubber, as a form of savings that may be utilised during periods of economic adversity. Farmers also hold the belief that fertilisers supplied to intercrops planted between rows of trees are absorbed by the trees. However, it is worth noting that the farmers typically only fertilise the trees during the initial planting phase.

The rationales for farmers' decision to plant trees can be classified into the subsequent categories: (1) The implementation or inception of the initiative can be attributed to the efforts of Forestry Research and Development, exemplified by the provision of *Dyera* sp. seeds through a forestry program, (2) This endeavour can be regarded as a substantial and enduring commitment aimed at benefiting future generations, (3) The cultivation of this crop exhibits compatibility with peatland environments and demonstrates a low mortality rate, (4) The act of cultivating this crop serves as a means of asserting land ownership, (5) Despite the relatively modest yield, the cultivation of this crop serves as a means of augmenting family income, as highlighted by Jaya et al. (2022).

When considering the selection of intercrops, several key factors come into consideration. Firstly, it is crucial to respond to market demand, ensuring that the chosen species align with current market needs. Secondly, the suitability and growth potential of species on peatland under shade trees should be carefully evaluated. This assessment is essential to determine the compatibility of intercrops with specific environmental conditions. Additionally, the potential for generating substantial income in the short term is an important consideration. Lastly, intercrops should also serve as a reliable food reserve, further enhancing their value in the overall agricultural system. According to the farmers, many crops, such as cassava, have the potential to act as food reserves in the case of scarcity. Additional justifications provided by farmers include their tendency to adhere to or replicate the crop selections made by their fellow farmers, as well as the availability of plant seeds.

Values of peat swamp forest ecosystems

Important livelihood values are associated with peat ecosystems for all agroforestry farmers, although in Central Kalimantan, these values vary between indigenous and Javanese migrant farmers. Javanese farmers who exclusively engage in agroforestry farming on peatlands may potentially generate a livelihood through this endeavour. Conversely, non-Javanese people, particularly the Dayak, who have a deep-rooted tradition of hunting and gathering, depend on the peatlands for fish and vegetable protein in addition to cultivation as a means of subsistence. As vegetables, this community gathers kelakai (*Stenochlaena palustris*, edible ferns), young pineapple (*Ananas comosus*), and crinum lily (*Crinum asiaticum*), while fish is caught for side dishes and provides protein. Goats also utilise the peatlands as a feed source, particularly the uyah-uyah plant (*Stemonurus secundiflorus*). Thus, the peat swamp forest and its associated aquatic ecosystems provide a vital means of livelihood.

Widespread deforestation has occurred in Central Kalimantan due to land conversion, timber exploitation, and wildfires, resulting in the destruction of former peat swamp forests. Although there has been some success with revegetation using native trees, the majority of farmers have chosen to plant non-native rubber trees in their household environments. Additionally, rubber cultivation takes place in riverside villages characterised by less intensive management demands due to the alluvial soils' fertility, in contrast to the less fertile peat soils. Certain agricultural farmers have established local nurseries to support indigenous peat swamp forest species. These nurseries provide other farmers with *Shorea belangeran* seedlings as well as *Alstonia pneumatophora* and meranti (*Shorea* spp.) trees. Additionally, they plant the tree seedlings they cultivate on their own land in addition to selling them. Typically established for commercial purposes in collaboration with government agencies that require tree seedlings for land rehabilitation efforts, nurseries are situated in close proximity to homeowners. Nursery operations are performed by members of the community, including non-agroforestry actors. During the flowering season, individuals search for seeds in the natural forest surrounding the village or obtain jelutung trees from farmers who own jelutung plantations (Jaya et al., 2022). In their study area of Central Kalimantan, Jaya et al. (2022) discovered that every agroforestry farmer acknowledged the significance of peatland drainage for crop cultivation and had constructed and utilised drainage canals. A single farmer documented encountering challenges with crop productivity due to the land's relatively low elevation, which frequently resulted in flooding, particularly during the rainy season. Conversely, these farmers cultivate annual crops in polybags. Certain communities located in the ex-PLG (formerly Mega Rice Project area) have resorted to repurposing abandoned irrigation canals as a means to generate supplementary revenue. These canals are covered with purun plants (*Lepironia articulata*), which are processed into environmentally friendly drinking straws. In addition, all peatland agroforestry farmers valued the aesthetic, shady, and tranquillising effects that trees impart as part of an agroforestry system. The environment is enhanced by comfortable temperatures and fresh air. Others had ecotourism in mind, while some farmers utilise the planted trees as a source of nectar and pollen to sustain kelulut (stingless bee) cultivation.

Low levels of income from this form of agroforestry farming and the lack of initial government support were, according to Jaya et al. (2022), suboptimal aspects of agroforestry management from the farmer's perspective. Nevertheless, according to the experience of a few farmers, the government's initial seed and fertiliser assistance actually encourages community involvement in agroforestry. Therefore, institutions that provide support are crucial for agricultural activities. The perspectives of farmers regarding the role and accessibility of institutions that assist in agroforestry management indicate that rural supporting institutions in the study area are inadequate to ensure sustainable agroforestry management.

Income from agroforestry in peatlands

Sustainable farming livelihoods, especially from agroforestry, depend on revenue. Peatlands benefit from agroforestry cultivation. Benefit and Cost Ratio (BCR) calculations for farmers on peatland in Central Kalimantan vary from 0.61-10.32. All but one farmer had a BCR greater than 1 (Jaya et al., 2022). Farmer households earn USD 2,277-9,867 per year, averaging USD 5,022, or USD 190-822 per month, averaging USD 418. Farmers obtain income from tree nurseries, horticulture farming, crops, goats, poultry, bees, fisheries, and other non-agricultural activities (retirement pension, teaching, trade). Farmers derive varying proportions of their income, ranging from 4% to 100%, from activities related to agriculture, animal husbandry, and fisheries. According to the findings, intercropping farmers derive a significant proportion of their yearly income, approximately 77%, from engaging in intensive agricultural practises within the interstitial spaces between trees. In contrast, less intensive farming methods yield a comparatively lower revenue of approximately 47%. The revenue generated by farmers through selling jelutung seeds or seedlings can range from 4% to 42% of their total income derived from planting trees. It is widely held among farmers that the practise of planting trees constitutes a strategic and enduring investment that is expected to yield economic benefits for the household over an extended period of time. According to a study conducted by Jaya et al. (2022), farmers who cultivate intercrops and sell jelutung tree products have the potential to generate an annual income of USD 5,568. In contrast, farmers involved in less intensive land management practises earn approximately USD 4,556 per year.

Intercropping yields considerable benefits, enabling *Dyera* sp. development in an agroforestry system more economically viable than monoculture. The BCR of agroforestry systems ranges from 0.61 to 10.32, indicating that intercropping advantages vary. Intercropping business activities like the cost of the production input components (fertilisers, seeds, etc.) and commodity selling prices affect the BCR. Even if the plants being grown are the same, there can be differences in the production inputs and the selling price, which alter the BCR; these prices are mostly set by middlemen. Fertilisers, herbicides, and labour are important agricultural inputs, with fertilisers accounting for the highest cost. Family labour and effective fertilisation can improve BCR in intercropping, as can the choice of crop. Agroforestry with pineapple, celery, spinach, and kangkung intercrops yields the highest BCR (10.32). Farmers particularly gain from planting pineapples that require little fertiliser, low upkeep, and thrive well on peatlands. Tree crops, tomatoes, maize, and animals yield the lowest profit (0.61). BCR is affected by the high investment associated with cattle, which reduces profit. BCR also depends on the selling prices of commodities.

Traders set the prices and sell agroforestry goods. Agroforestry actors share produce with collectors; therefore, they get a cheap price when the same commodity is abundant. According to data from the Sustainpeat Project, agroforestry patterns exhibit a greater BCR compared to monoculture on peatlands. This is attributed to the fact that certain agroforestry farmers continue to engage in the sale of *Dyera* sp. fruit. The BCR values recorded range between 2.12 and 10.08. Harun (2011) stated that *Dyera* sp. and the rubber agroforestry system exhibited a net present value (NPV) of USD 4816.36, a BCR of 8.68, and an internal rate of return (IRR) of 29. While in their study, Budiningsih and Effendi (2013) conducted an analysis to determine the NPV, BCR, and IRR for agroforestry systems were USD 638.10, 5.35, and 24.1, On the basis of average monthly income, the Central Bureau of Statistics classifies Indonesian incomes into four divisions: very high (exceeding USD 241.51), high (USD 172.51 to USD 241.51), medium (USD 103.50 to USD 172.51), and low (less than USD 103.50). Farmers, and the other two are high-income earners. On peatlands, agroforestry farmers can generally generate significant incomes. Their monthly mean income of USD 376.67 exceeds the minimal wage requirements of the Palangka Raya and Pulang Pisau Districts. The generated revenue exceeds the mean monthly income of USD 308.26 that was assessed by Surati et al. (2019) from a combination of land-based and non-land-based enterprises operating on peatlands. The authors additionally proposed the implementation of an agroforestry system adapted to peatlands. Despite having a substantial income, some tree farmers sell fruits/seeds of *Dyera* sp., which accounts for 10.2% of their total revenue. Agroforestry farmers express apprehension regarding the constrained markets for fruit, seeds, and *Dyera* sp. latex. Consequently, tree species are selected according to their biophysical suitability, economic value, and market availability.

Yanarita et al. (2020), in their research on peatlands in Central Kalimantan, discovered USD 82.92/ha/year (7.63%) from *Metroxylon sago*. *Metroxylon sago*'s contribution to agroforestry income was fourth, after rubber (42.29%), durian (17.09%), and paddy (110.14%). *Metroxylon sago* benefits from its quick harvest and the value of the palm leaves, with leaves being harvested 3-4 times a year. In Pilang Village, community sago-based agroforestry management was also practicable for development. The BCR value of agroforestry management based on *Metroxylon sago* plants is >1 or in the range of 4.33-7.48, indicating that the management pattern is feasible. Agroforestry land earns 23.47% from *Metroxylon sago*.

Silvianingsih et al. (2020) stated that fruit and rubber-based agroforestry is the primary source of income for farmers in Kalimantan, even though the farm price of rubber has fluctuated over the past few decades, from USD 1.13/kg in 2010 to USD 0.53/kg in 2018. At standard stand density, 300 trees may yield 15 kg of rubber every tapping day. The sales of rubber, based on pricing data from 2018, amount to a weekly revenue of USD 24,000, derived from a three-day tapping period. The wet season reduces rubber growers' agroforestry income since trees are only tapped once a week. In response to the decline in rubber prices, some farmers have initiated the cultivation of sengon (*Paraserianthes falcataria*) as an alternative crop for supplying local pulp and paper industries. But in 2022-2023, monoculture sengon plants, which replaced rubber trees, failed to deliver the predicted advantages. Fruits may provide an additional seasonal source of communal revenue, with Durian, a popular fruit with a high selling price.

Agroforestry on peatland performs slightly better from an economic than an ecological perspective, according to Surahman et al. (2018). Rice, oil palm, and rubber cultivation had 49.65, 44.68, and 46.48% sustainability ratings. However, growing oil palm and rubber planting on peatland in locations that are less suitable can reduce crop productivity, in which case BCR and farmer income suffer. Leverage analysis shows that plant productivity and product prices lower BCR. Next are input costs and agricultural revenue/total income ratio. Ecological and economic factors interact.

Soil, water, amelioration, fertilisation, and appropriate planting can increase peatland plant production (Subiksa et al., 2011). Product pricing also matters. Price fluctuations can threaten farming (Grega, 2002) through chances in the palm oil and rubber export markets. Thus, farmers' prices fluctuate with the variation in prices in the international markets. Government agencies might stabilise prices. Farmers' income is affected by price fluctuations, crop production, product pricing, BCR, and the farm revenue-to-total-income ratio. Management of farms is vital to ensuring economic sustainability. Price stabilisation is of equal importance. For degraded peatlands, Itta et al. (2015) suggested jelutung incorporating with corn, mustard greens, chilli, or green onion. Based on the BCR (which ranges from 3.1 to 4.5), jelutung, maize, chilli, and onions produce the greatest benefits.

Agroforestry for peat conservation and rehabilitation

Local peoples' tendency to clear peatlands for agricultural purposes is definitely detrimental to the conservation of peat resources. Farmers assert that during each dry season, peatlands in Central Kalimantan are affected by forest and land fires, which give rise to a multitude of negative impacts. Fires have destroyed peatlands and forests in Central Kalimantan since 1973 (Hoscilo et al., 2011) and continued through 2015 (Yulianti et al., 2020). The majority of undisturbed, forested peatlands, conversely, have never been affected by forest or land fires. Since its establishment in 1979-1980 in Central Kalimantan, the community of transmigrant farmers (Jaya et al., 2002) has encountered challenges in adapting to substandard peat soils and achieving successful crop cultivation.

Initially, they relied on ash from wood and peat fires as a fertiliser, but the prevalence of manure and artificial inorganic fertilisers has since increased. Recent years have seen significant fires in the transmigration area south of Palangka Raya, near Kalampangan, during the majority of dry seasons. In the years following the fire in 2015, the burned area was utilised for the cultivation of (mostly) fruits and vegetables. Agroforestry farmers in Central Kalimantan who were formerly Javanese immigrants typically apply crop cultivation knowledge gained from prior peatland cultivation prior to engaging in agroforestry endeavours. Furthermore, they typically consider the application of fertilisers in their practises. To illustrate, in the context of agroforestry involving the cultivation of jelutung trees on deep peat, an initial application of 1-1.5 kg of manure fertiliser is required (Jaya et al., 2021). Conversely, deep peatlands have historically been utilised exclusively by the Dayak community and certain indigenous immigrants for fishing purposes, particularly capture fisheries (ponds). Catfish (Blackskin catfish, *Clarias meladerma*), Haruan (Striped snakehead, *Channa striata*), sepat (*Trichopodus pectoralis*), papuyu (Climbing perch, *Anabas testudineus*), flotsam (*Belontia hasselti*), toman (Giant snakehead, *Channa micropeltes*), and cage (*Channa pleurophthalma*) are among the species found in Central Kalimantan (Nurseptiani et al., 2021). Farmers either gather these fish from the wild and commercialise them for their own use or consume them, or else they grow them in canals situated on their land using a system of cages. Yuptriani et al. (2020) further suggest that peatlands support the local community through fishery revenue, thus serving as a means of subsistence. Conversely, the Dayak people's perspectives are shaped by their assessments of the success of peatland cultivation by farmers (Fransiska et al., 2020).

Jelutung swamp (*Dyera polyphylla* (Miq.) Steenis) is an essential component of numerous subsistence agroforestry systems. The plant's natural habitat is flooded areas, and it has adapted to survive in tropical peat swamps. As a result, it can be effectively utilised in peat rehabilitation agroforestry systems, which are particularly advantageous for the environment (Harun, 2016). The timber undergoes various processing stages, including the production of pulp, plywood, and beams or boards; the sap is extracted and sold in the form of blocks or sheets that serve as insulating materials for tyres, electric cables, and rubber; and the resin finds application in cosmetics, varnishes, and essential oils (Tata et al., 2015). The decline in the groundwater table has been found to be associated with a decrease or removal of native peat forest cover (Wosten et al., 2006; Sumarga et al., 2016; Uda et al., 2017; Cooper et al., 2019). This groundwater table decrease impacts various soil properties, such as decomposition and compaction processes. Increased bulk density is the consequence of land subsidence (Sherwood et al., 2013; Evans et al., 2019; Sinclair et al., 2020). Farmers are generally unaware of the important role of trees in peat conservation. When they were queried about their awareness of the decomposition-induced reduction in peatland surface area subsequent to the deforestation of the peat swamp forest, this information became apparent. Each agroforestry actor expressed ignorance regarding these consequences.

Agroforestry and peatlands health

Soil chemical properties and microclimate conditions in agroforestry can be more favourable than in monocultures or non-productive peatland (i.e., peatland that has been deforested but is not under any agricultural use) (Harun and Yuwati, 2015; Table 1). Wijayanti et al. (2023) found that P in agroforestry on peatlands was 252.1-287.5 ppm compared to dragon fruit land and oil palm, which ranged from 83.9 to 93.9 ppm. Table 1 shows that the soil pH, Al_{exch}, H_{exch}, Al saturation, and H saturation in peat swamp with jelutung agroforestry is higher than in peat soil under a crop monoculture. The opposite pattern occurs for total N, organic C, K, Ca, Na_{exch}, Mg exch, CEC, BS, total P, total K, P Bray 1, and SO_4. In Tumbang Nusa Village, organic C, Na_{exch}, Mg_{exch}, CEC, H_{exch}, H saturation, K saturation, and total SO_4 in peat soil with jelutung agroforestry were higher than in abandoned peatland. The opposite pattern occurs for soil pH, total N, K_{exch}, Ca_{exch}, BS, total P, and P Bray-1. The cation exchange capacity (CEC) is very high (90-200 me/100 g) in all peatland typologies, which can cause very low availability of nutrients, especially K, Ca, and Mg, which reduce if the base saturation is low.

Table 1. Soil chemical properties in agroforestry in Peatlands of Central Kalimantan, Indonesia.

Parameter	**Kalampangan**		**Tumbang Nusa**	
	Agroforestry	**Monoculture Agriculture**	**Agroforestry**	**Non-Productive Land**
pH	3.94	3.93	3.67	4.00
Total N (%)	0.40	0.45	0.37	0.43
Organic C	48.58	51.78	55.12	54.76
C/N ratio	121.45	115.07	148.97	127.35
K_{exch} (me/100 g)	0.076	0.15	0.09	0.12
Na_{exch} (me/100 g)	0.014	0.06	0.04	0.03
Ca_{exch} (me/100 g)	2.34	4.13	1.28	2.47
Mg_{exch} (me/100 g)	1.76	2.58	0.90	0.88
CEC (me/100 g)	147.50	361.17	137.50	90.83
Al_{exch} (me/100 g)	2.40	2.30	0	0
H_{exch} (me/100 g)	5.27	3.03	2.83	2.00
Base Saturation (%)	2.86	3.76	1.80	4.24
Saturation of Al (%)	20.80	19.73	0	0
Saturation of H (%)	48.94	26.66	55.29.	37.18
Total Pl (mg/100 g P_2O_5)	4.21	24.50	7.82	12.71
Total K (mg/100 g P_2O_5)	4.32	18.33	6.94	5.51
P Bray 1 (ppm)	12.55	12.59	19.36	29.82
SO_4 (ppm)	102.12	119.20	112.66	101.69

Source: Harun and Yuwati (2015).

The high C/N ratio of peat causes less nitrogen to be available to plants even though the total N is high, whilst P is in the form of organic P and is less available to plants. The data presented in Table 1 indicates that the soil pH, Al_{exch}, H_{exch}, Al saturation, and H saturation levels in peat swamp areas with jelutung agroforestry are comparatively greater than those observed in peat soil areas under crop monoculture. The converse trend is observed in the case of total nitrogen (N), organic carbon (organic C), potassium (K), calcium (Ca), exchangeable sodium (Na_{exch}), exchangeable magnesium (Mg_{exch}), cation exchange capacity (CEC), base saturation (BS), total phosphorus (P), total potassium (K), Bray-1 phosphorus (P Bray-1), and sulphate (SO_4). The levels of organic C, Na_{exch}, Mg_{exch}, CEC, H_{exch}, K saturation, and total SO_4 in peat soil with jelutung agroforestry were found to be significantly greater compared to those in abandoned peatland in Tumbang Nusa Village. The inverse trend is shown in relation to soil pH, total nitrogen, K_{exch}, Ca_{exch}, base saturation, total P, and P Bray-1. Peatland typologies exhibit a notably high cation exchange capacity (CEC) ranging from 90 to 200 me/100 g. This characteristic might result in limited nutrient availability, particularly for potassium (K), calcium (Ca), and magnesium (Mg), especially when the base saturation is low. The elevated carbon-to-nitrogen (C/N) ratio observed in peat results in reduced nitrogen availability for plants despite the presence of a substantial total nitrogen content. Additionally, phosphorus exists in the form of organic phosphorus in peat, which limits its accessibility to plants.

Agroforestry and biological activities in of peat soils

There are not many studies investigating the microbial diversity of peatlands that are used for agroforestry. However, Supriati et al. (2023) note that agroforestry cropping patterns provide diversity in the variety of fungi that can be used as biological pest control (Table 2). Table 2 also shows the inhibition of fungi from the rhizosphere of plants with different cropping patterns in peatlands against the soil-borne pathogen (*Sclerotium rolfsii*). Table 2 shows the results of rhizosphere soil isolation obtained by 2 antagonistic fungal genera, namely *Trichoderma* and *Gliocladium*. The highest inhibitory ability was shown by *T. harzianum* (from sweet corn monoculture), and *Gliocladium* sp.1 (originating in the rhizosphere of soursop plants), and the two isolates showed the same inhibition against *S. rolfsii* and the ability of inhibition was higher than on other antagonist isolates. Differences in the inhibition of antagonistic fungal isolates against *S. rolfsii* pathogens are indicated because (1) different types of antagonistic isolates have different inhibitory abilities, which has something to do with the types of secondary metabolites and antibiotics produced (Dendang, 2015), (2) differences in methods cultivation of plants carried out by farmers, in this case the dosage and type of fertilizers, especially manure and synthetic pesticides used, (3) differences in the age of the plants and the types of plants that are managed.

In peat soils in Central Kalimantan, the plant rhizosphere can contain microbes, especially the fungus *Trichoderma longibrachiatum*, which acts as a biological control agent that is capable of controlling the soil-borne pathogen *Fusarium oxysporum f.sp. cubense* (Mulyani et al., 2018). Soil fungi of the *Trichoderma* genus play an antagonistic role against plant pathogens and also support the breakdown of organic material, which provides a source of nutrients for plant root systems (Gusnawaty et al., 2014). Jelutung plants are planted with an agroforestry pattern with soursop plants, no manure is given. Generally, farmers use chicken manure as a basic fertilizer and only give it to soursop plants with sufficient application. Manure, such as chicken manure, is a commonly used basic fertilizer in agroforestry that supports the growth and metabolism of soil microbes as well as being a direct source of plant nutrients. The results of this study support the finding of Hidayat et al. (2021) that the population and diversity of fauna and eukaryotic microbes (bacteria and fungi) are relatively diverse and predominate in oil palm areas in heap areas compared to disk areas due to a more favorable microclimate.

Table 2. Fungi inhibition originating from the rhizosphere of plants from peatland against *S. rolfsii.*

Planting pattern	**Origin of plant rhizosphere**	**Isolate**	**Inhibition (%)**
Intercropping mustard greens-sweet corn	Mustard	*Trichoderma* sp.1	46.3
	Sweet corn	*Trichoderma viride*	53.7
		Trichoderma koningii	48.2
Monoculture	Sweet corn	*Trichoderma harzianum*	57.4
Agroforestry	Jelutung	*Trichoderma harzianum*	44.4
	Soursop	*Gliocladium* sp.1	57.4
		Gliocladium sp.2	38.9

Source: Supriati et al. (2023).

In addition to organic matter, the exudates secreted by plant root systems can provide an advantage for the microbes (antagonists). Roots supply nutrients that contain food ingredients for microbial communities as vitamins, amino acids, sugars, and organic acids. The composition of the root exudate produced is influenced by the age and type of plant, with plants that are in the vegetative growth stage producing higher quality exudate (Zhao et al., 2021). Excessive use of synthetic pesticides can negatively affect the population and activity of potential microbes, especially antagonists. Pati et al. (2016) demonstrated that the application of synthetic pesticides can inhibit or kill certain groups of microbes but can also increase the number of other microbes because it frees them from competition.

In peatlands with agroforestry cropping patterns, entomopathogenic microbes from insect pests are also found, especially in the fungus group (Supriati et al., 2023). According to Risbianti (2015), it has been observed that variations exist in the rhizosphere of plants cultivated on peatland with diverse cropping patterns; many fungal isolates were found, namely 11 isolates in the mustard-sweet corn polyculture, five isolates in the mustard monoculture and five isolates in the sweet corn monoculture. However, only the entomopathogenic fungus *Metarhizium* sp. was able to eradicate *Plutela xylostella* larvae (mustard pest), while the other isolates found were opportunistic fungi. The percentage of *Tenebrio molitor* larvae infected with entomopathogenic fungi from five plant rhizospheres with different cultivation patterns is presented in Table 3. Risbianti (2015) stated that the presence of insect entomopathogenic fungi is influenced by the agroecosystem conditions from which the isolates originate, including the variety of shade plants, altitude, and cultivation techniques, as well as the different characteristics of each region where the isolates originate, including climatic conditions and land geology.

The entomopathogenic fungus *Metarhizium* sp. from the rhizosphere of the jelutung plant showed a higher ability to infect *T. molitor* larvae, namely 55% compared to other isolates. Soils that contain organic matter and rarely use synthetic pesticides contain a higher concentration and variety of microbes that fertilize the soil, including microbes that act as biological agents. Yanarita et al. (2021) conducted a study on macrofauna diversity within the framework of agroforestry. The researchers observed a total of soil macrofauna individuals, which were classified into six different groups, nine orders, and 13 families. The family Formicidae exhibits the highest population dominance in the surveyed region, with a total of 951 individuals, whilst the family Lumbricidae demonstrates the lowest population count, consisting of only 13 individuals.

The level of diversity of soil macrofauna species in jelutung-based agroforestry on peatlands is categorised as moderate (H' = 1.508), with medium species evenness (E = 0.588) and a significantly high species richness (DMg = 281.788). This level of diversity is found to be better than that observed in acacia plantations, as reported by Komala et al. (2016), which was classified as 'low' (H' = 0.87 and 0.78). The level of diversity of soil macrofauna species in jelutung-based agroforestry on peatlands is categorised as moderate (H' = 1.508), with medium species evenness (E = 0.588) and a significantly high species richness (DMg = 281.788). This level of diversity is found to be better than that observed in acacia plantations, as reported by Komala et al. (2016), which was classified as 'low' (H' = 0.87 and 0.78). Similarly, the secondary peatlands located in West Kalimantan exhibit a medium level (H' = 2.09). According to Handayani and Winara (2020), the level of macrofauna diversity in oil palm farms is comparatively reduced, with a recorded Shannon diversity index (H') value of 0.73. According to Gesriantuti et al. (2016), the diversity in burnt peatlands with an acacia monoculture restoration (H' = 0.48) is higher compared to the diversity observed in forest types with heterogenous protection (H' = 0.31). Therefore, it can be inferred that agroforestry systems utilising jelutung as a primary component provide a favourable environment for macrofauna species. Moreover, these systems have the potential to serve as a viable alternative for ecological restoration efforts in peatland ecosystems.

Table 3. *Tenebrio molitor* larval infection percentage by entomopathogenic fungi in five plant rhizospheres situated in peat soil.

Planting pattern	**Plant rhizosphere**	**Isolate**	**Infected larvae (%)**
Intercropping mustard greens-sweet corn	Mustard	*Beauveria* sp.	35
	Sweet corn	*Beauveria* sp.	40
Monoculture	Sweet corn	*Beauveria* sp.	30
Agroforestry	Jelutung	*Metarhizium* sp.	55
	Soursop	*Metarhizium* sp.	50

Source: Supriati et al. (2023).

Summary and Future Perspectives

Peatlands hold significant ecological significance on a worldwide scale due to their capacity for carbon sequestration and their economic importance to local communities. Global developments in peatland conservation and rehabilitation are strengthening, but there has, to date, been limited attention paid to peatland agroforestry systems. Yet despite this lack of dedicated research, this review indicates that the agroforestry practices carried out by farming communities on peatland in Kalimantan can generate favourable results for the environment and also the farming community, with limited interventions. Several studies have demonstrated that soil and environmental characteristics on peatlands managed with agroforestry patterns may be more favourable than those managed with monoculture patterns, although the number of such studies is still relatively small. When managed effectively, agroforestry has the potential to significantly contribute to the conservation and rehabilitation of peatlands.

Farmers have implemented agroforestry because they know that timber trees will become more limited in the future and that growing trees with intercrops can provide sufficient income. Thus, agroforestry may support households. Government support, especially for agroforestry-based peatland rehabilitation, is crucial, but the government and its agencies must evaluate each crop's effectiveness in local conditions before suggesting it to smallholders. Potential forms of government assistance may encompass the provision of seeds, fertilisers, support for agroforestry practises, as well as the establishment and development of jelutung latex markets. In order to promote the successful implementation of agroforestry through tree planting, it is imperative to acquire a comprehensive understanding of the adaptive mechanisms employed by trees in peatland environments. Additionally, it is crucial to assess and perhaps improve the accessibility of plant species that are well-suited to the specific geographical area (Tata and Susmianto, 2016).

Restoring peatlands through re-vegetation enhances humidity, decreases temperatures, and minimises fire danger in damaged peatlands. The level of peatland degradation determines the revegetation strategy. For example, hydrological restoration alone may be enough to regenerate peat swamp forest vegetation if logging and fire are prevented, but enrichment planting will be needed if few trees remain. Both hydrological restoration and replanting are needed after major fires. The choice of species mix should be made with reference to nearby and ecologically significant protected or conservation areas of peat swamp forest. But also, in the proximity to settlements, use of species with an economic value, including sago, jelutung, gelam, and *Alseodaphne*. Some tree species used in revegetation programmes require a long time to reach a stage where they have an economic value (Giesen and Sari, 2018).

This review reveals that agroforestry practitioners have the ability to manage many plant species, including *Dyera polyphylla, Shorea belangeran, Alstonia scholaris, Combretocarpus rotundatus*, and *Alseodaphne* sp. Sago (*Metroxylon sago*), banana (*Musa paradisiaca*), and pineapple (*Ananas comosus*) were identified as the preferred food crop plants, with kangkung (*Ipomoea aquatica*), edible fern (*Stenochlaena palustris*), tengkawang (*Shorea* spp.), dragon fruit (*Hylocereus undatus*), mangosteen (*Garcinia mangostana*), and sweet melon

(*Cucumis melo*) also being commonly consumed. Sago, pumpkin seeds, banana, pineapple, and sweet melon possess characteristics that contribute to their potential for market scalability, sustainability, and farmer acceptability (Uda et al., 2020). The tree survival rate of the Indonesian peatland revegetation program is poor (Nurohman et al., 2019), with the marginal economic returns from peatland agronomy cited as the major reason. Our research shows that government tree-planting programmes can boost agroforestry and increase farmers' income. However, many farmers and communities have not accepted the notion of beneficial tree planting and intercropping on peatlands. Farmers will adopt agroforestry if it produces high-value crops. Therefore, the agriculture and forestry departments should create compelling reasons for tropical peatland protection and rehabilitation through agroforestry to increase its adoption.

Utilising degraded land is critical and must be approached with extreme caution. For the purposes of peat conservation and fire prevention, the government may direct the transformation of degraded land into productive land; however, this cannot be overly intensively managed. The annual subsidence of peat by agroforestry and agricultural practises ranges from 0.41 to 3.21 cm (Evans et al., 2021), consequently elevating the vulnerability to flooding. On the other hand, peatlands have the potential to support animal-related industries, including horticulture, fish farming, and goat husbandry (Tan et al., 2020). Through the application of paludiculture principles and methods, intercropping can be modified to suit regions with low water tables.

Peatland drainage remains the principal aim of land management in agroforestry, as it ensures that the oxygen demands of plant root systems are adequately fulfilled (Dariah and Nurzakiah, 2014). In addition to improving the physical characteristics of peat, drainage can also remove a fraction of its phytotoxic organic acids. Conversely, drainage has adverse effects on peat deposit preservation due to its facilitation of decomposition processes and the release of greenhouse gases. Moreover, this renders peatlands vulnerable to fire hazards. Hence, it is customary to regulate peatlands utilised for agroforestry in a manner that minimises the requirement for drainage.

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References

Agus, C., Azmi, F.F., Widiyatno, Ilfana, Z.R., Wulandari, D., Rachmanadi, D., Harun, M.K. and Yuwati, T.W. 2019. The impact of forest fire on the biodiversity and the soil characteristics of tropical peatland. *Handbook of Climate Change and Biodiversity* pp.287-303.

Agustiyara, Purnomo, E.P. and Ramdani, R. 2021. Using artificial intelligence techniques in estimating fire hotspots of forest fires. *IOP Conference Series: Earth and Environmental Science* 717:012019, doi:10.1088/1755-1315/717/1/012019.

Alwi, M. and Hairani, A. 2007. Chemical characteristics of shallow peatlands and their potential for planting chilies and tomatoes. *Jurnal Agronomi Indonesia* 35(1):36-43 (*in Indonesian*).

Anda, M., Ritung. S., Suryani, E., Sukarman, Hikmat, M., Yatno, E., Mulyani, A., Subandiono, R.E., Suratman, and Husnain. 2021. Revisiting tropical peatlands in Indonesia: Semi-detailed mapping, extent and depth distribution assessment. *Geoderma* 402:115235, doi:10.1016/j.geoderma.2021.115235.

Anshari, G.Z., Afifudin, M., Nuriman, M., Gusmayanti, E., Arianie, L., Susana, R., Nusantara, R.W., Sugardjito, J. and Rafiastanto, A. 2010. Drainage and land use impacts on changes in selected peat properties and peat degradation in West Kalimantan Province, Indonesia. *Biogeosciences* 7(11):3403-3419. doi:10.5194/bg-7-3403-2010, 2010.

Anshari, G.Z., Gusmayanti, E. and Novita, N. 2021. The use of subsidence to estimate carbon loss from deforested and drained tropical peatlands in Indonesia. *Forests* 12(6):732, doi:10.3390/f12060732.

Applegate, G., Freeman, B., Tular, B., Sitadevi, L. and Jessup, T.C. 2022. Application of agroforestry business models to tropical peatland restoration. *Ambio* 51(4):863-874, doi:10.1007/s13280-021-01595-x.

Aryanti, E., Novlina, H. and Saragih, R. 2016. Macro nutrient content of peat soil with applying Azolla pinata compost at different doses and its effect on the growth of water spinach plants (*Ipomea reptans poir*). *Jurnal Agroteknologi*, *6*(2), pp.31-38. doi:10.24014/ja.v6i2.2238 (*in Indonesian*).

Baird, A.J., Low, R., Young, D., Swindles, G.T., Lopez, O.R. and Page, S. 2017. High permeability explains the vulnerability of the carbon stored in drained tropical peatlands. *Geophysical Research Letters* 44(3):1333-1339, doi:10.1002/2016GL072245.

Ballhorn, U., Siegert, F., Mason, M. and Limin, S., 2009. Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands. *Proceedings of the National Academy of Sciences* 106(50):21213-21218.

Blodau, C. 2002. Carbon cycling in peatlands - A review of processes and controls. *Environmental Reviews* 10:111-134, doi:10.1139/a02-004.

Budiningsih, K. and Effendi, R. 2013. Analysis of the financial feasibility of jelutung (*Dyera polyphylla*) plantation in Central Kalimantan. *Jurnal Penelitian Hutan Tanaman* 10(1):17-23, doi:10.20886/jpht.2013.10.1.17-23 (*in Indonesian*).

Cobb, A.R., Dommain, R., Tan, F., Heng, N.H.E. and Harvey, C.F. 2020. Carbon storage capacity of tropical peatlands in natural and artificial drainage networks. *Environmental Research Letters* 15:114009, doi:10.1088/1748-9326/aba867.

Cooper, H.V., Evers, S., Aplin, P., Crout, N., Dahalan, M.P.B. and Sjogersten, S. 2020. Greenhouse gas emissions resulting from conversion of peat swamp forest to oil palm plantation. *Nature*

Communications 11(1):407, doi:10.1038/s41467-020-14298-w.

Cooper, H.V., Vane, C.H., Evers, S., Aplin, P., Girkin, N.T. and Sjögersten, S. 2019. From peat swamp forest to oil palm plantations: the stability of tropical peatland carbon. *Geoderma* 342:109-117, doi:10.1016/j.geoderma.2019.02.021.

Dargie, G.C., Lewis, S.L., Lawson, I.T., Mitchard, E.T., Page, S.E., Bocko, Y.E. and Ifo, S.A. 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. *Nature* 542(7639):86-90, doi:10.1038/nature21048.

Dariah, A. and Nurzakiah, S. 2014. Peatland water management. In:_Nuraida, L.N. and Wihardjaka, A. (eds). Center for Research and Development of Agricultural Land Resources, Agricultural Research and Development Agency (*in Indonesian*).

Dendang B. 2015. Antagonism test of *Trichoderma spp.* against *Ganoderma* sp. which attacks sengon plants in vitro. *Jurnal Penelitian Kehutanan Wallacea* 4(2):147-156 (*in Indonesian*).

Dohong, A. 2019. Restoring degraded peatland in Indonesia: the 3R Approach. RSPO Manual on Best Management Practices (BMPs) for Management and Rehabilitation of Peatlands. 2nd Edition, RSPO, Kuala Lumpur.

Dommain, R., Couwenberg, J. and Joosten, H. 2010. Hydrological self-regulation of domed peatlands in Southeast Asia and consequences for conservation and restoration. *Mires and Peat* 6:1-17.

Draper, F.C., Honorio Coronado, E.N., Roucoux, K.H., Lawson, I.T., Pitman, A.N.C., Fine, A.P.V., Phillips, O.L., Montenegro, L.A.T., Sandoval, E.V., Mesones, I. and García-Villacorta, R. 2018. Peatland forests are the least diverse tree communities documented in Amazonia but contribute to high regional beta diversity. *Ecography* 41(8):1256-1269, doi:10.1111/ecog.03126.

Evans, C.D., Callaghan, N., Jaya, A., Grinham, A., Sjogersten, S., Page, S.E., Harrison, M.E., Kusin, K., Kho L.K., Ledger, M. and Evers, S. 2021. A novel low-cost, high-resolution camera system for measuring peat subsidence and water table dynamics. *Frontiers in Environmental Science* 9:1-13, doi:10.3389/fenvs.2021.630752.

Evans, C.D., Williamson, J.M., Kacaribu, F., Irawan, D., Suardiwerianto, Y., Hidayat, M.F., Laurén, A. and Page, S.E. 2019. Rates and spatial variability of peat subsidence in *Acacia* plantation and forest landscapes in Sumatra, Indonesia. *Geoderma* 338:410-421, doi:10.1016/ j.geoderma.2018.12.028.

Evers, S., Yule, C.M., Padfield, R., O'Reilly, P. and Varkkey, H. 2016. Keep wetlands wet: the myth of sustainable development of tropical peatlands - implications for policies and management. *Global Change Biology* 23(2):534-549, doi:10.1111/gcb.13422.

Firdaus, M.S., Gandaseca, S. and Ahmed, O.H. 2011. Effect of drainage and land clearing on selected peat soil physical properties of secondary peat swamp forest. *International Journal of Physical Sciences* 6(23):5462-5466. 10.5897/IJPS11.598.

Fransiska, M., Efriani, D.R.D., Bakara, L.K. and Ginting, E.S.S. 2020. Ecological adaptation of transmigration residents in Rasau Jaya Satu village). *Pangadereng: Jurnal Hasil Penelitian Ilmu Sosial dan Humaniora* 6(1):1-12, doi:10.36869/pjhpish.v6i1.124 (*in Indonesian*).

Gerwing, T.G., Hawkes, V.C., Gann, G.D. and Murphy, S.D. 2022. Restoration, reclamation, and rehabilitation: on the need for, and positing a definition of ecological reclamation. *Restoration Ecology* p.e13461, doi:10.1111/rec.13461.

Gesriantuti, N., Trantiati, R. and Badrun, Y. 2016. Diversity of surface insects in ex-fire peatlands and protected forests in Kasang Padang Village, Bonaidarusalam District, Rokan Hulu Regency, Riau Province. *Photon: Jurnal Sain dan Kesehatan* 7(01):147-155 (*in Indonesian*).

Giesen, W. and Sari, E.N.N. 2018. *Tropical Peatland Restoration Report: The Indonesian Case*. Technical Report, Berbak Green Prosperity Partnership, Euroconsult Mott MacDonald Jakarta and Mott MacDonald Arnhem (Netherlands), doi:10.13140/RG.2.2.30049. 40808, 82 pp.

Grega, L. 2002. Price stabilization as a factor of competitiveness of agriculture. *Agricultural Economics* 48(7):281-284, doi:10.17221/5321-AGRICECON.

Gusnawaty, H.S., Muhammad, T., Leni, T. and Asniah. 2014. Morphological characterization of *Trichoderma* spp. indigenous to Southeast Sulawesi. *Jurnal Agroteknos* 4(2):87-93 (*in Indonesian*).

Handayani, W. and Winara, A. 2020. Diversity of soil macrofauna in several peatland uses. *Jurnal Agroforestri Indonesia* 3(2):77-88 (*in Indonesian*).

Haraguchi, A. 2016. *Tropical Peatland Ecosystems* (Osaki, M. and Tsuji, N.) 297-311. Springer.

Harun, M.K. 2011. Analysis of Jelutung Development with an Agroforestry System to Restore Degraded Peatlands in Central Kalimantan Province. Master Thesis, Agricultural Institute, Bogor (*in Indonesian*).

Harun, M.K. 2016. Jelutung Swamp Based Agroforestry: Social, Economic and Environmental Solutions for Peat Land Management. Forda Press, Bogor, 254 pp (*in Indonesian*).

Harun, M.K. and Yuwati, T.W. 2015. Agroforestry system for rehabilitation of degraded peatland in Central Kalimantan. *Journal of Wetlands Environmental Management* 3(1):41-46, doi:10.20527/jwem.v3i1.8.

Harun, M.K., Anwar, S., Putri, E.I.K. and Arifin, H.S. 2020. Chemical properties and water level of peat in three types of land use in the physiography of peat domes and back swamps of KHG Kahayan-Sebangau. *Jurnal Hutan Tropis* 8(3):315-327, doi:10.20527/jht.v8i3.9632 (*in Indonesian*).

Harun, M.K., Arifin, H.S., Anwar, S., Putri, E.I.K. and Tata, H.L. 2022. Agroforestry approaches in the restoration of peatland landscapes in Central Kalimantan, Indonesia. In *Forest Dynamics and Conservation: Science, Innovations and Policies* (pp. 331-362). Singapore: Springer Nature Singapore.

Hidayat F, Farrasati, R. and Winarna. 2021. Study of density and diversity of peat soil organisms under oil palm plantation. *Jurnal Penelitian Kelapa Sawit* 29(2):115-126 (*in Indonesian*).

Holden, J., Evans, M.G., Burt, T.P. and Horton, M. 2006. Impact of land drainage on peatland hydrology. *Journal of Environmental Quality* 35(5):1764-1778, doi:10.2134/jeq2005.0477.

Hooijer, A., Page, S.E, Jauhiainen, J., Lee, W.A., Lu, X.X., Idris, A. and Anshari, G. 2012. Subsidence and carbon loss in drained tropical peatlands. *Biogeosciences* 9(3):1053-1071, doi:10.5194/bg-9-1053-2012.

Hooijer, A., Page, S.E., Canadell, J.G., Silvius, M., Kwadijk, J., Wösten, H. and Jauhiainen, J. 2010. Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences* 7:1505-1514, doi:10.5194/bg-7-1505-2010.

Hooijer, A., Page, S.E., Jauhiainen, J., Lee, W.A., Lu, X.X., Idris, A. and Anshari, G. 2012. Subsidence and carbon loss in drained tropical peatlands. *Biogeosciences* 9:1053-1071, doi:10.5194/bg-9-1053-2012.

Hoscilo, A., Page, S.E., Tansey, K.J. and Rieley, J.O. 2011. Effect of repeated fires on land-cover change on peatland in southern Central Kalimantan, Indonesia, from 1973 to 2005. *International Journal of Wildland Fire* 20(4):578-588, doi:10.1071/WF10029.

Hu, Y., Fernandez-Anez, N., Smith, T.E. and Rein, G. 2018. Review of emissions from smouldering peat fires and their contribution to regional haze episodes. *International Journal of Wildland Fire* 27(5):293-312, doi:10.1071/WF17084.

Huijnen, V., Wooster, M.J., Kaiser, J.W., Gaveau, D.L.A., Flemming, J., Parrington, M., Inness, A., Murdiyarso, D., Main, B. and Van Weele, M. 2016. Fire carbon emissions over maritime Southeast Asia in 2015 largest since 1997. *Scientific Reports* 6:1-8, doi:10.1038/srep26886.

Husnain, H., Sipahutar, I.A., Purnomo, J., Widyanto, H. and Nurhayati, N. 2017. CO_2 emissions from tropical peat soil affected by fertilization. *Journal of Tropical Soils* 22(1):1-9, doi:10.5400/jts.2017.22.1.1.

Idawati, I., Fatchiya, F. and Tjitropranoto, T. 2018. Adaptive capacity of cocoa farmers to climate change. *Journal TABARO Agriculture Science* 2(1):178-190, doi:10.35914/tabaro.v2i1.112 (*in Indonesian*).

Itta, D., Asysifa, A. and Trisnu, S. 2015. Peatland characteristics and agroforestry patterns in Kalampangan Village, Palangka Raya City, Central Kalimantan. *Proceedings of National Seminar on Agroforestry 2015*. Agroforestry Technology Research and Development Center (*in Indonesian*).

Jaenicke, J., Wösten, H., Budiman, A. and Siegert, F. 2010. Planning hydrological restoration of peatlands in Indonesia to mitigate carbon dioxide emissions. *Mitigation and Adaptation Strategies for Global Change* 15:223-239, doi:10.1007/s11027-010-9214-5.

Jauhiainen, J., Limin, S., Silvennoinen, H. and Vasander, H. 2008. Carbon dioxide and methane fluxes in drained tropical peat before and after hydrological restoration. *Ecology* 89(12):3503-3514, doi:10.1890/07-2038.1.

Jaya, A., Antang, E.U., Djaya, A.A. and Gunawan, H. 2021. Agroforestry farming system as peatland restoration efforts in Central Kalimantan, Indonesia. *IOP Conference Series: Earth and Environmental Science* 694:012016, doi:10.1088/1755-1315/694/1/012016.

Jaya, A., Elia, A., Antang, E.U., Octora, M., Ichriani, G.I., Dohong, S. and Sulistiyanto, Y. 2022. A study of agroforestry farming for tropical peatland conservation and rehabilitation in Central Kalimantan, Indonesia. *Mires and Peat* 28:22:34, doi:10.19189/MaP.2021.OMB.StA.2368.

Jaya, A., Sulastiyanto, Y., Jagau, Y., Rieley, J.O. and Artiningsih, T. 2002. Utilization of deep tropical peatland for agriculture in Central Kalimantan, Indonesia. *International Symposium on Tropical Peatlands, Jakarta (Indonesia),* 22-23 August 2002.

Joosten, H. 2015. Peatlands, climate change mitigation and biodiversity conservation: An issue brief on the importance of peatlands for carbon and biodiversity conservation and the role of drained peatlands as greenhouse gas emission hotspots (Vol. 2015727). Nordic Council of Ministers.

Jose, S. 2009. Agroforestry for ecosystem services and environmental benefits: an overview. *Agroforestry Systems* 76(1):1-10, doi:10.1007/s10457-009-9229-7.

Kallio, M.H., Kanninen, M. and Rohadi, D. 2011. Farmers'tree planting activity in Indonesia - Case studies in the Provinces of Central Java, Riau, and South Kalimantan. *Forests, Trees and Livelihoods* 20(2-3):191-209, doi:10.1080/14728028.2011.9756706.

Kelly, T.J., Baird, A.J., Roucoux, K.H., Baker, T.R., Honorio Coronado, E.N., Ríos, M. and Lawson, I.T. 2014. The high hydraulic conductivity of three wooded tropical peat swamps in northeast Peru: measurements and implications for hydrological function. *Hydrological Processes* 28(9):3373-3387, doi:10.1002/hyp.9884.

Khasanah, N.M. and van Noordwijk, M. 2019. Subsidence and carbon dioxide emissions in a smallholder peatland mosaic in Sumatra, Indonesia. *Mitigation and Adaptation Strategies for Global Change* 24(1):147-163, doi:10.1007/s11027-018-9803-2.

Kholifah, U.N., Wulandari, C., Santoso, T. and Kaskoyo, H. 2017. Contribution of agroforestry to farmers' income in Sumber Agung Village, Kemiling District, Bandar Lampung City. *Jurnal Sylva Lestari* 5(3):38-47. doi:10.23960/jsl3539-47 (*in Indonesian*).

Kiely, L., Spracklen, D.V., Wiedinmyer, C., Conibear, L., Reddington, C.L., Archer-Nicholls, S., Lowe, D., Arnold, S.R., Knote, C., Khan, M.F. and Latif, M.T. 2019. New estimate of particulate emissions from Indonesian peat fires in 2015. *Atmospheric Chemistry and Physics* 19(17):11105-11121.

Komala D.F., Djajakirana, G. and Suwardi. 2016. Abundance and diversity of soil macrofauna in three areas in Teluk Meranti, Pelalawan Regency, Riau Province. Available from https://repository.ipb.ac.id/handle/123456789/85133 (*in Indonesian*).

Könönen, M., Jauhiainen, J., Laiho, R., Kusin, K. and Vasander, H. 2015. Physical and chemical properties of tropical peat under stabilised land uses. *Mires and Peat* 16(8):1-13.

Kurnianto, S., Selker, J., Kauffman, J.B., Murdiyarso, D. and Peterson, J.T. 2019. The influence of land-cover changes on the variability of saturated hydraulic conductivity in tropical peatlands. *Mitigation and Adaptation Strategies for Global Change* 24:535-555, doi:10.1007/s11027-018-9802-3.

Lähteenoja, O. and Page, S. 2011. High diversity of tropical peatland ecosystem types in the Pastaza-Marañón basin, Peruvian Amazonia. *Journal of Geophysical Research: Biogeosciences* 116(G2), doi:10.1029/2010JG001508.

Lampela, M., Jauhiainen, J. and Vasander, H. 2014. Surface peat structure and chemistry in a tropical peat swamp forest. *Plant and Soil* 382:329-347, doi:10.1007/s11104-014-2187-5.

Laurén, A., Palviainen, M., Page, S., Evans, C., Urzainki, I. and Hökkä, H. 2021. Nutrient balance as a tool for maintaining yield and mitigating environmental impacts of Acacia plantation in drained tropical peatland - description of plantation simulator. *Forests* 12(3):312, doi:10.3390/f12030312.

Maftu'ah, E., Susilawati, A. and Sulaeman, Y. 2021. Agroforestry for restoration of degraded peatlands. *E3S Web of Conferences* 305: 03001.

Mamat, H.S. and Noor, M. 2019. Transmigration Development Strategy in Tidal Swamp Land: Lessons Learned from Old Patterns). Policy Brief 2019, Swamplands Support Food Sovereignty 57-64 (*in Indonesian*).

Marlier, M.E., DeFries, R.S., Kim, P.S., Gaveau, D.L., Koplitz, S.N., Jacob, D.J., Mickley, L.J., Margono, B.A. and Myers, S.S. 2015. Regional air quality impacts of future fire emissions in Sumatra and Kalimantan. *Environmental Research Letters* 10(5):054010, doi:10.1088/1748-9326/10/5/054010.

Marlier, M.E., DeFries, R.S., Voulgarakis, A., Kinney, P.L., Randerson, J.T., Shindell, D.T., Chen, Y. and Faluvegi, G. 2013. El Niño and health risks from landscape fire emissions in Southeast Asia. *Nature Climate Change* 3:131-136, doi:10.1038/nclimate1658.

Mezbahuddin, M., Grant, R.F. and Hirano, T. 2015. How hydrology determines seasonal and interannual variations in water table depth, surface energy exchange, and water stress in a tropical peatland: Modeling versus measurements. *Journal of Geophysical Research: Biogeosciences* 120(11):2132-2157, doi:10.1002/2015JG003005.

Miettinen, J., Shi, C. and Liew, S.C. 2016. Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra, and Borneo in 2015 with changes since 1990. *Global Ecology and Conservation* 6:67-78, doi:10.1016/j.gecco.2016.02.004.

Miettinen, J., Shi, C. and Liew, S.C. 2017. Fire distribution in Peninsular Malaysia, Sumatra, and Borneo in 2015 with special emphasis on peatland fires. *Environmental Management* 60(4):747-757, doi:10.1007/s00267-017-0911-7.

Mishra, S., Page, S.E., Cobb, A.R., Lee, J.S.H., Sancho, A.J.J., Sjögersten, S., Jaya, A., Aswandi, and Wardle, D.A. 2021. Degradation of Southeast Asian tropical peatlands and integrated strategies for their better management and restoration. *Journal of Applied Ecology* 58(7):1370-1387, doi:10.1111/1365-2664.13905.

Moriarty, K., Elchinger, M., Hill, G., Katz, J. and Barnett, J. 2014. *Cacao Intensification in Sulawesi: A Green Prosperity Model Project*. National Renewable Energy Laboratory, Denver, 122 pp.

Mulyani, R.B., Panupesi, H., Nion, Y.A. dan Gustiara, T. 2018. The potential of *Trichoderma longibrachiatum* from kelakai roots (*Stenochlaena palustris*) on peat soil for suppresses *Fusarium oxysporum f.sp. cubense*. *Proceedings of the National Seminar and Congress of the Indonesian Phytopathological Association, Strategic Role of Phytopathology and Other Supporting Sciences in Holistic Agricultural Development to National Food Sovereignty.* 393-401 pp. Department of Plant Protection, Faculty of Agriculture, Halu Oleo University (*in Indonesian*).

Mustamo, P., Hyvärinen, M., Ronkanen, A.K. and Kløve, B. 2016. Physical properties of peat soils under different land use options. *Soil Use and Management* 32(3):400-410, doi:10.1111/sum.12272.

Najiyati, S., Muslihat, L. and Suryadiputra, I.N.N. 2005. *Peatland Management Guide for Sustainable Agriculture*. Wetlands International, Bogor, 231 pp (*in Indonesian*).

Namwata, B.M.L., Masanyiwa, Z.S. and Miziral, O.B. 2012. Productivity of the agroforestry systems and its contribution to household income among farmers in Lushoto District, Tanzania. *International Journal of Physical and Social Sciences* 2(7):369-392.

Neupane, R.P. and Thapa, G.B. 2001. Impact of agroforestry intervention on soil fertility and farm income under the subsistence farming system of the middle hills, Nepal. *Agriculture, Ecosystems and Environment* 84(2):157-167, doi:10.1016/S0167-8809(00)00203-6.

Noor, M. 2012. History of peatlands development for agriculture in Indonesia. *Proceedings of the National Seminar on Sustainable Peatland Management*, Centre for Research and Development of Agricultural Land Resources, Bogor, 399-411 (*in Indonesian*).

Nopembereni, E.D., Sugiyanto, S.K. and Yuliati, Y. 2018. The System of shifting cultivation management of Dayak Ngaju local community in Central Kalimantan. *International Journal of Scientific and Research Publications* 8(8):707-713, doi:10.29322/IJSRP.8.8.2018.p8089.

Nurohman, A., Fauzi, H. and Bakri, S. 2020. Evaluation of revegetation plants in the peat restoration program in the Liang Anggang protected forest area, South Kalimantan. *Jurnal Sylva Scienteae* 2(5):804-812, doi:10.20527/jss.v2i5.1862 (*in Indonesian*).

Nurseptiani, S., Kamal, M.M. dan Taryono, T. 2021. The status of captured fisheries in the Sebangau River and Katingan River, Sebangau National Park, Central Kalimantan. *Jurnal Pengelolaan Perikanan Tropis 5*(1):1-10, doi:10.29244/jppt.v5i1.33767 (*in Indonesian*).

Osaki, M., Nursyamsi, D., Noor, M., Wahyunto, and Segah, H. 2016. Peatland in Indonesia. In: Osaki, M., Tsuji, N. (eds.) *Tropical Peatland Ecosystems*, Springer, Tokyo, 49-58.

Paembonan, S.A., Millang, S., Dassir, M. and Ridwan, M. 2018. Species variation in home garden agroforestry system in South Sulawesi, Indonesia and its contribution to farmers' income. *IOP Conference Series: Earth and Environmental Science* 157:012004, doi:10.1088/1755-1315/157/1/012004.

Page, S.E. and Baird, A.J. 2016. Peatlands and global change: response and resilience. *Annual Review of Environment and Resources* 41:35-57, doi:10.1146/annurev-environ-110615-085520.

Page, S.E. and Hooijer, A. 2016. In the line of fire: the peatlands of Southeast Asia. *Philosophical Transactions of the Royal Society B: Biological Sciences* 371(1696):20150176, doi:10.1098/rstb.2015.0176.

Page, S.E., Hoscilo, A., Langner, A., Tansey, K., Siegert, F., Limin, S. and Rieley, J. 2009. Tropical peatland fires in Southeast Asia. In: Cochrane, M.A. (ed.) *Tropical Fire Ecology: Climate Change, Land Use, and Ecosystem Dynamics*, Springer, Berlin/Heidelberg, 263–287, doi:10.1007/978-3-540-77381-8_9.

Page, S.E., Mishra, S., Agus, F., Anshari, G., Dargie, G., Evers, S., Jauhiainen, J., Jaya, A., Jovani-Sancho, A.J., Laurén, A. and Sjögersten, S. 2022. Anthropogenic impacts on lowland tropical peatland biogeochemistry. *Nature Reviews Earth & Environment 3*(7):426-443, doi:10.1038/s43017-022-00289-6.

Page, S.E., Rieley, J.O. and Banks, C.J. 2011. Global and regional importance of the tropical peatland carbon pool. *Global Change Biology* 17(2):798-818, doi:10.1111/j.1365-2486.2010.02279.x.

Page, S.E., Rieley, J.O. and Wüst, R. 2006. Lowland tropical peatlands of Southeast Asia. *Developments in Earth Surface Processes* 9:145-172, doi:10.1016/S0928-2025(06)09007-9.

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.D.V., Jaya, A. and Limin, S.2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* 420(6911):61-65, doi:10.1038/nature01131.

Pati, M.D., Anwar, S. and Widyastuti, R. 2016. Study of functional microbial populations in peat soils applied to two types of pesticides. *Jurnal Sumberdaya Hayati* 2(1):7-12 (*in Indonesian*).

Penot, E. 2004. From shifting agriculture to sustainable rubber complex agroforestry systems (jungle rubber) in Indonesia: an history of innovations production and adoption process. (synthèse CIRAD/ATP "Dynamiques forestières", CIRAD). In: Babin, D. (ed). *Beyond tropical deforestation*, UNESCO/CIRAD. p 221-250.

Penot, E., Chambon, B. and Wibawa, G. 2017. An history of rubber agroforestry systems development in Indonesia and Thailand as alternatives for a sustainable agriculture and income stability. *Proceedings of International Rubber Conference* 1-26.

Poulter, B., Fluet-Chouinard, E., Hugelius, G., Koven, C., Fatoyinbo, L., Page, S.E., Rosentreter, J.A., Smart, L.S., Taillie, P.J., Thomas, N. and Zhang, Z. 2021. A review of global wetland carbon stocks and management challenges. *Wetland Carbon and Environmental Management* pp.1-20, doi:10.1002/9781119639305.ch1.

Purnomo, E.P., Ramdani, R., Agustiyara, A., Tomaro, Q.P.V. and Samidjo, G.S. 2019. Land ownership transformation before and after forest fires in Indonesian palm oil plantation areas. *Journal of Land Use Science* 14(1):37-51, doi:10.1080/1747423X.2019.1614686.

Purnomo, E.P., Ramdani, R., Agustiyara, Nurmandi, A., Trisnawati, D.W. and Fathani, A.T. 2021a. Bureaucratic inertia in dealing with annual forest fires in Indonesia. *International Journal of Wildland Fire* 30(10):733–744, doi:10.1071/WF20168.

Purnomo, E.P., Rahmasari, F.V., Trisnawati, D.W., Agustiyara, and Erviana, R. 2021b. Observed data of forest fire hotspots effects on respiratory disorder by Arc-GIS in Riau Province, Indonesia. *IOP Conference Series: Earth and Environmental Science* 717:12036, doi:10.1088/ 1755-1315/717/1/012036.

Purnomo, E.P., Agustiyara, A., Ramdani, R., Trisnawati, D.W., Anand, P.B. and Fathani, A.T. 2021c. Developing the assessment and indicators for local institutions in dealing with forest fire dilemmas. *Forests* 12:704, doi:10.3390/f12060704.

Putikasari, V., Dahlan, E.N. and Prasetyo, L.B. 2014. Analysis of changes in land cover and socio-economic factors causing deforestation in the Kamojang Nature Reserve. *Media Konservasi* 19(2):126-140 (*in Indonesian*).

Rieley, J.O, and Page, S.E. 2016. Tropical peatland of the world. In *Tropical peatland ecosystems* (pp. 3-32). Springer, Tokyo.

Risbianti, E. 2015. Isolation of Insect Pathogenic Fungi from Peat Soil with Mustard-Corn and Mustard Planting Patterns in Central Kalimantan and Virulence Testing against *Plutella xylostella* Linnaeus (Lepidoptera: Plutellidae) in the Lab. Doctoral dissertation, Universitas Brawijaya (*in Indonesian*).

Rotinsulu, J.M., Afentina, Yanarita, Indrayanti, L., Nursiah, and Dewi, S. 2022. Finding strategies for peatland rehabilitation: agroforestry systems on various types of peat depth in three villages in Central Kalimantan. *Journal of Ecological Engineering* 23(2):150-158, doi:10.12911/22998993/144422.

Roucoux, K.H., Lawson, I.T., Jones, T.D., Baker, T.R., Coronado, E.H., Gosling, W.D. and Lähteenoja, O. 2013. Vegetation development in an Amazonian peatland. *Palaeogeography, Palaeoclimatology, Palaeoecology* 374:242-255, doi:10.1016/j.palaeo.2013.01.023.

Rydin, H., Jeglum, J.K. and Bennett, K.D. 2013. *The Biology of Peatlands, 2e*. OUP Oxford.

Sagastuy, M. and Krause, T. 2019. Agroforestry as a biodiversity conservation tool in the Atlantic Forest? Motivations and limitations for small-scale farmers to implement agroforestry systems in north-eastern Brazil. *Sustainability* 11(24):6932, doi:10.3390/su11246932.

Sherwood, J.H., Kettridge, N., Thompson, D.K., Morris, P.J., Silins, U. and Waddington, J.M. 2013. Effect of drainage and wildfire on peat hydrophysical properties. *Hydrological Processes* 27(13):1866-1874.

Silvianingsih, Y.A., Hairiah, K., Suprayogo, D. and van Noordwijk, M. 2020. Agroforests, swiddening and livelihoods between restored peat domes and river: effects of the 2015 fire ban in Central Kalimantan (Indonesia). *International Forestry Review* 22(3):382-396, doi:10.1505/146554820830405645.

Simpson, J.E., Wooster, M.J., Smith, T.E., Trivedi, M., Vernimmen, R.R., Dedi, R., Shakti, M. and Dinata, Y. 2016. Tropical peatland burn depth and combustion heterogeneity assessed using UAV photogrammetry and airborne LiDAR. *Remote Sensing* 8(12):1000, doi:10.3390/rs8121000.

Sinclair, A.L., Graham, L.L., Putra, E.I., Saharjo, B.H., Applegate, G., Grover, S.P. and Cochrane, M.A. 2020. Effects of distance from canal and degradation history on peat bulk density in a degraded tropical peatland. *Science of The Total Environment* 699:134199, doi:10.1016/j.scitotenv.2019.134199.

Sjögersten, S., Black, C.R., Evers, S., Hoyos-Santillan, J., Wright, E.L. and Turner, B.L. 2014. Tropical wetlands: a missing link in the global carbon cycle?. *Global Biogeochemical Cycles* 28(12):1371-1386, doi:10.1002/2014GB004844.

Stockwell, C.E., Jayarathne, T., Cochrane, M.A., Ryan, K.C., Putra, E.I., Saharjo, B.H., Nurhayati, A.D., Albar, I., Blake, D.R., Simpson, I.J. and Stone, E.A. 2016. Field measurements of trace gases and aerosols emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño. *Atmospheric Chemistry and Physics* 16(18):11711-11732, doi:10.5194/acp-16-11711-2016.

Subagio, H., Noor, M., Yusuf, W.A. and Khairulah, I. 2015. Swamp Land Development Policy. Online at: http://repository.pertanian. go.id/handle/123456789/7414, accessed 03 May 2021 (*in Indonesian*).

Subiksa, I.G.M., Hartatik, W. and Agus, F. 2011. *Sustainable Peatland Management*. Center for Agricultural Land Resources Research and Development, IAARD (*in Indonesian*).

Suharti, S. 2015. Increasing community income through cultivating various forestry commodities. *Proceedings of the National Seminar of the Indonesian Biodiversity*

Society 1(6):1416-1419, doi:10.13057/psnmbi/m010626 (*in Indonesian*).

Sumarga, E., Hein, L., Hooijer, A. and Vernimmen, R. 2016. Hydrological and economic effects of oil palm cultivation in Indonesian peatlands. *Ecology and Society* 21(2):52-71.

Supriati, L., Melhanah, M., Oemar, O. and Milenia, S. 2023. Exploration of fungal biological agents from the rhizosphere in peatlands with different planting Patterns. *AgriPeat* 24(2):31-39, doi:10.36873/agp.v24i2.8658 (*in Indonesian*).

Surahman, A., Soni, P. and Shivakoti, G.P. 2018. Are peatland farming systems sustainable? Case study on assessing existing farming systems in the peatland of Central Kalimantan, Indonesia. *Journal of Integrative Environmental Sciences* 15(1):1-19.

Surati, S., Irawanti, S., Hidayat, D.C., Handoyo, H., Ariawan, K., Kurniawan, A.S. and Mulyadin, R.M. 2019. Analysis of livelihoods on peatlands: The case of West Tanjung Jabung Regency. *Jurnal Penelitian Sosial dan Ekonomi Kehutanan* 16(2):81-93 (*in Indonesian*).

Sutikno, S., Nasrul, B., Gunawan, H., Jayadi, R., Saputra, E. and Yamamoto, K. 2019. The effectiveness of canal blocking for hydrological restoration in tropical peatland. *MATEC Web of Conferences* 276:06003.

Tacconi, L. 2003. *Fires in Indonesia: Causes, Costs and Policy Implications*. Occasional Paper No. 38, Center for International Forestry Research (CIFOR), Bogor, vi + 24 pp. ISSN: 0854-9818.

Tan, Z.D., Lupascu, M. and Wijedasa, L.S. 2020. Paludiculture as a sustainable land use alternative for tropical peatlands: A review. *Science of The Total Environment* 753:142111, doi:10.1016/j.scitotenv.2020.142111.

Tata, H.L. and Susmianto, A. 2016. *Prospects for Indonesian Peat Ecosystem Paludiculture*. Forda Press, Bogor, 71 pp (*in Indonesian*).

Tata, H.L., Bastoni, M., Sofiyuddin, Mulyoutami, E., Perdana, A. and Janudianto. 2015. Jelutung Rawa: Cultivation Techniques and Economic Prospects. ICRAF, Bogor, 62 pp (*in Indonesian*).

Taufik, M., Torfs, P.J., Uijlenhoet, R., Jones, P.D., Murdiyarso, D. and Van Lanen, H.A. 2017. Amplification of wildfire area burnt by hydrological drought in the humid tropics. *Nature Climate Change* 7(6):428-431, doi.org/10.1038/nclimate3280.

Taufik, M., Veldhuizen, A.A., Wösten, J.H.M. and Van Lanen, H.A.J. 2019. Exploration of the importance of physical properties of Indonesian peatlands to assess critical groundwater table depths, associated drought and fire hazard. *Geoderma* 347:160-169. doi:10.1016/j.geoderma.2019.04.001.

Uda, S.K., Hein, L. and Adventa, A. 2020. Towards better use of Indonesian peatlands with paludiculture and low-drainage food crops. *Wetlands Ecology and Management* 28:509-526, doi:10.1007/s11273-020-09728-x.

Uda, S.K., Hein, L. and Atmoko, D. 2019. Assessing the health impacts of peatland fires: a case study for Central Kalimantan, Indonesia. *Environmental Science and Pollution Research* 26(30):31315-31327, doi:10.1007/s11356-019-06264-x.

Uda, S.K., Hein, L. and Sumarga, E. 2017. Towards sustainable management of Indonesian tropical peatlands. *Wetlands Ecology and Management* 25(6):683-701, doi:10.1007/s11273-017-9544-0.

Vitt, D.H. and Short, P. 2020. *Peatlands* (pp. 27-36). CRC Press.

Waddington, J.M. and Price, J.S. 2000. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Physical Geography* 21(5):433-451. doi:10.1080/02723646.2000.10642719.

Warren, M., Hergoualc'h, K., Kaufman, J.B., Murdiyarso, D. and Kolka, R. 2017. An appraisal of Indonesia's immense peat carbon stock using national peatland maps: uncertainties and potential losses from conversion. *Carbon Balance and Management* 12, doi:10.1186/s13021-017-0080-2.

Weiss, D., Shotyk, W., Rieley, J., Page, S., Gloor, M., Reese, S. and Martinez-Cortizas, A. 2002. The geochemistry of major and selected trace elements in a forested peat bog, Kalimantan, SE Asia, and its implications for past atmospheric dust deposition. *Geochimica et Cosmochimica Acta* 66(13):2307-2323, doi:10.1016/S0016-7037(02)00834-7.

Whittington, P.N. and Price, J.S. 2006. The effects of water table draw-down (as a surrogate for climate change) on the hydrology of a fen peatland, Canada. *Hydrological Processes* 20(17):3589-3600, doi:10.1002/hyp.6376.

Widyati, E. 2011. Study of optimizing peatland management and climate change issues. *Tekno Hutan Tanaman* 4(2):57-68 (*in Indonesian*).

Wijayanti, F., Aditya, H.F., Jaya, A., Ramadhani, W.S. and Tarigan, R.A. 2023. Effect of land use differences on pH and available phosphorus in peatland, Kelampangan, Central Kalimantan. *Nusantara Science and Technology Proceedings* 24-27.

Wijedasa, L.S., Sloan, S., Page, S.E., Clements, G.R., Lupascu, M. and Evans, T.A., 2018. Carbon emissions from South-East Asian peatlands will increase despite emission-reduction schemes. *Global Change Biology* 24(10):4598-4613, doi.org/10.1111/gcb.14340.

Wildayana, E. 2017. Challenging constraints of livelihoods for farmers in the South Sumatra peatlands, Indonesia. *Bulgarian Journal of Agricultural Science* 23(6):894-905.

Wong, L.S., Hashim, R. and Ali, F.H., 2009. A review on hydraulic conductivity and compressibility of peat. *Journal of Applied Sciences* 9(18):3207-3218.

Wösten, J.H.M., Van Den Berg, J., Van Eijk, P., Gevers, G.J.M., Giesen, W.B.J.T., Hooijer, A., Idris, A., Leenman, P.H., Rais, D.S., Siderius, C. and Silvius, M.J. 2006. Interrelationships between hydrology and ecology in fire degraded tropical peat swamp forests. *Water Resources Development* 22(1):157-174.

Wright, E.L., Black, C.R., Cheesman, A.W., Turner, B.L. and Sjögersten, S. 2013. Impact of simulated changes in water table depth on ex situ decomposition of leaf litter from a neotropical peatland. *Wetlands* 33:217-226, doi:10.1007/s13157-012-0369-6.

Yanarita, Afentina, Sosilawaty, Birawa, C. and Monika, S. 2020. Social and economic analysis of agroforestry based on sago (*Metroxylon sago*): Alternative rehabilitation of forests and peatlands. *Jurnal Hutan Tropis* 8(3):306-314 (*in Indonesian*).

Yanarita, Indrayanti, L., Johanna, and Afentina. 2021. Biodiversity of soil macrofauna in jelutong (*Dyera lowii* Hook. F) based agroforestry system on peatlands. *Journal of Ecological Engineering* 22(7), doi:10.12911/22998993/139000.

Yin, Y., Ciais, P., Chevallier, F., Van der Werf, G.R., Fanin, T., Broquet, G., Boesch, H., Cozic, A., Hauglustaine, D., Szopa, S. and Wang, Y. 2016. Variability of fire carbon emissions in equatorial Asia and its nonlinear sensitivity to El Niño. *Geophysical Research Letters* 43(19):10-472, doi:10.1002/2016GL070971.

Yu, Z., Beilman, D.W., Frolking, S., MacDonald, G.M., Roulet, N.T., Camill, P. and Charman, D.J. 2011. Peatlands and their role in the global carbon cycle. *EOS, Transactions American Geophysical Union* 92(12):97-98, doi:10.1029/2011EO120001.

Yulianti, N., Kusin, K., Naito, D., Kawasaki, M., Kozan, O. and Susatyo, K.E. 2020. The linkage of El Niño-induced peat fires and its relation to current haze condition in Central Kalimantan. *Journal of Wetlands Environmental Management* 8(2):100-116, doi:10.20527/jwem.v8i2.221.

Yuptriani, S.P., Rizal, M., Prasetyo, A., Fahlifi, R., Situmorang, J., Rahmadini, D., Siahaan, E.R., Sumantri, D.P., Sinambela, M., Aprilyani, R. and Rindhianto, A.F. 2020. Management of peat swamp fisheries resources to improve the economy of the people of Tanjung Taruna Village, Pulang Pisau Regency. *UNRI Conference Series: Community Engagement* 2:372-378 (*in Indonesian*).

Yuwariah, Y.A.S. 2016. The potential of agroforestry to increase the nation's independent income and improve the environment. *Proceedings of the 2015 National Agroforestry Seminar: Agroforestry Innovation Supports National Independence*, Research and Development Centre for Agroforestry Technology, Bandung, 1-21 (*in Indonesian*).

Zhao, M., Zhao, J., Yuan, J., Hale, L., Wen, T., Huang, Q., Vivanco, J.M., Zhou, J., Kowalchuk, G.A. and Shen, Q. 2021. Root exudates drive soil-microbe-nutrient feedbacks in response to plant growth. *Plant, Cell & Environment* 44(2):613-628, doi:10.1111/pce.13928.