The performance of paludiculture commodities at different peat depths in Central Kalimantan

T W Yuwati*, D Rachmanadi, M A Qirom, P B Santosa, W Halwany, S Hakim and D Alimah
Banjarbaru Environment and Forestry Research and Development Institute, Jl. A Yani km 28.7 Landasan Ulin, Banjarbaru, Indonesia

*E-mail: yuwatitriwira@gmail.com

Abstract. Paludiculture is one of the alternative efforts to restore degraded peatland. It involves rewetting, revegetation and revitalization of local livelihood. This research evaluated three paludiculture demonstration plots at Central Kalimantan, one in the shallow peat of Pilang village and two plots in the deep peat of Tumbang Nusa village. The plots were evaluated in terms of the plant's growth, productivity, commodities introduced and environmental monitoring, including water table, soil physical and chemical properties, carbon stocks and CO₂ emission. The results showed that the three plots were categorized as "compromised" paludiculture plots because some of the commodities were not local peatland species. Belangeran (Shorea balangeran) and horticultural plant species such as rambutan (Nephelium lappaceum) and pineapple (Ananas comosus) showed good growth performance. Liberica coffee (Coffea liberica) was not suitable for deep peat due to its low survival rate and poor growth. The result also showed that soil peat characteristics of the sites were still in good condition; however, the impact of peatland utilization should have been monitored to support land-use sustainability. Moreover, stingless bee cultivation and vegetables could become potential commodities to be developed in shallow and deep peatland.

1. Introduction
The tropical peatland covers 44 million hectares or approximately 11% of the total world's peatland [1]. Twenty-one million hectares of it lie in Indonesia [2]. Tropical peatlands have ecologically important functions in carbon storage, hydrological control, and habitat for flora, fauna, and microbes [3]. However, the tropical peatland in Southeast Asia has experienced massive changes, and only 6% remains in pristine condition as of 2015 [4]. The massive changes in tropical peatlands were caused by fire, logging, and drainage for the conversion into other land uses such as agriculture, oil palm plantations, Acacia plantations and smallholdings [3, 5, 6]. To restore Indonesia's tropical peatland, the Indonesian government established the Peatland Restoration Agency or Badan Restorasi Gambut (BRG) in early 2016. The establishment of BRG was motivated by 2015 land fires that had burned 2.6 million hectares of land [7]. The restoration action policy includes rewetting, revegetation, and revitalization of local livelihoods. The rewetting activities have established the rewetting infrastructures, which comprise 11,800 deep wells, 5,936 canal blockings, and 242 canal backfillings by the end of 2018 [7]. Moreover, in revegetation activities, BRG claimed to have built the construction of 713 revegetation demonstration plots across Riau, Jambi, South Sumatra, South Kalimantan, and Central
Kalimantan. Paludiculture is one way to restore the degraded tropical peatland in Indonesia [8]. It is not just an act of revegetation but also has the potential to contribute to the revitalization of local livelihoods [7].

According to [8], "paludiculture comprises any biomass use from wet and rewetted peatlands, from using spontaneous vegetation on natural sites to harvesting artificially established crops on rewetted sites". Furthermore, [9] stated that paludiculture can be defined as a sustainable alternative for peatland utilization without drainage, including growing crops in peatland. However, a previous study by [10] and [11] has identified Sumatera and Central Kalimantan projects that adopted paludiculture principles. Moreover, [12] stated that most paludiculture projects studied can be categorized as "compromised" paludiculture because they unfollowed the paludiculture principles such as rewetting before revegetation and using local peatland species.

Banjarbaru Environment & Forestry Research and Development Institute has established three paludiculture demonstration plots in Central Kalimantan. They can also be called "compromised" paludiculture because various species selected were not local peatland species. However, following [12], "paludiculture should be a win-win solution to restoring degraded peatlands, reducing emissions, avoiding fire risks and improving food security". Therefore, this paper aims to evaluate three paludiculture demonstration plots in Central Kalimantan regarding the plant's growth, productivity and environmental monitoring.

2. Materials and Methods

2.1. Location

The three paludiculture demonstration plots were located in Jabiren Raya sub-district, Pulang Pisau district, Central Kalimantan province. Two plots were located in the deep peat of Tumbang Nusa village, and one plot was in the thin peat of Pilang village.

2.2. Site description

The first plot is located in the Tumbang Nusa Forest Research Station (KHDTK Tumbang Nusa). The plot was established by the end of 2019. There are various plant species planted in this plot. We combined local peat swamp forest species such as ramin (Gonystilus bancanus), gerunggang (Cratoxylon glaucum) and Belangeran (Shorea balangeran) with horticulture species such as rambutan (Nephelium lappaceum), pinang (Areca catechu), kopi Liberika (Coffea liberica) and pineapple (Ananas comosus). There were three treatments for ramin, gerunggang, belangeran, rambutan, pinang and coffee. Those were control, compost application and biochar application.

The second plot is located in the farmer's land of Tumbang Nusa village (Pak Stomo's). The plot was established by the end of 2017. In this location, there is a natural growth of gerunggang that has been kept from the 2015 fire. At the end of 2020, under this stand, we introduced commodity of10 boxes of stingless bee (Trigona sp.) and flowering plants such as jengger ayam (Celosia crestitata), matahari mini (Helianthus annuus) and kaliandra (Calliandra sp.). We also planted rambutan, pineapple and liberica coffee under this stand. Adjacent to the gerunggang stand, the farmer planted rubber (Hevea braziliensis), and we established a beje fish pond adjacent to the rubber plantation. Under the four-year-old rubber stand, we introduced vegetables such as chili (Capsicum frutescens), eggplants (Solanum melongena) and keladi kentang (Colocasia esculenta).

The third plot is located in the rubber garden of Pilang village (Ibu Jenta's). Under this stand, we introduce commodities such as ten boxes of stingless bees, flowering plants of jengger ayam, matahari mini, kaliandra and vegetables such as chili, eggplants, water spinach (Ipomoea aquatica), turmeric, lemongrass and ginger.

2.3. Methods

The three demonstration plots were evaluated. We recorded the plant's growth, the productivity of the introduced commodities, and environmental monitoring such as water table, soil physical properties, carbon stocks, and CO₂ emissions. The water table monitoring was conducted with an automatic water logger, which was set to record every 6 hours. We collected soil samples for physical and chemical
analysis. The CO$_2$ emission was carried out by the oven close chamber method [13]. The prediction of carbon stock potential was conducted using allometric tree models. We did a survey and took non-destructive sampling for trees and destructive sampling for litters, understorey and necromass. The litters, understorey, and necromass samples were recorded for total fresh weight, collected 100 grams each, and oven at 103°C ± 3°C until they reached constant weight [14].

3. Results and Discussion

3.1. Demonstration plot at KHDTK Tumbang Nusa

The survival rate of six plant species in the KHDTK Tumbang Nusa plot is presented in Figure 1.

![Survival Rate (%)](image)

**Figure 1.** Survival rate (%) of six plant species with different treatments namely control, compost and biochar application at paludiculture plot of KHDTK Tumbang Nusa, Central Kalimantan.
The height and diameter relative growth rate performance of the six species is presented in Table 1. Relative height and diameter growth rate of six plant species 7 months after planting at KHDTK Tumbang Nusa plot with compost and biochar application compared with control.

| Species   | Treatment | Relative Growth Rate |   |   |
|-----------|-----------|----------------------|---|---|
|           |           | height (cm)          |   |   |
| Ramin     | Control   | 0.007                | 0.020|
|           | Compost   | 0.005                | 0.013|
|           | Biochar   | 0.012                | 0.022|
| Rambutan  | Control   | 0.007                | 0.316|
|           | Compost   | 0.014                | 0.313|
|           | Biochar   | 0.199                | 0.312|
| Belangeran| Control   | 0.013                | 0.387|
|           | Compost   | 0.019                | 0.373|
|           | Biochar   | 0.167                | 0.014|
| Pinang    | Control   | 2.474                | 2.024|
|           | Compost   | 2.788                | 2.195|
|           | Biochar   | 2.931                | 1.945|
| Coffee    | Control   | 2.838                | 1.097|
|           | Compost   | 2.729                | 1.036|
|           | Biochar   | 2.899                | 1.065|
| Gerunggang| Control   | 0.057                | 0.434|
|           | Compost   | 0.072                | 0.437|
|           | Biochar   | 0.066                | 0.406|

Table 1 showed that the application of biochar (mixture of charcoal, compost, and microbes) relatively supported plants' height and diameter growth. The biochar mixture is an organic fertilizer mixed with organic fertilizer and bio-activator as the decomposer. In addition, the application of charcoal proved to increase pH and support the plan's growth.

The soil physical characteristic at the KHDTK Tumbang Nusa plot is presented in Table 2.

| Peat depth (cm) | Water content (%) | Bulk Density (g cm\(^{-3}\)) | Porosity (%) |
|----------------|-------------------|-------------------------------|--------------|
| 0              | 297.22            | 0.24                          | 91.06        |
| 10             | 401.70            | 0.18                          | 93.10        |
| 20             | 506.89            | 0.18                          | 93.15        |
| 30             | 392.74            | 0.18                          | 93.08        |
| 40             | 352.39            | 0.20                          | 92.53        |
| 60             | 828.06            | 0.10                          | 96.40        |

The soil's physical characteristics showed that there were alterations after the fire. The location of this plot was severely burnt in 2015, which lasted for more than three months. Based on the theory, the water content and bulk density will increase along with the peat depth [15]. Based on the table, we can see that at 30-40 cm peat depth, there was a decrease in the value of water content, while for the deeper depth, the water content increased. Therefore, it was predicted that the fire had reached 30-40 cm of the peat layer. However, if we look at the bulk density, fire indicates to happen until 60 cm
depth because this layer should have a higher bulk density value compared with the previous layer. The higher value of bulk density showed that there was peat compaction due to forest fire.

3.2. Demonstration plot at Tumbang Nusa village (Pak Stomo's)

The commodities at the paludiculture plot at pak Stomo's are presented in Table 3.

| Commodity          | Planting pattern                  | Reasons for species selection                                             |
|--------------------|-----------------------------------|---------------------------------------------------------------------------|
| Gerunggang         | Natural regeneration              | Natural regeneration maintained by the farmer                              |
| Beje fish pond     | Integrated with pak Stomo's rubber plantation | Source of local fish and source of water for fire management.               |
| Rambutan           | Strip planting                    | Adaptive and productive in peatland                                       |
| Liberica Coffee    | 5m x 5m under gerunggang          | Success story from Jambi province                                          |
| Pineapple          | 50 cm x 50 cm at the border of rubber plantation | Adaptive, but needs mounding                                              |
| Stingless bee      | Placed under gerunggang stand of 10 boxes | Non-timber forest product with high economic value                         |
| Celosia flower/jengger ayam | Planted adjacent to the stingless bee boxes | Source of food for stingless bee                                           |
| Mini sunflower/matahari mini | Planted adjacent to stingless bee boxes | Source of food for stingless bee                                           |
| Caliandra sp.      | Planted under Gerunggang stand    | Source of food for stingless bee                                           |
| Chilli             | Planted in a permanent compartment of 2 x 5 m (2 compartments) filled with topsoil and organic fertilizer | Adaptable short term crops for peatland farmers                            |
| Eggplant           | Planted in a permanent compartment of 2 x 5 m (2 compartments) filled with topsoil and organic fertilizer | Adaptable short term crops for peatland farmers                            |
| Keladi kentang (Colocasia sp.) | Planted at the border of rubber plantation | Adaptable to inundated condition, source of vegetable                     |

The coffee (Coffea liberica) survival rate was 40%, while rambutan and pineapple were 80%. The planting of vegetables was directed at the permanent compartment. The vegetable planting was concentrated only inside the permanent compartment because we did not want to disturb the peat soil. Therefore, the environmental manipulation for vegetable growth was only carried out inside the compartment. The agricultural activities in peatland are expected to align with the paludiculture concept, which is minimum tillage or wet cultivation and no drainage.

Trigona sp. (stingless bee) honey is getting popular nowadays due to its higher economic value compared with Apis honey. Moreover, it is believed that stingless bee honey contains antioxidants, antitoxin, and antibiotics to support our immune and health. Due to the high demand, sometimes the stingless bee honey stock is limited despite its high price. Although it is not yet known for local people at peatland, it has a high potential to be developed. The advantages of stingless beekeeping are that it is flexible to be kept in various locations, and the higher price of honey and the bee are stingless. The stingless bee productivity is 1.5-2 liter of honey per month. Stingless bee honey is more expensive than other bee honey (IDR 400,000 per liter). It means it contributed to the farmer's income of IDR 600,000 - 800,000 per month.

It is also expected that the biophysical condition of the area is monitored and maintained for its sustainability. One aspect of monitoring the environmental condition is the soil physical characteristic, as presented in Table 4.
Table 4. Soil physical characteristic at deep peat fo Tumbang Nusa village (pak Stomo's).

| Peat layer (cm) | Water content (%) | Bulk density (g cm\(^{-3}\)) | Porosity | Hydraulic conductivity (m day\(^{-1}\)) | Peat maturity |
|----------------|------------------|---------------------------|----------|----------------------------------------|---------------|
| 0-10           | 533.21           | 0.14                      | 94.74    | 0.23                                   | Hemic         |
| 10-20          | 836.77           | 0.10                      | 96.19    | 0.09                                   | Fibric – Hemic|

Soil physical characteristics important for agriculture include water content, bulk density, bearing capacity, subsidence, and irreversible drying. The peat soil water content ranges from 100-1300% of its dry weight. Another peat soil physical characteristic is irreversible drying, where the water content is less than 200%. The normal peat water content is 1000%. In Pak Stomo's, the soil water content ranges from 533.21% - 836.77%. It was caused by several factors such as repeated fire, over drainage, and vegetation cover changes. Although the condition has changed, the soil water content is still in good condition, and there is no sign of irreversible drying.

The water table at the paludiculture plot was monitored, and the water table fluctuation is presented in Figure 2.

![Figure 2](image_url)

**Figure 2.** Water table fluctuation at Pak Stomo’s plot under Rubber and Gerunggang stand (15 August 2020-2 December 2020).

Figure 2 shows that the water table fluctuation under Gerunggang and rubber stand have a similar trend. The lowest water table reached 40-50 cm below the soil surface, and the highest reached 15 cm upper soil surface. Since the lowest water table still reached 40 cm, it can still be categorized as paludiculture.

3.3. *Demonstration plot at Pilang village (Ibu Jenta's)*

The commodities at the paludiculture plot of Bu Jenta's are presented in Table 5.
Table 5. Commodities, planting pattern, and reason of species selection at Bu Jenta's plot, Pilang village.

| Commodities       | Planting pattern                              | Reasons for species selection                                      |
|-------------------|-----------------------------------------------|---------------------------------------------------------------------|
| Rubber            | Planted in 2016 (3 x 3m)                      | Farmer preference                                                  |
| Stingless bee     | Placed under rubber stand of 10 boxes         | Non-timber forest product with high economic value                |
| Celosia flower    | Planted adjacent to the stingless bee boxes    | Source of food for stingless bee                                   |
| Mini sunflower    | Planted adjacent to stingless bee boxes        | Source of food for stingless bee                                   |
| Caliandra sp.     | Planted in stripe 50 cm x 50 cm under the rubber | Source of food for stingless bee                                   |
| Chili             | Planted in stripe 50 cm x 50 cm under the rubber | Adaptable short term crops for peatland farmers                    |
| Eggplant          | Planted in stripe 50 cm x 50 cm under the rubber | Adaptable short term crops for peatland farmers                    |
| Water spinach     | Planted in stripe under the rubber            | Farmer preference, good price                                       |
| Ginger            | Planted in stripe under the rubber            | Farmer preference, good price                                       |
| Turmeric          | Planted in stripe under the rubber            | Farmer preference, good price                                       |
| Lemongrass        | Planted in stripe under the rubber            | Farmer preference, good price                                       |

The productivity of eggplants at Bu Jenta's in three months was 3 kilograms. There were 25 eggplants in total. The eggplants were sold to the market at the price of IDR 8000 per kilogram. It means, in total, eggplants contribute to the income of IDR 200,000 per month. The productivity of chili was 1-1.5 kg plant$^{-1}$ for eight months. There were 75 chili plants. The chilis were sold to the market at the price of IDR 30,000 kg$^{-1}$. During eight months, it contributed to the income of 2.25 million rupiahs or IDR 300,000 month$^{-1}$. As for water spinach (kangkung), Bu Jenta received IDR 150,000 month$^{-1}$. It means, from vegetables (chili, eggplant and water spinach), she received an additional income of IDR 650,000 month$^{-1}$.

One month after the stingless bee boxes were set up, Bu Jenta harvested 1.8 liters of honey. The price of stingless bee honey (madu kelulut) is IDR 400,000 per liter. It means that stingless bees gave a monthly income contribution of IDR 720,000.

The plot is located at thin peat surrounded by an oil palm plantation. The Peatland Restoration Agency set up several canal blockings in 2016. Though located at the cultivation function, the land-use sustainability shall be maintained. The soil physical characteristic in Bu Jenta's is presented in Table 6.

Table 6. Soil physical characteristic at thin peat of Pilang village.

| Water content (%) | Bulk density (g cm$^{-3}$) | Porosity | Hydraulic conductivity (m day$^{-1}$) | Peat maturity |
|-------------------|----------------------------|----------|--------------------------------------|---------------|
| 383.46-692.15     | 0.136-0.214                | 77.52-86.65 | 3.6-5.00 | Hemic                       |

The soil physical characteristic showed that soil water content is more than 200%. It means that there is no irreversible drying. However, the hydraulic conductivity value showed that the thin peat was constantly burnt every year. Based on the literature, land utilization and fertilizer application resulted from peat soil compaction and are related to the lower hydraulic conductivity [15-17].

3.4. Carbon stock prediction

Land management will affect the changes in biotic and abiotic conditions [18]. The changes can be monitored by recording the land potential as a carbon sequester. Intensive management contributes to the decreasing carbon stock potential, especially for underground vegetation. However, the total carbon stock did not change. Figure 5 showed carbon stock potential in the form of above-ground biomass at various land utilization in Central Kalimantan. The above-ground biomass includes litter, understorey and planted vegetation. On the surface biomass, vegetation served as the biggest carbon stock. In the early stage of growth, silvicultural intervention caused the decrease in carbon stock, and
it will gradually increase as time passes [19, 20]. This condition happened at natural regeneration after fire at Tumbang Nusa (Pak Stomo’s) and agroforestry at Pilang village (Bu Jenta’s). The changes in the carbon stock as an indicator of land utilization impact on environmental conditions. Moreover, with this value, we can determine the minimal limit of land utilization, which is not harmful to the environment; however, it is economically feasible.

![Figure 3. Carbon stock potential at various land utilization in Central Kalimantan.](image)

3.5. CO₂ emission
Table 7 presents the CO₂ emission at three paludiculture plots of Central Kalimantan. We measured the CO₂ emission two times. The first measurement was carried out on 8 August 2020, and the second was carried out on 15 August 2020. The measurement was conducted for 10 minutes at each location by putting six chambers. The mean of the CO₂ emission for six chambers and two times measurement is presented in Table 7.

| Location                                         | Temperature | CO₂ emission (mg C m⁻²h⁻¹) |
|--------------------------------------------------|-------------|-----------------------------|
| KHDTK plot (open area)                           | 35.6        | 360.68                      |
| KHDTK plot (plantation)                          | 35.8        | 275.41                      |
| Stomo's (Gerunggang stand)                       | 32.9        | 260.08                      |
| Stomo's (rubber planted 2018)                    | 33.3        | 354.32                      |
| Stomo's (bush)                                   | 34.8        | 336.29                      |
| Jenta's (rubber planted 2016/non-intensive)      | 35.1        | 386.23                      |
| Jenta's (rubber planted 2016/intensive)          | 32.9        | 358.82                      |

The result showed that revegetation activities, especially with perennials, are proven to be a carbon sequester due to the lower carbon gas under the trees compared with the open areas. Moreover, we can see that tending or intensive management had a strong impact on CO₂ emission as we know that
tending activity reduces understorey and will increase CO$_2$ gases emission. It means that understorey is highly contributed to the value of CO$_2$ emission from the root respiration.

4. Conclusion

Environmental monitoring such as soil physical characteristics, water table, subsidence, carbon stock, CO2 emission is needed to ensure peat land-use sustainability after cultivation. Stingless bees and vegetables are potential as the alternative livelihood in Central Kalimantan peatland.

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**Acknowledgments**

The authors gratefully acknowledge Food Estate Program (PEN-BLI-KLHK) 2020 for providing financial support for this study. The authors would also wish to thank farmers and government officials of Central Kalimantan for their contributions to this research.

**Author's contribution**

All authors equally contributed to designing the research, collecting data, data analysis and writing the manuscript.