Mixed farming systems on peatlands in Jambi and Central Kalimantan provinces, Indonesia: should they be described as paludiculture?

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SUMMARY

Indonesia has about 150,000 km² of peatlands that until recently were largely unused, except by the few local communities living near peatlands who have been using non-timber forest products and cultivating sago for many years. However, mismanagement and over-exploitation have now changed the natural peatland ecosystems into degraded peatlands. Since the peat fire disaster of 2015, the Government of Indonesia has taken serious action to begin the restoration of degraded and burnt peatland. Paludiculture offers a management option for degraded peatlands that would promote the objectives of the country's new peatland restoration strategy. Existing agricultural practice on peatland in Indonesia is site specific and depends on peatland type. Previous studies of farming practices in two provinces, namely Jambi on the island of Sumatra and Central Kalimantan on Borneo, have shown that this type of farming system is beneficial for human livelihoods. However, the evidence reported here indicates that it is not appropriate to describe current farming practices at these two locations as paludiculture because they do not achieve conditions of high water table and low greenhouse gas emissions. It is recommended that management of hydrology, including temporary or permanent blocking of canals, should be undertaken in order to reduce subsidence and CO_2 emissions. To achieve sustainable productive use of degraded peatlands, they should be rewetted and planted with suitable crops and tree species.

KEY WORDS: agroforestry, cultivation, peat swamp, Sumatra, Kalimantan

INTRODUCTION

Indonesia has the third largest peatland area of any country in the tropics (after countries in the Amazon and Congo Basins), estimated at 148,300 km^2 or 8.2 % of the total land area (Xu *et al*. 2018). Peat swamp forest (PSF) is distributed across the whole of the Indonesian archipelago, occurring along the west coast of Aceh province (north-west Sumatra), the eastern coastlines of Riau, Jambi and South Sumatra, from West to East Kalimantan and on Papua (Wahyunto *et al.* 2003, Wahyunto *et al.* 2004, Wahyunto *et al.* 2006, Ritung *et al.* 2011).

Peat swamp forest has high floristic diversity (Page *et al.* 1999). A recent report on biodiversity in the Sebangau tropical PSF showed that total tree species recorded 215 taxa and 92 non-tree flora (Husson *et al.* 2018). The total number of plant species encountered in Southeast Asian swamps is 1441. Of these, 32 and 41 are restricted to peat swamp forest in Indonesia and on Borneo, respectively (Giesen *et al.* 2018). Poesie *et al.* (2011) reported that the mixed PSF of Sebangau in Central Kalimantan had high tree diversity with a Shannon-Wiener diversity index of 3.57, and was dominated by *Palaquium leiocarpum, Shorea teysmanniana* and *Combretocarpus rotundatus*. A study in the secondary PSF of Tumbang Nusa in Central Kalimantan showed that the Shannon-Wiener diversity index of the tree stage was 3.30, and this PSF was dominated by *Calophyllum macrocarpum, Neoscortechinia kingii* and *Shorea teysmanniana* (Tata & Pradjadinata 2013). Bram Itam mixed PSF in Jambi has a Shannon-Wiener diversity index of 3.35 (Siregar *et al.* 2016). Additionally, PSF provides habitat for wildlife including flagship species such as orangutan (Wich *et al*. 2011, Bastian *et al.* 2012), tiger (Sunarto *et al*. 2013), gibbon (Vogel *et al.* 2009) and various birds (Posa & Marques 2012). Sebangau PSF also has a high faunal diversity, for example among the ants, butterflies, spiders, dragonflies, damselflies, freshwater fish, amphibians, reptiles, birds and mammals (Husson *et al.* 2018).

Another ecosystem service provided by PSF is that it has long supported human livelihoods. Various freshwater fish species are used by local people. In Central Kalimantan, Osaki *et al.* (2016) report that 27 species of freshwater fish have been found in the

Kahayan River, while Thornton *et al*. (2018) identified 29 fish species in logging canals and tip-up pools inside the PSF of Sebangau National Park, and trapping in the adjacent Sebangau River brought the total to 55 species from 16 families. More than 500 PSF plant species provide tangible benefits in the form of food, timber, latex, rattan, medicines or cultural value (Giesen 2015, Tata & Susmianto 2016, Giesen *et al.* 2018). Some communities have managed peatland as agricultural land (Noor 2010, Osaki *et al.* 2016) by draining the peat-water (Noor 2010) and practising 'slash-and-burn' agriculture (Saharjo 2007, Osaki *et al*. 2016, Murniati & Suharti 2018).

During the last two decades, large areas of peatland have been transformed into managed cultivation systems such as industrial and smallholder plantations (Miettinen *et al.* 2016). Industrial plantations (both *Acacia* and oil palm) covered 3.1 ha in 2015 (Miettinen *et al.* 2016). Tree-based agroforestry or mixed planting is nowadays commonly practised by farmers on Sumatra (Tata *et al*. 2016, Widayati *et al*. 2016, Khasanah & van Noordwijk 2018) and in Kalimantan (Osaki *et al.* 2016, Surahman *et al.* 2018). The rate of change in PSF cover on Sumatra and in Kalimantan (Indonesian Borneo) has been increasingly rapid and the corresponding loss of 1.8 Mha of natural PSF (on Sumatra and Borneo) reflects a deforestation rate of 4.1 % per year during the period 2007–2015 (Miettinen *et al*. 2016).

Human activities such as logging, drainage, shifting agriculture and plantation forestry disturb the peatland ecosystem. In particular, canal construction is detrimental because it causes the water table to fall so the organic material of the peat experiences drying, which may not be reversible after long droughts, and becomes susceptible to fire (Miettinen et al. 2017, Prayoto *et al.* 2017, Tata *et al*. 2018). Even without fires there is continued biological oxidation of peat in drained peatlands, leading to a loss of 4–5 cm of peat per year.

According to Indonesian Law No. 32 (2009) about protection and management of the environment, local communities are allowed to use fire to open up to 2 ha of land with certain conditions. However, since the catastrophic peat fires of 2015, land clearance by burning has been restricted to 'prescribed burning' according to the Regulation of the Minister of Environment and Forestry (MoEF) No. P.32 (2016) on forest and land fire control. The Government of Indonesia (GoI) has set a target for restoration of degraded and burnt peatland of about 2 Mha by 2020. Relevant legislation includes MoEF Regulation No. 16 (2017) on the technical guidelines on recovery of peat ecosystem functions, and the Strategic Plan of the Peatland Restoration Agency No. P5 (2016). The peatland restoration effort combines three approaches, namely rewetting, revegetation and revitalisation of human communities (BRG 2016). A basic principle is that the 'central zone' of the peatland hydrological unit (PHU) must be protected. This means that the water table must be raised by canal blocking and maintained at a high level perennially. The appendix of the Minister's regulation lists some native tree species for reinstatement as appropriate vegetation which may also produce economic benefit for local communities. In the 'zone of production' of the PHU, a greater variety of species can be planted in agroforestry systems. However, management of the hydrology is a critical point, because the Government Regulation (PP No. 57/2016) states that the water table here must be no deeper than 40 cm below ground level (and preferably maintained well above this level).

Paludiculture, which is the productive cultivation of wet and rewetted peatlands (Joosten *et al*. 2012, Wichtmann *et al*. 2016), is an alternative approach to farming on degraded peatland. Its main goal is to reduce CO_2 emissions by maintaining a high water table so that the peat stock is preserved, while at the same time allowing people to derive economic benefit from the land (Joosten *et al.* 2012, Wichtmann *et al.* 2016). Preservation of the peat stock is particularly important as over time the loss of peat will lead to peatland becoming flooded, at least for much of the year, and largely unproductive. As such it is the only sustainable use option for degraded peatlands. Paludiculture utilises plant species indigenous to the PSF habitat that are capable of growing on wet and rewetted peatlands and can be cropped to provide a source of livelihood for farmers. Thus, paludiculture aligns with current Indonesian legislation for the 'zone of protection' of a PHU, and would simultaneously support the needs identified above for both degraded peatlands and the human population.

This article combines biophysical information about the mixed farming system practised in Central Kalimantan province with data from agroforestry demonstration plots established in Jambi province to address the following three questions:

(i) Is current farming practice compatible with Indonesia's peatland restoration strategy?
(ii) Can current farming systems be categorised as paludiculture?
(iii) What strategy is needed to improve the management of current farming practice on drained peatland?

METHODS

Study sites

The study sites are peatland ecosystems in two locations, namely Tanjung Jabung Barat (abbreviated as Tanjabar) district, Jambi province and Tumbang Nusa village in the Pulang Pisau district of Central Kalimantan province. These two sites were selected in order to examine differences in farming practice between two Indonesian islands where peatland is widespread. The study sites are shown in Figure 1.

Tanjabar district lies between 0° 53'–01° 41' S and 103° 23'–104° 21' E and comprises a total area of 500,000 ha covered by forest, agricultural crops (rice

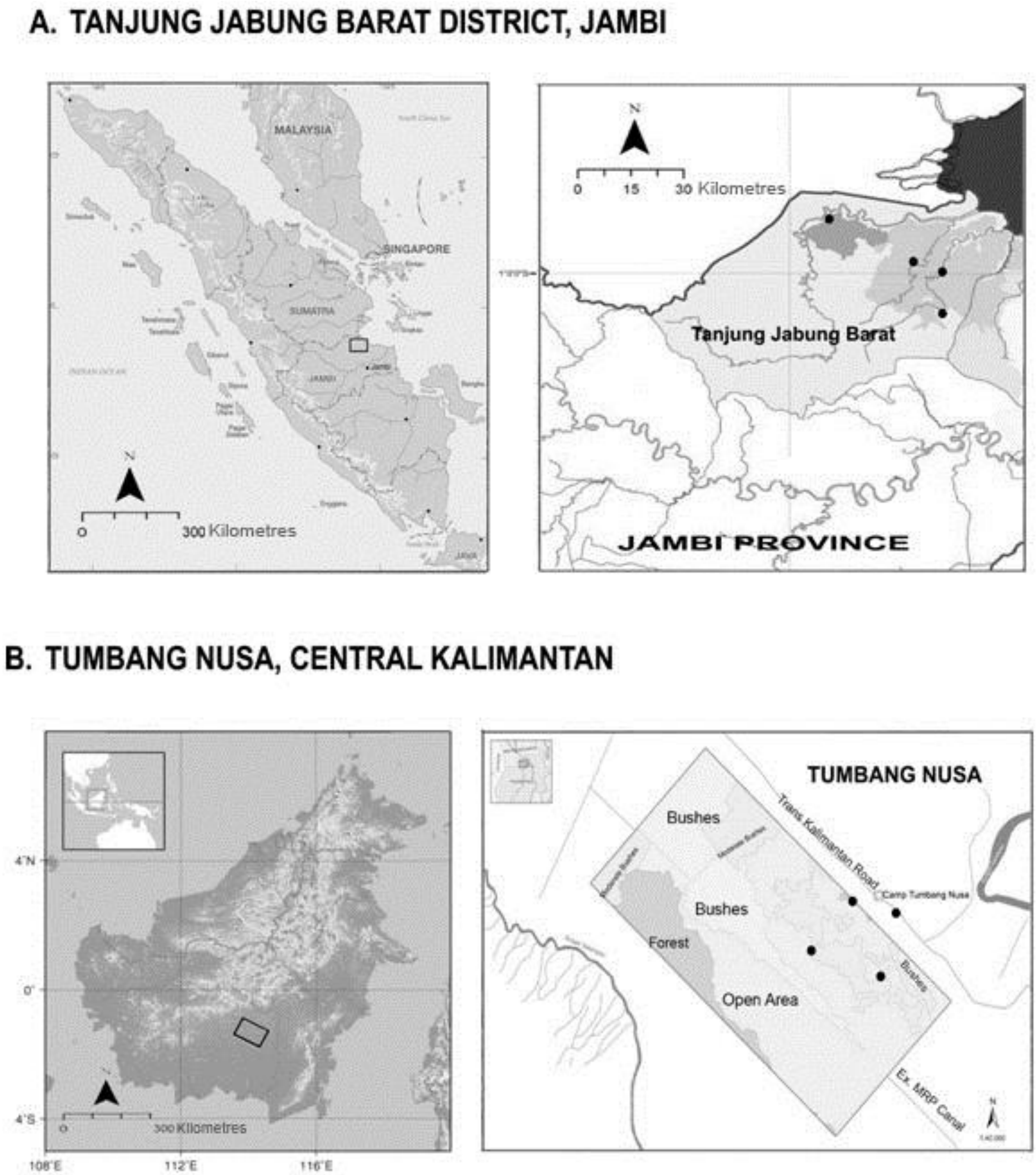


Figure 1. The study sites. A: Tanjung Jabung Barat (Tanjabar) district of Jambi province (on Sumatra); B: Tumbang Nusa in Central Kalimantan province (on Borneo). Black filled circles indicate the locations of plots used in this study.

and vegetables) and tree-based systems. The tree-based systems are rubber (*Hevea brasiliensis*), coffee (*Coffea liberica*), coconut (*Cocos nucifera*) and betel nut (*Areca catechu*) agroforests, *Acacia* plantations and oil palm (*Elaeis guinensis*) smallholdings (Mulia *et al*. 2014, Khasanah & van Noordwijk 2018). About 40 % of the total area of Tanjabar district is peatland (Mulia *et al.* 2014), which belongs to the PHU of the Baung and Betara rivers (BRG 2016) and is subject to the tidal effect of the South China Sea. The peatland is covered by natural PSF, *Acacia* plantations, oil palm plantations, oil palm smallholdings, monoculture smallholdings, crop-based agroforestry estates, shrubland and open areas. The PSF (Bram Itam peat forest reserve) is designated as the protected zone of the PHU, and private land belonging to smallholder farmers is mostly considered to lie within the production zone of the PHU. Enrichment planting of *Dyera polyphylla* (known locally as 'jelutung') in the peat forest reserve was initiated in 2005 by the District Forest Service (Mulia *et al*. 2013, Tata *et al.* 2016). The *Dyera polyphylla* was planted in mixtures with other crop trees such as rubber, oil palm, coffee and betel nut (Tata *et al.* 2016).

The total area of Pulang Pisau district (2° 19'–2° 26' S, 114° 04'–114° 16' E) is 899,700 ha, of which 30.99 % (278,900 ha) is peatland (FMP 2014). Our study here focused on Tumbang Nusa village on the west side of the Kahayan river, where patches of PSF have survived. The forest is designated as a Forest Area with Specific Purpose (*Kawasan Hutan dengan Tujuan Khusus, KHDTK*) and is surrounded by other land use types such as agroforestry (rubber, ramboostan and jelutung) and rubber monoculture. There are also abandoned burnt peatlands which are dominated by *Melaleuca cajuputi* (known locally as 'gelam'), *Combretocarpus rotundatus* ('tumih'), *Acacia mangium* and ferns.

Photographs showing the conditions at both study sites are provided in Figure 2.

Procedures

The data presented here arise from two different studies. The procedures employed at the two study sites were not the same because a comparative study

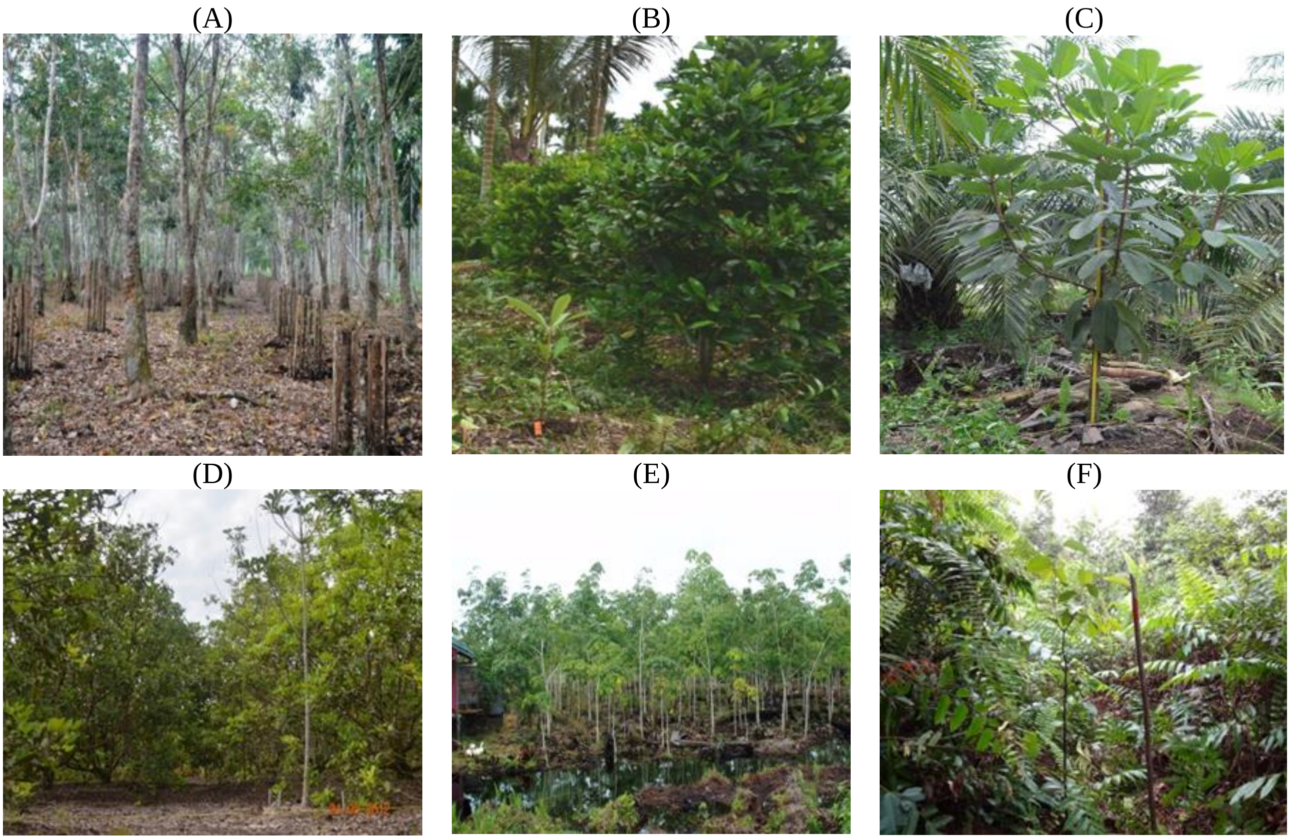


Figure 2. Farming systems on peatlands in Tanjabar (A–C) and Tumbang Nusa (D–F). (A) Mixed rubber+jelutung. (B) Mixed coffee+jelutung+betel nut. (C) Mixed oil palm+jelutung. (D) Mixed jelutung+rambutan. (E) Mixed rubber+jelutung+*Shorea balangeran*. (F) Enrichment planting of *Shorea balangeran*+jelutung on shrub peatlands.

was not intended originally. The Tanjabar study (January to December 2014) was more extensive than the one at Tumbang Nusa (conducted in 2013). A summary of the datasets collected from the two sites is shown in Table 1.

In Tanjabar, demonstration plots were established where jelutung was introduced into existing farming systems of oil palm, mixed coffee and betel nut, and rubber ('enrichment planting'). A control plot was a 1 ha area of peatland with jelutung in a monoculture system. The chemical properties of the peat soils in the demonstration plots and growth of the planted jelutung were reported by Tata *et al.* (2016). Here we discuss data on water level, subsidence and CO_2 emissions from the demonstration plots.

In Tumbang Nusa village (Central Kalimantan), several assessments were undertaken, such as above-ground carbon stock assessment, CO_2 emission (derived from conversion of the above-ground stock of carbon), and soil properties of some land use types. The pre-existing land use types studied in Tumbang Nusa were: peat swamp forest (PSF), PSF that burned in 1997 (BP_97), PSF that burned in 2004 (BP_04), and mix farming (agroforestry) of jelutung+rubber trees (AFJK), jelutung+rambutan (*Nephelium lappaceum*) (AFJR), and jelutung+*Acacia* (AFJW). The existing AF plots at Tumbang Nusa were established 5–6 years prior to this study. Here we discuss biophysical data such as water table level (relative to ground level), subsidence, carbon stocks, macro nutrient properties of the peat chemistry, and estimated CO_2 sequestrations from the example plots in the existing land use types.

Rainfall and water level

Rainfall data for Jambi were collected by '*Balai Wilayah Sungai'* (Unit of River Area), Jambi province; while precipitation data for Tumbang Nusa was collected by the KHDTK Tumbang Nusa Forest Research Institute in Banjarbaru.

Water table levels were monitored in 5 cm (two-inch) diameter perforated PVC pipes. The first pipe was installed at a minimum distance of 5 m from the front ditch, and up to 800 m from it depending on the distance of the plot from the ditch. The second pipe was installed 200 m beyond the first pipe. Water table levels (relative to ground level) at the Tanjabar and Tumbang Nusa sites were measured manually every two weeks.

Subsidence

To monitor subsidence, a metal pipe (5 cm diameter, unperforated) was driven into the substratum beneath the peat. Both at Tumbang Nusa and in Tanjabar, subsidence was measured at six-month intervals for one year at a single location within each demonstration plot.

Above-ground carbon stocks and chemical properties of peat

At Tumbang Nusa the above-ground carbon stocks of four different land use types, namely PSF, PSF burnt in 1997 (BP_97), PSF burnt in 2004 (BP_04) and the existing jelutung agroforestry (AF) (jelutung+rubber, jelutung+*N. lappaceum* and jelutung+*Acacia*) were measured and quantified according to the method described by Hairiah & Rahayu (2007), considering three carbon pools, namely: necromass, understorey and main-canopy trees. The total CO_2 sequestration ($Mg\ ha^{-1}$) represented by these C pools was estimated on the basis of conversion of the above-ground carbon stock (Hairiah & Rahayu 2007).

The peat from four land use types in Tumbang Nusa was collected using an Eijkelkamp peat auger. The peat samples were then brought to the soil laboratory of the Soil Research Institute in Bogor for further analysis. Sub-samples of the peat soils were collected from the same plots and analysed for chemical properties such as pH (H_2O and KCl), organic C, P (Bray method), total N (Kjeldhal

Table 1. Summary of datasets collected across the two study sites of Tanjabar (Jambi) and Tumbang Nusa (Central Kalimantan). * indicates data published in Tata *et al.* (2016) and not reported here; + indicates data collected; - indicates data not collected.

No.	Type of data	Tanjabar	Tumbang Nusa
1.	Analysis of peat soil characteristics	*	+
2.	Above-ground C stock measurement	-	+
3.	Estimation of total CO_2 sequestration	-	+
3.	Estimation of CO_2 emission based on LOI method	+	-
4.	Measurement of subsidence and water table	+	+
5.	Rainfall data (secondary data)	+	+

method) and macro nutrients (sodium, potassium, calcium, magnesium) using the standard method of 1N NH_4Oac pH 7.0. The chemical properties of peat soil were determined at the Soil Laboratory (Soil Department) of Bogor Agricultural University.

CO_2 emissions
Additional peat soil samples were collected in Tanjabar and at Tumbang Nusa using a frame with dimensions 20 cm × 20 cm × 10 cm, and analysed for bulk density, organic matter and ash content. The peat soils from Tanjabar were collected and analysed on two occasions and the CO_2 emission from that site was estimated and calculated using the Loss on Ignition (LOI) method (Maswar *et al.* 2011a, Khasanah & Van Noordwijk 2018). The peat soils from Tumbang Nusa were collected only once; hence, they were excluded from the calculations of CO_2 emissions. Physical properties of peat such as bulk density, organic matter and ash content were measured at the soil laboratory of the Soil Research Institute in Bogor.

Farming practices and traditions
Unstructured interviews were conducted with key stakeholders such as leaders of farmer groups, participant farmers, agricultural instructors and forestry district officers, to collect information about agricultural practices and land use history in the peatland landscapes.

Data analysis
Data on soil chemical properties from PSF, AF and burned peatland plots at Tumbang Nusa were analysed based on the General Linear Model (GLM) multivariate of two factors, *e.g.* peat depth and land use type. Duncan's Multiple Range Test was used as a post-hoc analysis. Data on soil properties from burned peatland in 1997 and 2004, which were not replicated, were initially analysed by a comparison of means. When all variables were not significantly different, they were then combined as replication. SPSS ver.22 was employed for statistical analysis.

RESULTS

Infrastructure and people

Tanjabar
According to the relevant government regulation (*Peraturan Pemerintah)* No. 57 of 2016, the minimum water table level in the production zone of the Tanjabar PHU is -40 cm (i.e. 40 cm below ground level). Usually, the main drain is a ditch 1–1.5 m wide and 1.5 m deep which drains peat-water into the river and is used for transportation. A connecting narrow-ditch ('*parit cacing'*) 50–70 cm wide and 70–80 cm deep is then developed within each of the farms located along the main drainage ditch. The front ditch is usually dug by a 'ditch leader' ('*ketua parit'*). Along with establishment of the ditch, a path is constructed by mounding up dug peat and substratum. The spacing of narrow ditches is 10 *'depa'* (about 250 m). Hence, the water table falls far below the ground surface (Figure 3). In the five demonstration plots established in four villages, the participating farmers had developed a narrow ditch on each farm, the larger main ditch having been developed earlier alongside a road or path.

Some parts of the Bram Itam peat forest reserve are occupied by migrant farmers who have planted oil palm and other cash crops, and several extensive ditch systems have been established. Some farmers are aware of the importance of maintaining a high water table for fire prevention, and during the dry season they place planks across the outlets of ditches to reduce drainage of peat-water into the river and thus retain moisture in the peatland. This effort effectively minimises the fire incidents in the Bram Itam forest reserve area. No fire incidents were reported during 2015 in that area (Handoyo, personal communication 2016). Nevertheless, the position of the water table must be regularly monitored by the institution which has a mandate on this, for example the Forest Management Unit (FMU) or the concession holders.

Tumbang Nusa
The peatlands of Tumbang Nusa are classified as having deep to very deep peat. The range of peat depths at the demonstration plots was 384–600 cm (Table 2). Most villagers make a living by catching fish from the river. Mixed planting of rubber, fruit trees and rattan is an old farming system that has traditionally been practised on the alluvial mineral soils along the Kahayan River. The villagers also maintain 'purun' grass (*Lepironia articulata*), which can be used for household purposes such as roofing, mats, baskets, *etc*. Most of the Tumbang Nusa villagers belong to the Dayak Ngaju tribe, who are not accustomed to cultivating peatlands (Osaki *et al.* 2016). After the main road connecting the cities of Palangkaraya and Banjarmasin was established, some villagers moved from the old village to a new settlement along the road. Drains had been installed along both sides of the road, and the villagers living there planted fruit trees such as rambutan (*Nephelium lappaceum*), cempedak (*Artocarpus integer*) and pineapple (*Ananas comosus*) in their farms. Some

farmers established private nurseries of forest tree species, which are increasingly in demand for reforestation and the peatland restoration programme. Sumarhani & Tata (2018) reported that the incomes of some farmers in Tumbang Nusa are derived exclusively by selling forest tree seedlings such as jelutung, *Alstonia pneumatophora*, *Shorea balangeran* and *M. cajuputi*, amongst others. In 2013, when that study was conducted, most of the Tumbang Nusa farmers did not have any preference for planting oil palm. However, an oil palm plantation company recently established in Tumbang Nusa, and smallholder farmers may be attracted to follow their lead.

The farmers on peatlands in Tumbang Nusa also developed a small ditch inside each farm to lower the water table. These ditches were narrower than the '*parit cacing*' in Tanjabar, with dimensions of 30 cm width and 30–50 cm depth.

Water table

The water table levels measured during the calendar year 2014 in the plots of jelutung mixed with other crop trees at Tanjabar are shown in Figure 3. The water table remained above -40 cm throughout the year in the two plots with jelutung+rubber and one plot with jelutung only. In the second 'jelutung only' plot, it remained above -60 cm. The jelutung+rubber plots were located on areas of 'peaty soil', i.e. peat depth was less than 50 cm (see Table 2 later), so the water table may have been below the base of the peat layer at times. The water table was generally lower in plots with oil palm+jelutung and coffee+jelutung, and fell farthest (93.6 cm) below the ground surface in one of the oil palm + jelutung plots in March, when there was no rain.

Only limited water level data could be collected during the study at Tumbang Nusa and, unfortunately, no data were collected during the rainy season, which usually lasts from December until February. The water table was generally closer to ground level in the burnt peat swamp forest plot (range -20 to -60 cm) than in the agroforestry plots (range -20 to -140 cm) (Figure 4). The main effect appeared to be an inverse relationship between water table depth below ground surface and distance from the ditch, as also reported by Maswar *et al.* (2011b) and Hooijer *et al.* (2012).

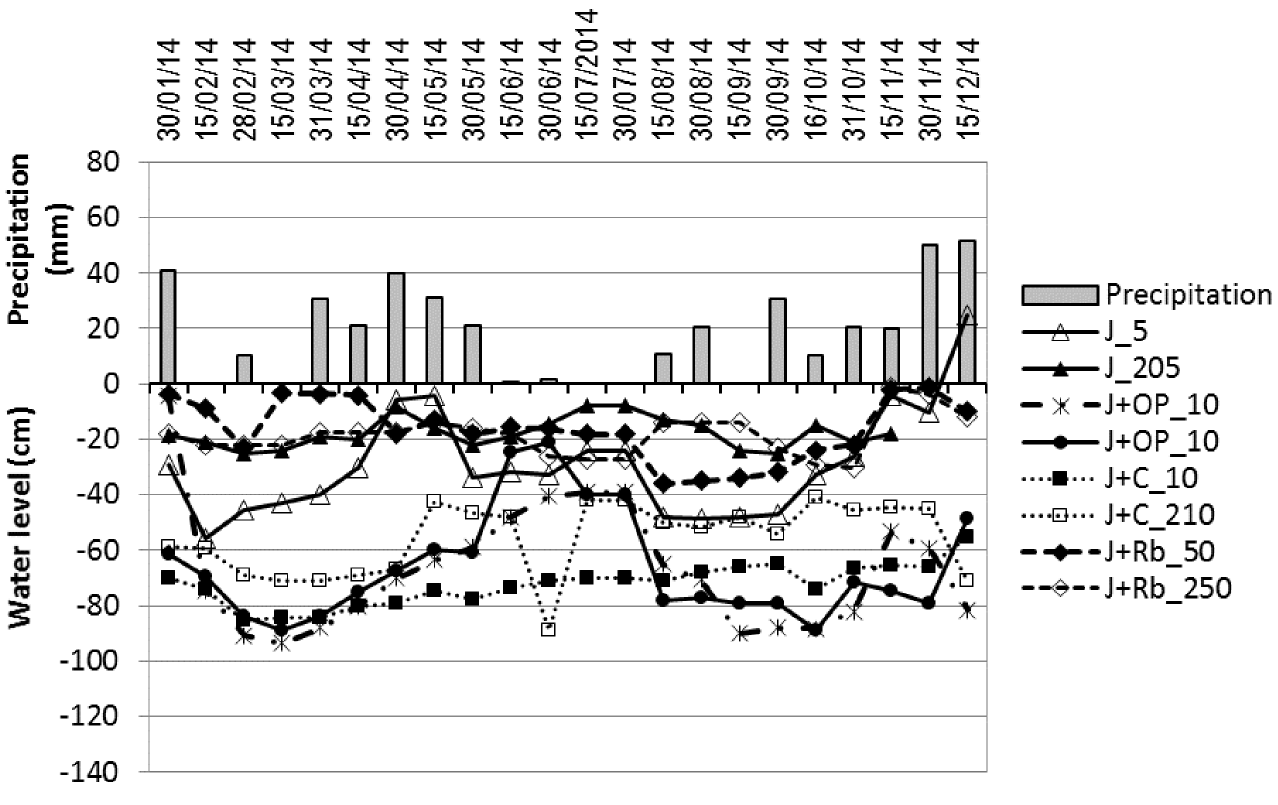


Figure 3. Water table level in the demonstration plots of 'enrichment planting' in Tanjabar, Jambi. J = 'jelutung', J+OP = 'jelutung'+oil palm, J+C = 'jelutung'+coffee+betel nut, J+Rb = 'jelutung'+rubber. Numbers in the legend indicate distances from the front ditch. Approximately 2-week intervals from 30 Jan 2014 to 15 Dec 2014.

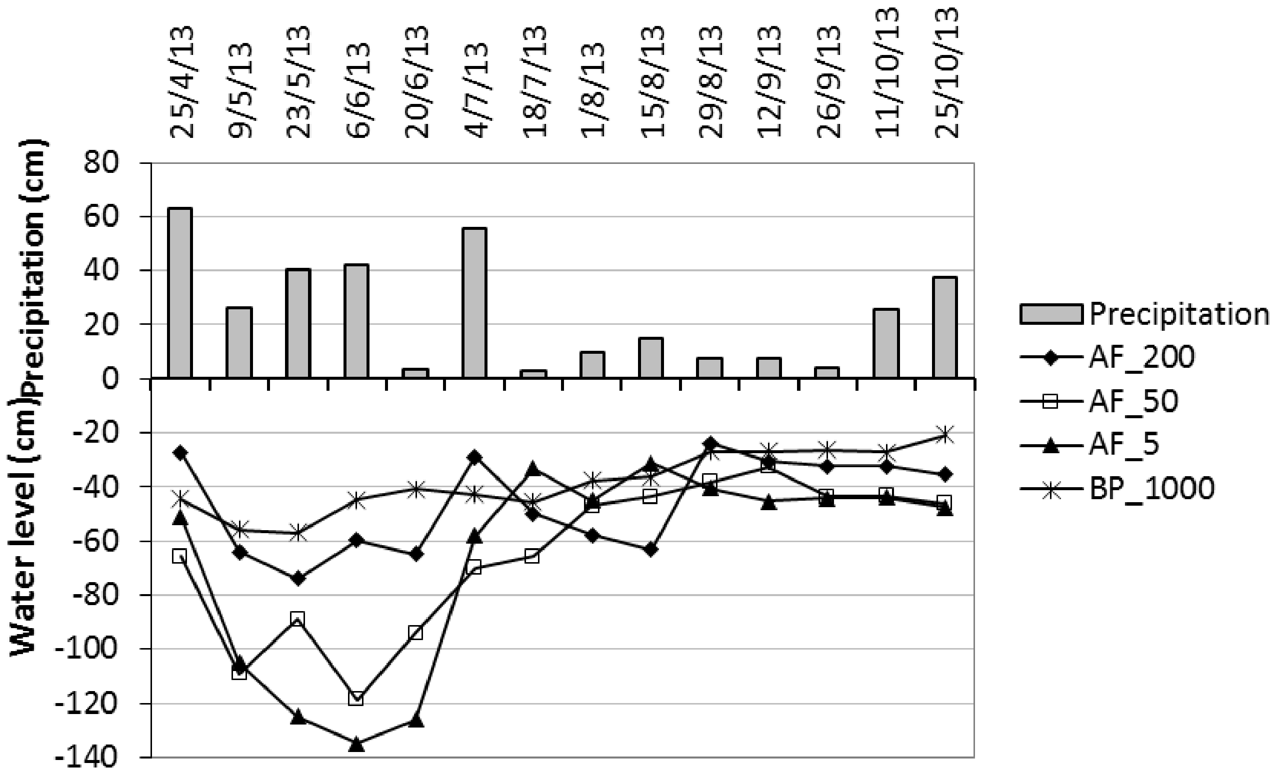


Figure 4. Tumbang Nusa, Central Kalimantan: rainfall and water table levels in the four demonstration plots (three plots with jelutung agroforest (AF) and one on burnt peatland). The numbers in the legend indicate the distance (m) of the plot from the ditch. Data were collected at intervals of approximately two weeks from April to October 2013.

Subsidence

At Tanjabar the range of subsidence rates was 1–10 cm per year during the first year of observation in 2014. The highest subsidence rate was observed in the oil palm plots (Table 2).

The range of subsidence rates observed at Tumbang Nusa (2–10 cm per year) was similar to that seen in Tanjabar (Table 3). Rates were highest, at 9–10 cm per year, in two of the recently developed ‘jelutung’ agroforestry plots (mixed planting of jelutung+*S. balangeran*+rambutan). Khasanah & van Noordwijk (2018) report a relationship between subsidence and increased bulk density and CO_2 emissions. Thus, the high rate of subsidence in the recently developed AF plot suggests a high decomposition rate. Table 3 also shows the results for bulk density, organic matter and organic C contents of the surface 10 cm of peat at these plots. As these measurements were not repeated at a later date, they could not be used to estimate carbon emission rates as intended, but they are shown here to provide additional information about the peat at Tumbang Nusa and to allow comparison with the results from Tanjabar presented later. The bulk density of peat soils collected from three land use types showed that it varies between 0.11 and 0.20 g cm^{-3}. The bulk density of surface peat in the AF plots, established recently on previously abandoned shrubland, was low (0.11–0.17 g cm^{-3}) and similar to that in PSF (0.13–0.19 g cm^{-3}) whereas bulk density was higher on the peatland that burned in 2004 (0.19–0.20 g cm^{-3}).

Above-ground carbon stocks

The above-ground carbon stocks corresponding to land cover types PSF, BP_97, BP_04 and jelutung AF at Tumbang Nusa are shown in Figure 5. For all land cover types, most of the above-ground carbon was located in trees and the second-largest carbon pool was in litter. PSF had the highest total carbon stock (111.07 Mg ha^{-1}), representing 407.64 Mg ha^{-1} of CO_2 sequestered from the atmosphere, whereas the above-ground carbon stock of peatland that was burned in 2004 (i.e. 9 years previously; BP_04) was only 13.38 Mg ha^{-1}. The above-ground carbon stock of peatland burned in 1997 (i.e. 16 years previously; BP_97) had recovered to 87.43 Mg ha^{-1}, whereas C storage on the AF plot was less than double that on the more-recently burned peatland.

Table 2. Peat depths and subsidence rates at four mixed farming systems in Tanjabar (Jambi). Notes: * = peaty soil; § = the information was given by key informants in the field.

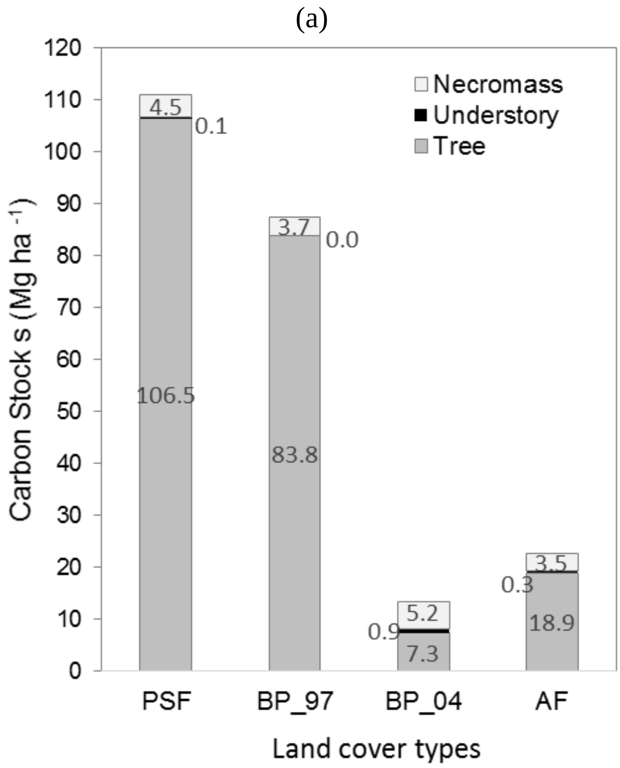
Farming system	Years after drainage§	GPS point	Peat depth (cm)	Subsidence (cm year^{-1})	Distance from front ditch (m)
Jelutung	>5	01° 03' 10.1" S 103° 22' 38.6" E	47.5*	5	5
			39*	4	205
Oil palm + jelutung (a)	>10	00° 59' 22.0" S 103° 20' 09.1" E	166	10	10
			172	8	210
Oil palm + jelutung (b)	>10	00° 59' 21.6" S 103° 20' 11.0" E	152	4	10
			160	6	210
Coffee + betel nut + jelutung	>10	00° 59' 59.5" S 103° 24' 09.0" E	79	3	10
			109	6	210
Rubber + jelutung	>25	00° 59' 59.5" S 103° 24' 09.9" E	24*	1	50
			20*	1	250

Table 3. Peat depths and subsidence rates measured in 2013 in the example plots of jelutung agroforestry (*D. polyhylla*+rambutan+*S. balangeran*), peatland (PSF) that burned in 2004 (BP_04) and unfelled/unburnt PSF at Tumbang Nusa (Central Kalimantan). The bulk density, organic matter and organic carbon (Corg) of peat under different land uses was measured in the depth range 0–10 cm.

Land use type	GPS	Peat depth (cm)	Subsidence rate (cm y^{-1})	Distance from ditch (m)	Bulk density (g ml^{-1})	Organic matter (%)	Corg (%)
Jelutung agroforestry	2° 22' 08.00" S 114° 06' 38.90" E	484	10	50	0.17	98.19	51.09
		600	9	250	0.11	97.17	50.09
BP_04	2° 22' 06.48" S 114° 06' 08.64" E	490	5	800	0.19	98.32	51.16
		442	5	1000	0.20	99.1	51.56
PSF	2° 21' 28.20" S 114° 05' 05.76" E	384	4	250	0.13	99.2	51.62
		484	2	500	0.19	97.56	50.76

CO_2 emission rates from peat

The calculation of CO_2 emission rates based on ash content difference from the mixed farming systems in Tanjabar is shown in Table 4. Using the very limited data that we collected, the highest mean value of CO_2 emission rate (381 Mg ha^{-1} y^{-1}) was from the mixed farming system of oil palm and jelutung and the lowest (256 Mg ha^{-1} y^{-1}) was for jelutung. The emission rate for the jelutung+rubber plot was slightly higher than that for the jelutung plot. These emission rates were higher than the emission rates from cleared and drained forest land reported by IPCC (IPCC 2014). Using the same approach (loss on ignition), Maswar *et al*. (2011a,b) reported higher CO_2 emissions in an oil palm plantation in Aceh, which ranged from 4,341 to 48,098 Mg ha^{-1} y^{-1}. In other cases of oil palm plantation in the ex-mega rice project area of Central Kalimantan, Dohong *et al.* (2018) reported annual average CO_2e emissions of 8.87 Mt. Our data show a positive relationship between CO_2 emission rate and depth of the water table (Figure 3). This is in line with the findings of other authors who have noted that drainage of peatland both increases CO_2 emissions and accelerates subsidence (Maswar *et al*. 2011a, Jauhianen *et al*. 2016, Khasanah & van Noordwijk 2018).



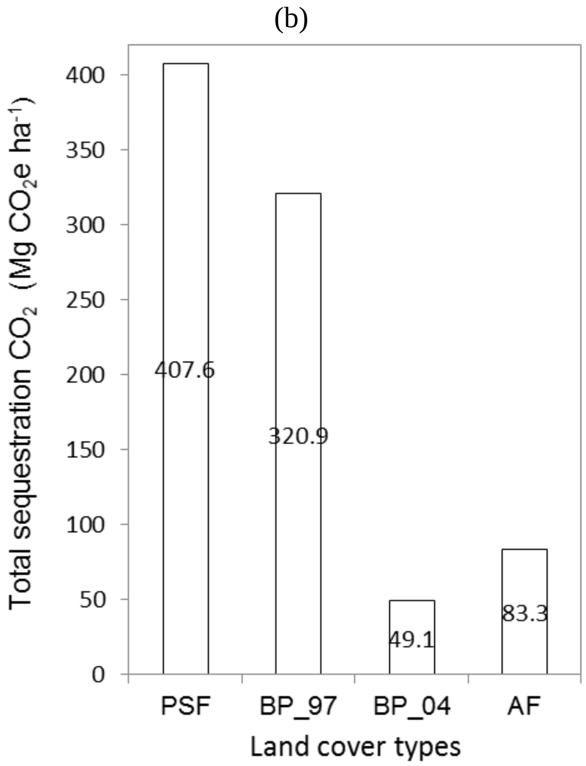


Figure 5. Above-ground carbon stocks (a) and total sequestered CO_2e (b) corresponding to four land cover types at Tumbang Nusa. The land cover types are: peat swamp forest (PSF; 2 plots), peatland burned in 1997 (BP_97; 1 plot), peatland burned in 2004 (1 plot), and agroforestry (AF; 3 plots with jelutung+rubber, jelutung+*N. lappaceum* and jelutung+*Acacia*, respectively).

Table 4. Change of ash content, bulk density, and estimation of CO_2 emission from mixed farming system (jelutung demo-plots) in Tanjabar, Jambi in the depth range 0–10 cm. The first measurement was on 2 January 2014 and the second measurement was on 8 December 2014.

Farming system	Plot name	Mean of BD (g ml^{-1})		Mean of Ash content (%)		Corg (%)	CO_2 emission (Mg ha^{-1}y^{-1})
		1st	2nd	1st	2nd		
Jelutung	HR1	0.26	0.24	39.40	76.44	75.79	278.14
	HR2	0.14	0.24	48.68	64.15	63.88	234.45
	Mean	0.20	0.24	44.04	70.30	69.84	256.30
Oil palm+ jelutung	KS1	0.14	0.24	8.34	93.93	102.91	377.67
	KS2	0.16	0.24	7.91	93.20	104.89	384.96
	Mean	0.15	0.24	8.13	93.56	103.90	381.32
Coffee+Betel nut +Jelutung	KD1	0.15	0.24	10.93	89.90	95.45	350.31
	KD2	0.15	0.24	21.99	96.04	98.18	360.30
	Mean	0.15	0.24	16.46	92.97	96.81	355.31
Rubber+ Jelutung	MS1	0.24	0.24	12.26	81.09	87.41	320.80
	MS2	0.17	0.24	23.78	55.01	56.37	206.86
	Mean	0.21	0.24	18.02	68.05	71.89	263.83

pH and macro nutrients in peat

pH and macro nutrient contents of peat from plots at Tumbang Nusa (PSF, AF and burnt peatlands) are shown in Figure 6 and 7. These are the plots for which above-ground carbon stocks were calculated above. Analysis of variance of macro nutrients data for different peat layers and land uses showed that peat depth and land use type did not affect the pH and macro nutrient content of peat soils (see Appendix). AF has low pH, but contains high levels of P and Mg; while peat from burned peatland (BPF) has high Ntotal, Ca, and Na (Figures 6 and 7).

DISCUSSION

According to the results of this study, the answer to the first of our three questions is that the peatland farming systems currently practised by farmers on our demonstration plots do contribute to Indonesia's peatland restoration strategy. In terms of reinstatement of vegetation, above-ground carbon stocks in AF plots at Tumbang Nusa were almost double those on peatland that had burned nine years previously (Figure 5), and soil nutrients were not significantly different among sites (nutrient level;

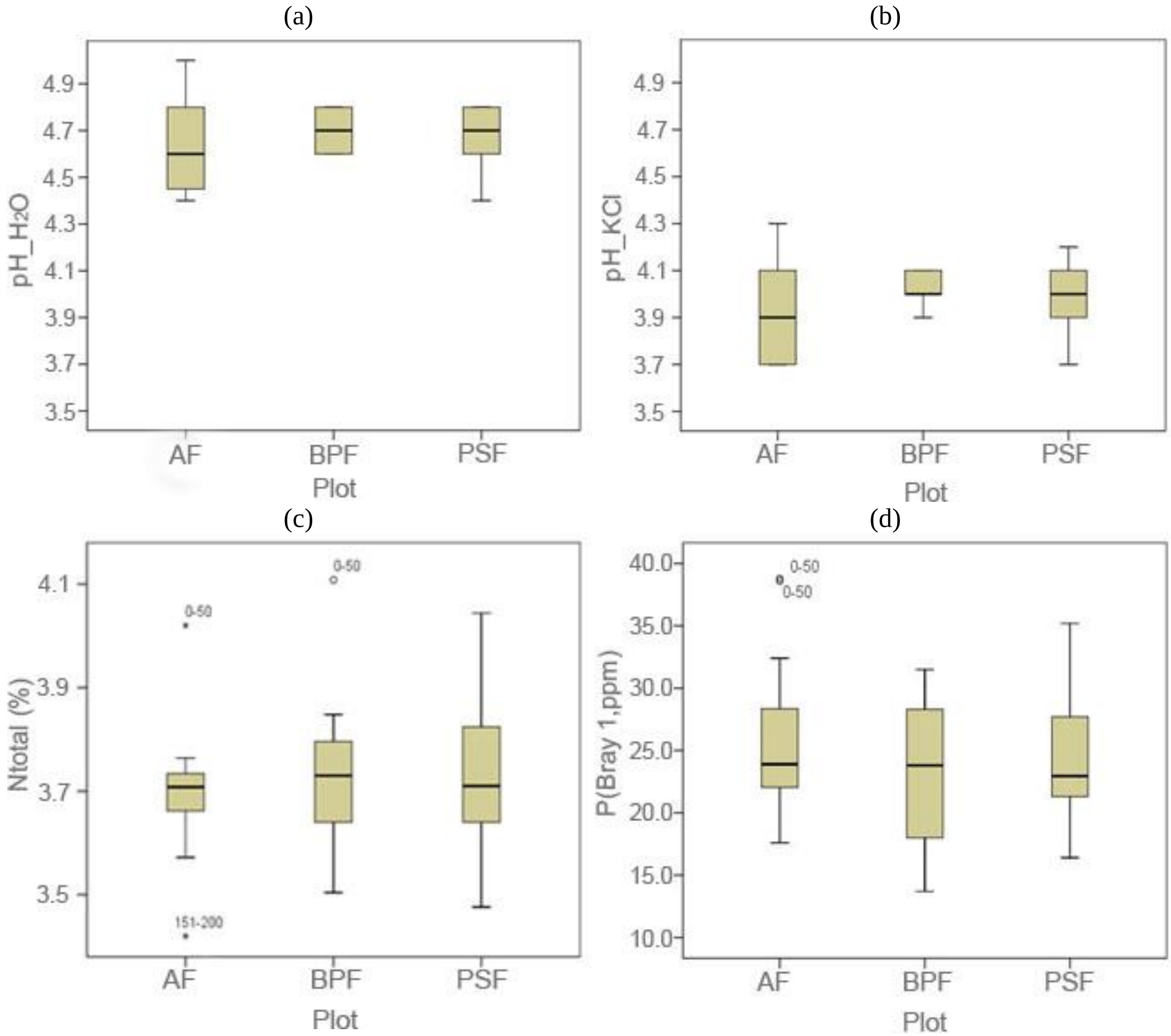


Figure 6. Peat properties of pH (H_2O and KCl), total N and available P from peat swamp forest (PSF-2 plots), burned peatland (BPF, 2 plots from peatland burned in 1997 and 2004) and agroforestry (AFJ; 3 plots with jelutung+rubber, jelutong+*N. lappaceum* and jelutung+*Acacia*, respectively). a) pH H_2O, b) pH KCl, c) N total, d) P available.

Figure 6, Figure 7). However, the practice of farming systems in both Tanjabar and Tumbang Nusa indicate that they are associated with fast peat decomposition. Application of fertiliser may increase soil productivity, but it accelerates peat decomposition and increases emissions of CO_2 (Khasanah & van Nordwijk 2018). However, other data presented here indicate that revegetation focusing on planting forest and crop tree species to improve local livelihoods, as currently practised, does not sufficiently support success in achieving the other main targets set by the strategy, namely reducing CO_2 emissions and increasing water level. Sixteen years after burning, above-ground carbon stocks (i.e. biomass in standing vegetation) in naturally recovering plots had increased to four times those on cropped plots, but remained below those in unburnt PSF (Figure 5). Moreover, Figures 3 and 4 show that the water table in mixed planting and agroforestry systems (without water management and canal blocking) often falls below the '-40 cm' level prescribed by Government Regulation No. 27 of 2016 for the 'zone of production' of the PHU.

Addressing our second question, the current farming systems in Tanjabar and at Tumbang Nusa are incompatible with the main goal of paludiculture. In short, current peatland farming practices in Tanjabar and Tumbang Nusa cannot be categorised

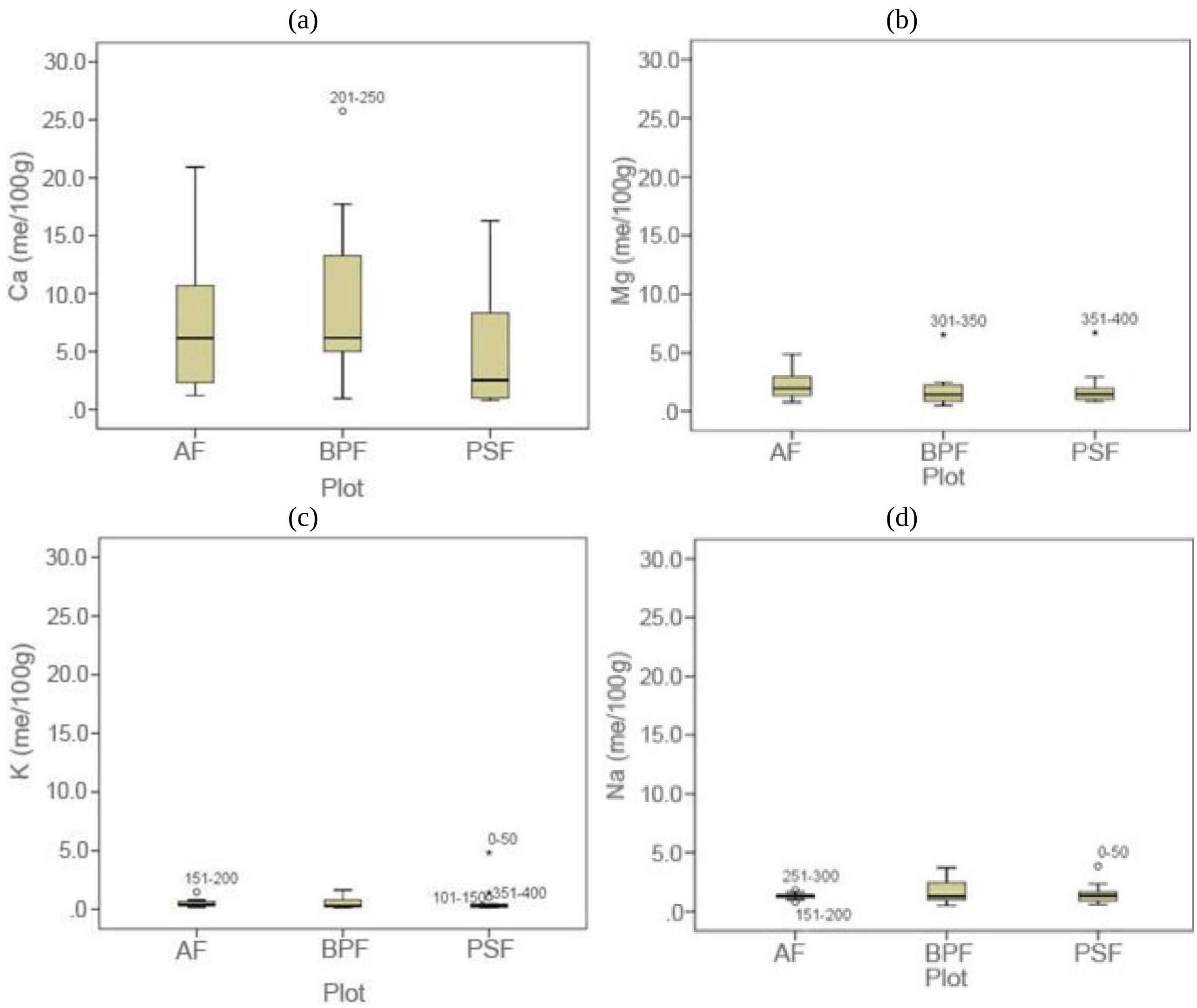


Figure 7. Soil macro nutrients of Ca, Mg, K, and Na from land cover types in Tumbang Nusa. The land cover types are: peat swamp forest (PSF; 2 plots), burnt peatland (BPF; 2 plots from peatland burned in 1997 and 2004), and agroforestry (AF; 3 plots with jelutung+rubber, jelutung+*N. lappaceum* and jelutung+*Acacia*, respectively). a) Ca, b) Mg, c) K, d) Na. Calcium has a wide range of values among land covers compared with other nutrients.

as paludiculture because the water table is not maintained at a sufficiently high level (the same reason these farming practices do not meet peatland restoration goals). In the context of paludiculture, however, the main goal is to reduce CO_2 emissions from farmed peatland so that the peat layer is preserved. Although above-ground carbon stocks in AF plots at Tumbang Nusa were higher than those on peatland that had burned nine years previously (Figure 5), the subsidence rate was double (Table 3), indicating ongoing losses of peat. The subsidence data from Tanjabar show differences between crop systems, but peat subsidence and net CO_2 emissions from peat were occurring in all cases (Tables 2–4). Moreover, the subsidence rate in recently developed plots was higher than in older plots, which may be due to high initial rates of decomposition of organic matter as reported by many researchers (van Noordwijk *et al.* 2014, Jauhiainen *et al.* 2016, Khasanah & van Noordwijk 2018, Astiani *et al*. 2018). It seems that further studies on decomposition and peat soil respiration are needed to support the evidence base for the recommendation of different mixed farming systems as appropriate land use in this specific situation. However, several more general strategies and guidelines on technical practices for responsible peatland management have been published (Schumann & Joosten 2008, Clarke & Rieley 2010, Joosten *et al*. 2012, Hergoualc'h *et al*. 2017, Ministry of Environment & Forestry of Indonesia Republic 2018). Joosten *et al*. (2012) suggest that wet agroforestry may offer a route to achieving productive use of peatlands in circumstances where canal blocking does not work or cannot be practically implemented, but this is not the land use that would best promote peat preservation under many circumstances. Wet (but not completely rewetted) agroforestry will slow down the rate of loss, but not stop it completely. It is estimated that raising the water table to -40 cm may reduce emissions (and peat loss) by 25–50 % (pers. comm. S. Page, in Giesen & Nirmala 2018).

Turning to our third question, in order to improve success in approaching the objectives of the peatland restoration strategy and the fully compatible goals of paludiculture, the main change to present farming practice that is required is improved management of hydrology. Water regulation and blocking of canals and ditches is recommended, such that the water table rises towards ground level, subsidence is reduced to a minimum (ideally zero or net accumulation) and the rate of CO_2 emission from peat decreases (Ritzema *et al*. 2014, Astiani *et al*. 2018). Indeed, success of the peatland restoration initiative requires this crucial step in water management. There is already evidence that many native PSF tree species adapt well to the environmental conditions in wet and rewetted peatlands (Banjarbaru Forestry Institute & Graham 2014, Lampela *et al.* 2016, Fan *et al*. 2017) and that they can be used for economic benefit by local communities (Giesen 2015, Tata & Susmianto 2016). Some perennial crops, such as pineapple (Astiani *et al*. 2015), grow optimally when the maximum water table level is -30 cm and when they are resistant to flooding (Tata & Tampubolon 2016). There is also vast potential for developing new 'crops' and products, since ~1,376 plant species have been identified growing in natural PSF and 534 of these already have recognised uses (Giesen 2015).

Dohong *et al.* (2018) added the suggestion that, to achieve successful peatland restoration, a meaningful land use policy and reform of governance will be needed since current policies and guidelines on peatland management do not take full account of the hydrological requirements for ecosystem function (Evers *et al.* 2016). In the context of existing smallholder farming systems on peatlands, we would add a requirement for peatland farmers and practitioners to embrace a paradigm shift in their approach to water management.

This study was necessarily limited to only a small number of sites and a short period of time for making measurements of water table depth and subsidence. Given the potential for variation of the factors we measured over time and space, research efforts should now prioritise expanding this dataset to encompass more sites and a longer time span. The results of such larger scale work are likely to carry more weight with policy makers and be more readily translated into management and policy recommendations. Nevertheless, our study has shown biophysical evidence from the existing farming systems on peatlands and provides an excellent starting point for a large scale investigation.

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Appendix: Analysis of Variance of soil macro nutrients from Tumbang Nusa (2 plots of peat swamp forest, 2 plots of burned peatland, 3 plots of agroforest jelutung).

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Plot	pH_H2O	0.016	2	0.008	0.545	0.586
	pH_KCl	0.048	2	0.024	1.307	0.288
	Ntotal	0.084	2	0.042	0.309	0.737
	P	43.484	2	21.742	0.821	0.452
	Ca	144.540	2	72.270	1.894	0.171
	Mg	3.325	2	1.662	1.037	0.369
	K	0.295	2	0.147	0.263	0.771
	Na	0.774	2	0.387	0.914	0.414
Depth	pH_H2O	0.248	8	0.031	2.109	0.074
	pH_KCl	0.255	8	0.032	1.726	0.141
	Ntotal	1.339	8	0.167	1.235	0.320
	P	160.103	8	20.013	0.755	0.644
	Ca	357.236	8	44.655	1.170	0.355
	Mg	28.150	8	3.519	2.194	0.064
	K	3.212	8	0.402	0.717	0.674
	Na	3.579	8	0.447	1.058	0.422
Plot * Depth	pH_H2O	0.238	11	0.022	1.473	0.203
	pH_KCl	0.263	11	0.024	1.296	0.283
	Ntotal	0.654	11	0.059	0.439	0.923
	P	587.659	11	53.424	2.016	0.071
	Ca	398.865	11	36.260	0.950	0.512
	Mg	10.051	11	0.914	0.570	0.835
	K	7.770	11	0.706	1.262	0.301
	Na	9.055	11	0.823	1.946	0.081