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Tamanu (Calophyllum inophyllum) growth performance on different types of degraded peatlands in Central Kalimantan

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Abstract. To achieve its national goals in climate and landscape resilience, including bioenergy production, the Government of Indonesia has launched an initiative to restore 14 million hectares of degraded land, including 2 million hectares of peatlands, by 2030. Here we present early findings on *tamanu* adaptability and tree growth (height, diameter and branches) on two types of degraded peatlands in Central Kalimantan. The paper reports peatland type and *tamanu* tree growth and adaptability in a 3-ha plantation trial plot over three years and a 2-ha plot over two years in Kalampangan and Buntoi villages. Results show survival rates of 82% in the plot on ombrogenous peat in Kalampangan and 81% on topogenous peat in Buntoi. Furthermore, the growth performance of 2-year-old *tamanu* trees on topogenous peat in Buntoi with an average height of 1.74 m and diameter of 3.97 cm at 5 cm above ground level and 15 branches was better than on ombrogenous peat in Kalampangan with an average height of 0.68 m and diameter of 1.43 cm at 5cm above ground level and five branches. While initial survival and tree growth results are promising, further monitoring of flowering and fruiting is necessary to determine *tamanu*'s viability for biodiesel production on degraded peatlands.

1. Introduction

The energy demand is increasing globally, and Indonesia is no exception as it is among the fastest-growing energy consumers. Indonesia is the world's fourth most populous country, the fourth-largest producer and leading exporter of coal, the largest biofuel producer, and the biggest supplier of gas in Southeast Asia [1]. It is estimated that Indonesia's energy demand will increase by 80% from 2015 to 2030, while electricity demand is projected to rise triple in the same period. [2]. Therefore, the Government of Indonesia (GoI) has set a policy towards a transition to renewable energy.

Indonesia's national energy policy 2014 mandates to advance renewable energy into 23 % and 31% of the total primary energy supply by 2025 and 2050, respectively. GoI has several policies and regulations to support this initiative. Government Regulation No. 5/2006 [3] was an essential first step in developing Indonesia's National Energy Policy (*Kebijakan Energi Nasional*). The national energy target was increased in 2014 through Regulation No. 79/2014 [4], where provisions regulating new and renewable energy (NRE) include the procurement and use of biofuels. In addition, the President mandated other government agencies to act in advancing all stages of biofuel development from feedstock supply to commercialization of biofuel technologies and increased biofuel consumption (Presidential Instruction No. 1/2006) [5]. This included giving the Minister of Forestry a mandate to grant permits for using unproductive forest land to develop biofuel feedstocks. In 2018, GoI launched an initiative to restore approximately 14 million hectares of degraded lands [6] by 2030 to achieve national climate and landscape resilience goals, including bioenergy production, with the added benefits of restoring degraded land and providing food and livelihoods for local communities. The restoration target includes 2 million hectares of degraded peatlands.

For biofuel policies to support Indonesia's commitment to achieving low carbon growth, it is imperative to select sustainable and environmentally friendly raw materials. Indonesia has abundant biomass sources, but some of them are carbon-intensive. In addition, many first generations of biofuels used edible oils and were linked to emissions from land-use change. However, second-generation biofuels are less carbon-intensive because they use various raw materials, including non-edible oils, to avoid competition with food production [7].

Tamanu (Calophyllum inophyllum) is a tropical tree species with potential for biofuel production and an ideal alternative for biodiesel as it grows well under harsh environmental conditions on generally unproductive land [8], and produces significant amounts of non-edible kernel oil [9]. The species produces flowers and fruit in profusion all year round, and its seeds can be harvested repeatedly from trees aged from 4 to 5 until 50 years old [10]. *Tamanu* trees generally grow in warm temperatures under wet or moderate conditions and tolerate wind, salt spray, drought and brief periods of waterlogging [8]. Due to its high tolerance to harsh environmental conditions, since more than 50 years ago, the species has been planted for conservation and land rehabilitation purposes in southern regions of the island, Indonesia [11]. Reports on *tamanu* performance in mineral soils in Indonesia have shown it grows well in coastal areas [12], on marginal land [13], rocky soils [12] and burnt land [14]. However, there is a gap in studies on *tamanu* survival and growth on degraded peatlands. This study aims to fill this gap.

A study on bioenergy species trials on degraded peatlands in Central Kalimantan for *Gliricidia sepium*, *Calliandra calothyrsus*, *Reutealis trisperma* and *Calophyllum inophyllum* reported that of the four tested species, *tamanu* was the most adaptable for growth with an 88% survival rate [15]. In 2018, plantation trials were established on degraded peatlands in Central Kalimantan to determine the adaptability and growth of *tamanu* on a broader scale. This paper aims to share early findings on *tamanu* adaptability and tree growth on two types of degraded peatlands in Central Kalimantan, i.e., topogenous and ombrogenous peat in Buntoi and Kalampangan villages, respectively.

2. Materials and Methods

2.1. Site description

In the research sites in Buntoi village, Pulang Pisau district and Kalampangan village, Palangkayaya district, Central Kalimantan (Figure 1), trial plots for bioenergy species were established in 2018. The plot in Buntoi is on two hectares of degraded peatland. The area was a private small-scale rubber plantation managed by a local farmer affected by fire in 2015. The plot in Kalampangan is located on *etalase bioenergi* land on three hectares managed by the Central Kalimantan Provincial Energy and Mineral Resources Office (*Distamben*). The *etalase bioenergi* showcased bioenergy species plantations on degraded peatlands and was initiated by the Ministry of Energy and Mineral Resources (ESDM) and the local government. Site characteristics of the trial plots in Kalampangan and Buntoi Villages are shown in Table 1.

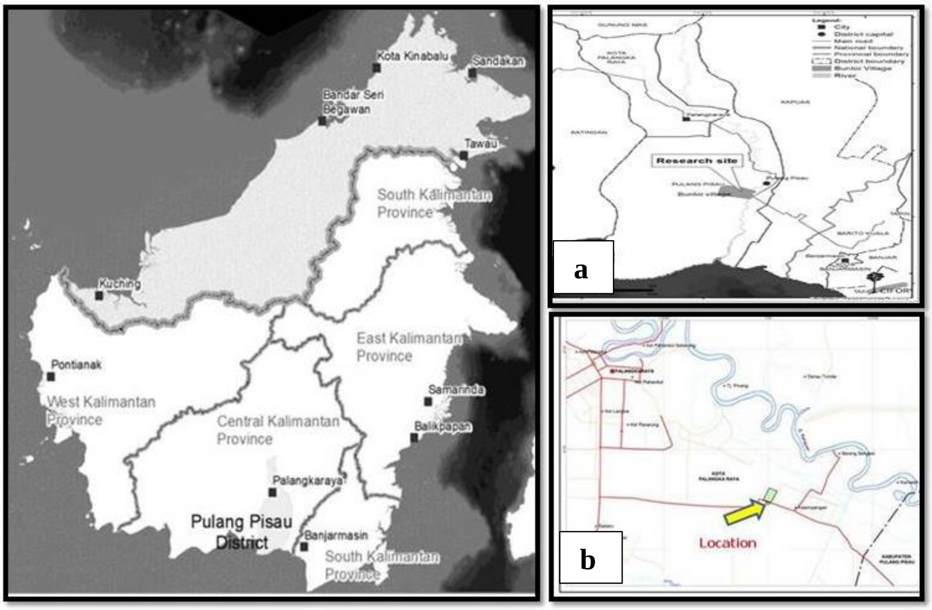

Figure 1. Locations of the research sites in a) Buntoi (Pulang Pisau) and b) Kalampangan (Palangkaraya) (Map created by CIFOR, 2021).

Table 1. Site characteristics in Kalampangan (Palangkaraya) and Buntoi (Pulang Pisau).

Site characteristics	Kalampangan	Buntoi
Plot area (Ha)	3	2
Latitude (South)	102^0 27'52.4"	102^0 48' 59.4"
Longitude (East)	113^0 99'97.8"	114^0 10'47.3"
Average annual rainfall (mm)	287.6	239.2
Temperature (^{0}C)	23-35^0 C	26.5-27.5 ^{0}C
Altitude (m asl.)	12	10-50
Vegetation cover	Acacia, shrub	Ex-burned smallholder rubber plantation
Last burned	2014, 2015	2015
Soil type	Peatland with black solid layer/spodosol	Peatland and alluvial
Type of peatland	Ombrogenous	Topogenous
Average peat depth (cm)[1]	276	61.3
Water level (cm)[2]	24.9-143.08	-6.7-89.9
Canal	No	Yes l[3]

Sources: [15, 16]
Remarks:
[1] based on 2018 measurement
[2] based on 2018-2019 measurement
[3] 1 small canal (1 m wide) developed by the previous landowner is inside the plot and used to divide the plot into the front and rear parts. Additional canals were constructed surrounding the plot functioned as a fire break with 1 m wide and 1 m depth surrounding the plot. The plot locates closely to a canal constructed under the 1-million-hectare peat project in 1995

2.2. Material and equipment

Tamanu trees were planted using genetic material (seeds) from provenance seed stand in Wonogiri (Central Java) and natural stand from Dompu (West Nusa Tenggara) for Kalampangan and Buntoi, respectively. The seed from these provenances has the highest oil content compared to other provenances in and outside Java [9]. Materials used included NPK fertilizer, aluminum foil and plastic seals for soil samples. Tools used for carrying out the research included calipers, meter tapes, piezometers and augers.

2.3. Soil sampling and method

Peat soil samples in both Buntoi and Kalampangan were collected using Russian D-shape peat corers. For determining soil physical properties, samples were collected at nine and six randomly selected points in Kalampangan and Buntoi, respectively. Soil samples collected from each point were composited for physical property analysis. The samples for determining soil chemical properties were collected at three blocks in three different layers (0-50 cm and 50-100 cm), resulting in 6 samples in Kalampangan and at eight randomly selected points in Buntoi. Composites for chemical analysis were from samples collected in three different permanent unit plots (PUPs) for 50 g, 100 g and 200 g NPK). The physical and chemical properties of each sample were analyzed in the Soil Laboratory at Bogor Agriculture University Faculty of Agriculture to examine soil fertility and peat quality. In addition, 28 piezometers were installed, of which 12 and 16 units are in Kalampangan and Buntoi, respectively, to observe the water level of both trial plots. The water level was regularly monitored every three months between 2018 and 2019.

The following analyses were carried out on each soil sample according to manuals on soil, water, plant and fertilizer analyses [17]: soil pH by digital pH meter on water suspension for actual pH (ApH) and on HCl solution in soil suspension for potential pH (PpH); Organic Carbon using the Walkley & Black method; total nitrogen (TN) using the Kjeldahl method; available phosphorus (AP) using the Bray-1 method; total phosphorus (TP) by HCl 25% extraction, base cations such as natrium (Na^+), potassium (K^+), calcium (Ca^+) and magnesium (Mg^+) were extracted using an acetic acid-ammonium solution. In addition, soil samples and peat depth were measured from each trial plot to examine soil fertility and peat quality.

2.4. Research plot design

The trial plot in Kalampangan was arranged in a randomized complete block design (RCBD). In February 2018, 1200 *tamanu* seedlings were planted on a three-hectare area with a spacing of 5m x 5m. The trial plot was divided into three blocks consisting of three permanent measurement plots (PMPs) in blocks 1 and 2 and five PMPs in block 3, with different doses of NPK fertilizer application (i.e., 50 g, 100 g and 200 g). Furthermore, 134 trees were randomly selected and monitored quarterly between February 2018 and December 2020. The trial plot in Buntoi did not apply a special design. The two-hectare plot was divided into two blocks and five PMPs with 100 g doses of NPK fertilizer application. In December 2018, 313 *tamanu* seedlings were planted with a spacing of 8m x 8m and 54 trees were randomly selected for regular quarterly monitoring up to December 2020. Growth characteristics of height, diameter (measured from 5 cm above ground level), and numbers of branches were measured during the regular monitoring in both plots.

2.5. Data analysis

In the trial plot in Kalampangan, a one-way ANOVA statistical model was applied to examine growth response to different treatments. One-way ANOVA analysis is commonly used to compare the effects of different treatments between two populations [18]. An SAS (Statistical Analysis System) ver. 9.0 program was used to analyze the data.

ANOVA was performed using the plot's mean data (Y_{ij}) for growth, with the following linear model:

$$Y_{ij} = m + T_i + e_{ij}$$

where m is the overall mean, T_i is the i-th treatment effect, and e_{ij} is the experimental error for Y_{ij}.

In Buntoi, data from periodical measurement in PMPs were averaged to examine *tamanu* growth performance.

3. Results and Discussion

3.1. Soil physical and chemical properties in trial plots

Peatlands in Kalampangan and Buntoi villages have slightly different physical and chemical soil characteristics, as shown in Tables 2 and 3. However, physical properties fell in the same categories, i.e., very high, extremely high, and low for water-filled pore space (WFPS), moisture content and bulk density, respectively. Meanwhile, peat depth in Kalampangan was thicker than in Buntoi (Table 2).

Table 2. Soil physical properties in trial plots in Kalampangan and Buntoi.

Soil Physical Properties	Kalampangan			Buntoi		
	Range	Average	Category[1]	Range	Average	Category[1]
Peat depth (cm)	225-304	275.78	Deep	40-93	61.33	Shallow
Bulk density (g cm^{-3})	0.27-0.41	0.34	Low	0.5-0.63	0.56	Low
Moisture content (%)	117-221	153	Extremely high	40-91	57	Extremely high
WFPS (%)	76-137	112	Very high	–128-217	163	Very high

Remark: [1] USDA Soil Taxonomy 2014

Soil chemical properties were analyzed for 11 characteristics, as shown in Table 3. The results show that Kalampangan and Buntoi have the same categories for all observed soil chemical characteristics. However, average values for chemical properties except for the C/N ratio, total P, Ca² + and K+ were higher in Kalampangan than in Buntoi.

Table 3. Soil chemical properties in trial plots in Kalampangan and Buntoi.

Soil Chemical Properties	Kalampangan						Buntoi		
	0 - 50 cm depth			50 - 100 cm depth					
	Range	Mean	Category	Range	Mean	Category	Range	Mean	Category
ApH	3.6-3.7	3.7	VA	3.6-3.7	3.67	VA	3.1-3.7	3.4	VA
PpH	3.1-3.2	3.2	VA	3.2-3.4	3.3	VA	3.0-3.6	3.4	VA
Organic C (%)	8.6-8.7	8.7	VH	3.6-3.8	8.7	VH	4.4-8.2	7.2	VH
TN (%)	0.24-0.30	0.27	M	0.25-0.29	0.27	M	0.17-0.28	0.21	M
C/N ratio (%)	28.78-32.04	30.41	H	30.50-34.17	32.34	H	21.87-43.26	35.4	H
AP (ppm)	1.6-1.80	1.7	V L	1.6-2.2	1.9	V L	0.9-12.0	6.5	L
TP (ppm)	9-12	10	V L		8	V L	37-339	133	VH
Ca^{2+} (cmol(+) kg^{-1})		0.20	L		0.21	L	0.05-0.45	0.24	L
Mg^{2+} (cmol(+) kg^{-1})	0.15-1.34	0.74	L	1.21-2.23	1.72	M	0.05-0.59	0.31	L
K^{+} (cmol(+) kg^{-1})	0.09-0.23	0.16	L	0.10-0.18	0.14	L	0.16-0.41	0.23	L
Na^{+} (cmol(+) kg^{-1})	0.20-0.24	0.22	L	0.14-0.19	0.17	L	0.17-0.27	0.22	L

Remarks: ApH = actual pH, PpH = potential pH, TN = total N, AP = available P, TP = total P, VA = Very Acidic, VL = very low, L = low, M = moderate, H = high, VH = very high

The process of peat formation starts from shallow waterlogged basins, which are slowly overgrown by aquatic plants and wetland vegetation [19]. The dead and decaying plants gradually form a layer that then becomes a transitional layer between the peat layer and the substratum (mineral soil). Subsequent crops grow more in broader basins until they are fully covered with dead and decaying plants. Roots of plants living on thin peat will take mineral nutrients from the substratum, most of which are contributed from rivers, to form fertile topogenous peat. As the peat layer thickens, plants or vegetation living on it can no longer absorb nutrients from the mineral layer. Nutrients are supplied only from rainwater and/or decomposed organic matter, leading to the formation of infertile ombrogenous peat.

The peatland in Kalampangan is categorized as ombrogenous peat formed by rainwater, while the peatland in Buntoi is categorized as topogenous peat formed by the topography of the basin area. The peatland in Kalampangan, with its peat depths ranging from 225-304 cm, is classified as deep peat, whereas peatland in Buntoi, with peat depths ranging from 40-93 cm, is classified as shallow peat (Table 2). Shallow peat has higher fertility and lower environmental risks than deep peat [20]. Results indicate that peatland conditions in Buntoi are more favorable to *tamanu* growth performance, as evidenced by both height and branch growth values being higher than in Kalampangan. At 11 months, the height in Buntoi reached 80 cm on average, while in Kalampangan, it was below 60 cm. The average numbers of branches for *tamanu* trees were eight and below four in Buntoi and Kalampangan, respectively (Figure 3a and Figure 4a)

In general, peatlands were classified as marginally suitable (low suitability), with the main limiting factors being an acidic medium containing toxic organic acids, low nutrients and drainage [21]. However, agriculture expansion on drained peatland has led to peatland degradation. Degradation of peatlands decreases their capacity as media for plant growth, as characterized by one or combinations of the following characteristics: lower water holding capacity, higher soil acidity, lower total organic carbon (TOC) and total N [22]. Tropical peatlands vary widely, both spatially and vertically, in terms of physical and chemical properties. Peatland characteristics are determined mainly by the thickness of the peat, substratum, or mineral soil under the peat, maturity, and the enrichment from surrounding river overflow [21].

Dry peat, with moisture content <100%, will no longer be able to absorb water when rewetted (irreversibly dry). Dry peat is light and easily blown away by the wind, floats when submerged, is sensitive to fire, and forms pseudo sand (similar to sandy soil), which is unable or less able to hold water [23]. These opposites with the condition in Buntoi, in which the moisture content is 57% (below 100). However, the WFPS value showed between 128 and 217% (Table 2). This indicates that peat in Buntoi is still able to hold water.

Peatlands in Indonesia, mainly in Kalimantan, are generally categorized as low fertility oligotrophic peat [19]. Oligotrophic peat, especially thick peat, has very low contents of alkaline cations such as Ca, Mg, K and Na. The deeper the peat, the lower the bases it contains and the more acidic the soil reaction becomes [24]. In this study, alkaline cations in two layers in Kalampangan (0-50 and 50-100 cm) and Buntoi were low, with similar values (Table 3). Generally, soil acidity in peatlands is highly acid ranging from pH 3-4 [25]. Soil acidity at the two layers in Kalampangan and Buntoi was similar and classified as very acidic (Table 3). The level of acidity in peatlands relates closely to poor drainage and hydrolysis of organic acids (humic acid and fulvic acid), some of which are toxic and affect plant growth and nutrient holding capacity [26, 27]. Phenolic acid, a lignin decomposition product, will damage plant root cells causing amino acids and other materials to flow out of plant cells, inhibiting root growth and nutrient uptake [20]. The low pH will indirectly inhibit the availability of macronutrients such as P, K and Ca, and some micronutrients [28, 29]. In this study, macronutrient levels (P, K, Ca, Mg) were low in Kalampangan and Buntoi (Table 3). Therefore, nutrient enrichment with applications of fertilizer containing N, P, K, Ca and Mg was essential. Ameliorants such as lime, mineral soil, manure and ash can be applied to increase soil pH and alkalinity [30-32].

Peatlands are rich in organic matter (organic C > 18%) with thicknesses of 50 cm or more [20]. High organic C is a result of peatlands being formed by the process of organic matter deposition from plant debris accumulated in waterlogged environments. The high organic content consists of humic compounds at around 10% to 20%, while other compounds include lignin, cellulose, hemicellulose, wax, tannins, resins, suberins and proteins [20]. The peat C/N ratio is relatively high, ranges from 20-45 and increases with depth [33]. C/N ratio was classified as high (C/N > 30%), ranging from 28.78-32.04% at 0-50 cm depth, and 30.50-34.17% at 50-100 cm depth in Kalampangan and 21.87-43.26 in Buntoi. The higher C/N ratio indicates undecomposed peat in which nutrients will not be released, resulting in infertile peat.

Total N content was categorized as moderate, ranging from 0.24-0.30% at 0-50 cm depth and 0.25-0.29% at 50-100 cm depth in Kalampangan and 0.17-0.28% in Buntoi. Most nitrogen sources in peat soils are organic compounds; thus, only about 1% N is available for plants [34]. Plants absorb N as NH_4 and NO_3 -. These two compounds are formed after processes of ammonization, ammonification and nitrification. In soils with pH levels below 4.0, these processes run very slowly, resulting in a very slow release of NH_4 and NO_3 -.

Available P was categorized as very low in Kalampangan, ranging from 1.6-1.8 ppm at 0-50 cm depth and 1.6-2.2 ppm at 50-100 cm depth, whereas in Buntoi available P was classified as low (0.9-12.0 ppm). Total P was also categorized as very low (10 ppm at 0-50 cm depth and 8 ppm at 50-100 cm depth) in Kalampangan, but very high level (37-339 ppm) in Buntoi. Peat soils contain P mostly in the form of organic P [35, 36]. Inositol hexaphosphate, a P organic fraction, can react with Fe or Al to form insoluble salts that are unavailable for plants.

Degraded peatlands have the potential to be restored for productive land. Some research shows that well-managed peatlands and sufficient inputs could provide good yields for crops [37-39]. Therefore, the commodities selection with good and stable peatland adaptability is crucial for achieving high crop productivity. In addition to adaptability, the selection of commodities should consider economic value, capital capacity, skills, market availability, and landowner preference.

3.2. Survival rates in Kalampangan and Buntoi

The survival rate is a common parameter indicating plant health and depends on environmental stress [40]. The first-year survival of transplanted seedlings plays a crucial role in the subsequent success of plantations [41]. In our study sites, the *tamanu* survival rate three years after planting in Kalampangan ranged from 75.0% (200 g doses) to 91.67% (50 g doses). There were no significant differences in survival rate between treatments, but results indicate that the application of 50 g NPK doses gives a higher survival rate than other doses (see Figure 2).

In the Buntoi plot, the *tamanu* survival rate reached 81.25% eight months after planting. However, the trial plot was affected by fires in July and October 2019, causing several plants to die. Consequently, survival rate data was abnormal after the surface fires, with the survival rate becoming 55.21% at the end of observation (2 years after planting).

The survival rate is an attribute that relates to the adaptation of a species to environmental conditions [43]. Geographic variation is often the most important characteristic relating to survival and adaptability [11]. Survival rates in Kalampangan were not influenced significantly by fertilizer dosage. The mean survival rate from all treatments reached 91.44% at seven months after planting and 82.0% at the end of observations (see Figure 2). Meanwhile, the mean survival rate in Buntoi was 81.25% at eight months after planting. At the same age, *tamanu* trees in Kalampangan had an 88.56% survival rate (see Figure 2). The high survival rates indicate that *tamanu* is adaptable to the degraded peatlands in Kalampangan and Buntoi. These results are consistent with those from a previous *tamanu* trial on degraded peatlands [15]. Although the sites have different peatland types, Tamanu survival rates were very similar in Kalampangan and Buntoi (see Tables 1 and 2). Thus, early indications are of *tamanu* adaptation stability on degraded peatlands.

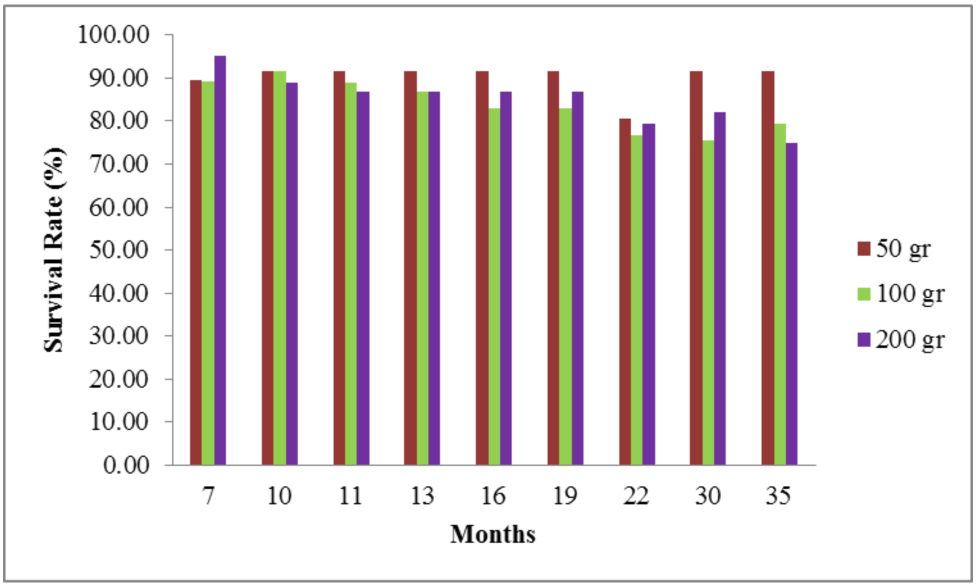

Figure 2. *Tamanu* survival rates in Kalampangan under different NPK doses.

With the criterion of a survival rate of more than 75% being an indicator of successful planting, *tamanu* meets requirements as a species that can be developed for peatland rehabilitation [44]. Other studies in East Kalimantan and Java reveal *tamanu*'s adaptability on several types of degraded land, including degraded burnt land in Bukit Soeharto in East Kalimantan, demonstrating a 90% survival rate two years after planting [14]. A *tamanu* provenance trial plot on sandy coastal soil in Pangandaran, West Java, showed a mean survival rate of 79.33% two years after planting [45]. Another trial on rocky land with thin topsoil in Gunung Kidul, Java, showed *tamanu* survival rates between 77 and 86% [46] at the same age. *Tamanu* had the highest survival rates among five species planted on former tin mining land, at 52.4-78.7% one year after planting [47]. These studies provide evidence that *tamanu* is tolerant of harsh environmental conditions [11].

3.3. Growth performance in Kalampangan and Buntoi

Tamanu growth performance in Kalampangan varied between treatments, ranging from heights of 0.93-1.13 m, diameters of 1.75-1.89 cm, and numbers of branches at 8.08-10.51 up to two years after planting. There were no significant differences for all growth characteristics between treatments. Findings indicate NPK applications of 50 g doses providing the highest growth performance compared to other doses during observations (see Table 4 and Figure 3).

Table 4. Variance analysis of *tamanu* growth performance after three different doses of NPK fertilizer in Kalampangan.

Source of variation	df	Mean square (month)								
		7	10	11	13	16	19	22	30	35
1. Height										
Block	2	0.0024^{ns}	0.0091^{ns}	0.0046^{ns}	0.0049^{ns}	0.0134^{ns}	0.0218^{ns}	0.0461^{ns}	0.0433^{ns}	0.0672^{ns}
Fertilizer	2	0.0004^{ns}	0.0001^{ns}	0.0011^{ns}	0.0064^{ns}	0.0182^{ns}	0.0191^{ns}	0.0347^{ns}	0.0766^{ns}	0.0341^{ns}
Error	8	0.0005	0.0018	0.0033	0.0066	0.0089	0.0132	0.0130	0.0178	0.0532
2. Diameter										
Block	2	0.0338^{ns}	0.1216*	0.0504^{ns}	0.0494^{ns}	0.0663^{ns}	0.0807^{ns}	0.3889*	0.1497^{ns}	0.2928^{ns}
Fertilizer	2	0.0123^{ns}	0.0151^{ns}	0.0061^{ns}	0.0198^{ns}	0.0310^{ns}	0.0123^{ns}	0.1181^{ns}	0.0795^{ns}	0.0184^{ns}
Error	8	0.0143	0.0157	0.0082	0.0255	0.0316	0.0189	0.0476	0.0689	0.1860
3. Number of branches										
Block	2			0.0554^{ns}	0.6566^{ns}	0.8498^{ns}	0.9807^{ns}	0.5645^{ns}	1.8732^{ns}	4.5696^{ns}
Fertilizer	2			0.1187^{ns}	0.3663^{ns}	0.0658^{ns}	0.2758^{ns}	3.4098^{ns}	3.1462^{ns}	3.5292^{ns}
Error	8			0.3456	0.6598	0.4469	0.9696	5.419	1.1082	1.5842

Remarks: df = degree of freedom; ns = non-significant; * = significant difference at 0.05 level

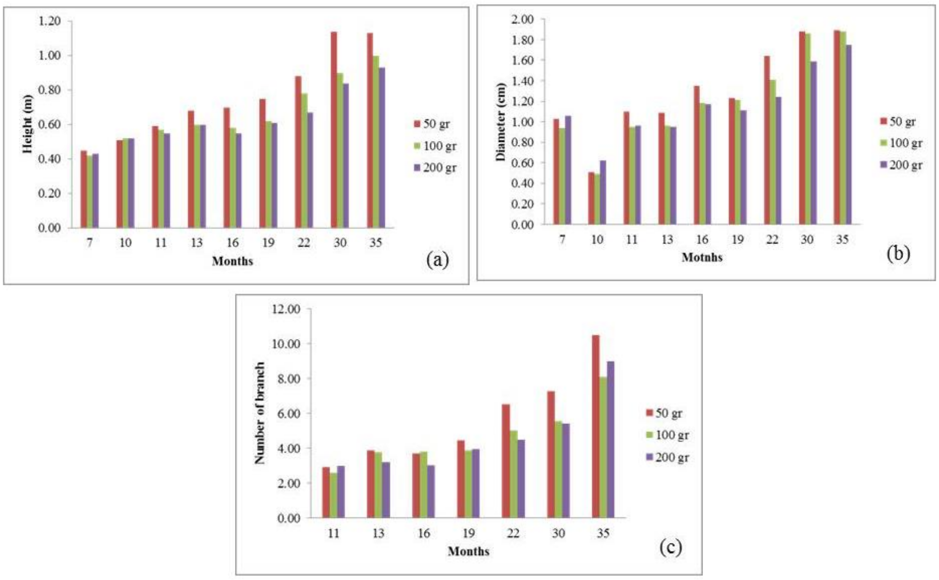

Figure 3. Mean growth performance after three different doses of NPK fertilizer in the trial plot in Kalampangan (a) height, (b) diameter and (c) number of branches.

There were increasing trends for all measured characteristics of mean growth performance for *tamanu* trees in Buntoi (see Figure 4). Observations showed growth in height, diameter and numbers of branches tending to increase rapidly after 19 months. *Tamanu* trees had a mean height of 1.75 m, a mean diameter of 3.97 cm and a mean number of branches at 14.77, 24 months after planting.

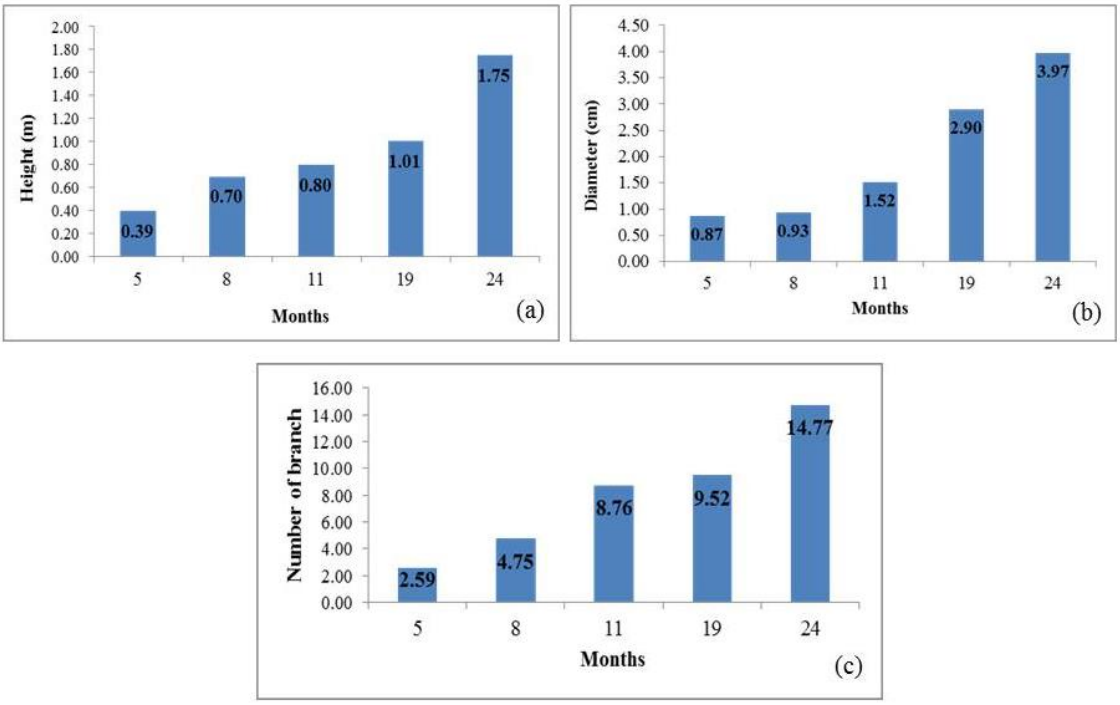

Figure 4. Mean growth performance in the trial plot in Buntoi (a) height, (b) diameter and (c) number of branches.

Height and diameter correlation in Kalampangan varied between treatments from 0.59 at seven months to 0.84 at 11 months, as shown in Table 5, while average height and diameter correlation in Buntoi varied between PMPs from 0.69 at 11 months to 0.88 at eight months, as shown in Table 6. Thus, the height-diameter relationship of a species depends on local environmental conditions and varies within a geographic region [42].

Table 5. Height and diameter correlation in Kalampangan.

Treatment	Age (months)								
	7	10	11	13	16	19	22	30	35
50	0.63	0.65	0.82	0.63	0.79	0.66	0.61	0.78	0.83
100	0.52	0.57	0.78	0.80	0.79	0.75	0.70	0.71	0.78
200	0.62	0.81	0.91	0.79	0.67	0.74	0.79	0.82	0.88
Average	0.59	0.68	0.84	0.74	0.75	0.72	0.70	0.77	0.83

Table 6. Height and diameter correlation in Buntoi.

PMPs	Age (months)				
	5	8	11	19	24
1	0.94	0.94			0.76
2	0.91	1.00			
3	0.72	0.92	0.77		
4	0.67	0.67	0.81	0.69	0.93
5		0.89	0.50	0.82	
Average	0.81	0.88	0.69	0.76	0.85

Growth performance for all measured characteristics in Kalampangan did not differ significantly between fertilizer dosage treatments during observation. Until the age of 3 years old, *tamanu* trees with a fertilizer dose of 50 g demonstrated the best average growth in height, diameter and numbers of branches at 1.13 m, 1.89 cm and 10.51, respectively (see Table 4 and Figure 3). Thus, NPK fertilization at a dose of 50 g per plant was more effective and economical for *tamanu* trees in early growth in Kalampangan. A dose of 50 g also provided the best average growth rate at the age of 2 years old for *tamanu* trees in a burnt area in Bukit Soeharto, East Kalimantan [14]. While the recommended NPK fertilizer dosage for *tamanu* trees in a sandy coastal area in Pangandaran, West Java, was 100 g applied twice yearly combined with 5 kg of manure for base fertilizer [48]. Unlike in Kalampangan, only one dose of 100 g was applied to each *tamanu* plant in Buntoi. At two years old, *tamanu* growth performance in Buntoi averaged 1.75 m (height), 3.97 cm (diameter) and 14.77 (number of branches). At one year old, *tamanu* trees in the trial plot in Buntoi had heights of 1.4-1.7 m. This was higher than *tamanu* trees in Kalampangan given the same dose and other doses. This might be caused by the different peat types affecting soil fertility levels. Kalampangan has an ombrogenous peat type, while Buntoi has topogenous peat, containing more nutrients and minerals (see Table 3) [49, 50]. The same applies to oil palm, where productivity was consistently higher at the same ages and using the same cultivation techniques in topogenous than ombrogenous peat areas [50]. Thus, to obtain optimum results, *tamanu* should be planted on degraded peatlands with topogenous peat.

Tamanu trees planted in mineral soil on burnt degraded land in Bukit Soeharto, East Kalimantan, had heights of 3.8-5.5 m, diameters of 5.9-9.1 cm and 8.5-16.5 branches at two years old [14]. On rocky land with thin topsoil in Gunungkidul, 2-year-old *tamanu* trees had heights ranging from 1.16-1.80 m [47]. At the same age, mean heights for *tamanu* trees planted in mineral soil on degraded land in Wonogiri and sandy coastal soil in Pangandaran were 2.87 m and 1.15 m, respectively [12]. At the same age, the mean growth performance of *tamanu* trees on degraded peatlands was lower than for burnt land in East Kalimantan, rocky land with thin topsoil in Gunungkidul, and degraded mineral land in Wonogiri. Nevertheless, height and diameter correlations in Kalampangan and Buntoi were positive in moderate to strong categories (see Tables 5 and 6). This correlation is common in forest plants. The relationship between diameter at breast height and total tree height is fundamental for developing growth and yield models for forest stands [42]. The survival rate and height and diameter growth can be related to environmental conditions, such as light, soil moisture, temperature, nutrient availability, soil type, and many other factors that drive the survival and growth of species [51, 52]. The highly acidic soil pH of the peatlands (see Table 3) causes lower soil fertility than in the other trials in East Kalimantan, Gunungkidul and Wonogiri [12, 14].

Tamanu trees have shown adaptation stability on degraded peatlands since the species trials in 2016 in Buntoi and through broader development in the plantation trials in Kalampangan and Buntoi. *Tamanu* trees demonstrated favorable growth performance on peatlands, though slower than other trials on mineral soils. Utilizing *tamanu* trees without cutting would increase carbon stock and fauna biodiversity while improving the quality of degraded peatlands in the future. Thus, the restoration of degraded land with multipurpose species such as *tamanu* through agroforestry planting patterns can help meet targets for energy self-sufficiency and improved community wellbeing.

4. Conclusion

Tamanu (*Calophyllum inophyllum*) is a non-native peatland species and is highly adaptable to various types of degraded land. This study indicates the species is adaptable to degraded peatlands in Kalampangan and Buntoi Villages in Central Kalimantan, where it demonstrated survival rates of 82% and 81.25%, respectively. Furthermore, the growth performance of 2-year-old *tamanu* trees on topogenous peat in Buntoi (average height of 1.74 m and diameter of 3.97 cm at 5 cm above ground level and 15 branches) was better than on ombrogenous peat in Kalampangan (average height of 0.68 m and diameter of 1.43 cm at 5 cm above ground level and five branches). These initial results indicate that *tamanu* is promising for restoring peatland and renewable biofuel and grows better on topogenous peat. However, further research is needed to examine the potential ecosystem services associated with growing *tamanu* on degraded peatlands and adoption for upscaling this model.

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Authors' contributions
The authors contributed equally to this work as the main contributor