




Impact of Land Use Conversion on Carbon Stocks and Selected Peat Physico-chemical Properties in the Leyte Sab-a Basin Peatland, Philippines

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Abstract

Peatlands are unique wetland ecosystems that provide various ecosystem services such as carbon storage and biogeochemical cycling, however being threatened by anthropogenic activities. The present study was conducted to explore the impact of land use conversion on carbon stocks and peat properties in a tropical peatland in the Leyte Sab-a Basin Peatland (LSBP) in Northeastern Leyte, Philippines. The carbon stocks (aboveground and belowground) and physico-chemical properties of peat soil were compared among peat swamp forest, grassland and peatland with cultivation. Land use conversion resulted in the significant reduction of the total aboveground carbon stock. The peat swamp forest had the highest carbon stocks ($38.56 \pm 4.58 \text{ Mg ha}^{-1}$), and when converted to grassland and peatland with cultivation, it has resulted to carbon loss of as much as 86.59 and 90.45%, respectively. The belowground root carbon stock was highest in the peat swamp forest ($5.05 \pm 0.64 \text{ Mg ha}^{-1}$), also while highest peat carbon stock (1 m depth) was observed in the cultivation areas ($45.28 \pm 2.25 - 61.27 \pm 3.07 \text{ Mg ha}^{-1}$). However, peat swamp forests with very deep peat deposits potentially store a significant amount of carbon than in peatland with cultivation that was characterized by shallower compressed peats. In addition, land use conversion altered the physico-chemical properties of peat such as water content, organic matter, and porosity, and bulk density which all indicated peatland degradation. Finally, the overall result of this study highlights the importance to develop and implement management and conservation plans for LSBP.

Keywords Tropical peatland · Peat swamp forest · Peatland degradation · Aboveground carbon stocks · Peat soil

Introduction

Tropical peatlands are great stores of terrestrial carbon (Lampela et al. 2014). They can be ombrotrophic or minerotrophic wetland ecosystems that sequester carbon (C) into vegetation and, especially, into thick peat (often > 10 m) below the forest floor (Page et al. 2010; Könönen

et al. 2015). According to recent estimates, the carbon stored in global tropical peat soils is equivalent to about 40% of the total carbon stored in woody vegetation in the entire tropics. It is estimated that tropical peatlands cover an area between 368,000 and 441,025 km² that represents 8–11% of global peatland area (4,000,000 km²) (Hergoualc'h et al. 2017; Clarke and Rieley 2019). Due to its waterlogged and acidic condition, peatlands constitute the top long-term carbon stock in the terrestrial biosphere. This ultimately slows down the decomposition rate over preservation rate resulting in peat accumulation (Anshari et al. 2010; Alibo and Lasco 2012). This long-term ability of peatlands to absorb atmospheric carbon dioxide (CO₂) from the atmosphere means that they play a major role in the regulation of global climate and greenhouse gas emissions (Alibo and Lasco 2012; Leifeld and Menichetti 2018).

However, land-use conversion associated with deforestation has resulted in the degradation of large areas of

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tropical peatlands. The degradation of tropical peats usually starts when the government drains and clears peat forests into open peats used for food crops, oil palm and industrial timber plantations (Anshari et al. 2010). And now, the degradation of the tropical peatlands due to land use conversion became a global concern due to large carbon emission (Anshari et al. 2010). In particular, peatlands now serve as an important source of CO₂ and as well methane (CH₄) to the atmosphere (Krüger et al. 2015; Hoyos-Santillan et al. 2016). The decline of water table depths in peatland as a result of drainage increases the thickness of the oxidative layer (acrotelm), which is rich in oxygen (aerobic), fresh litter and moist. This accelerates the aerobic microbial decay compared to anaerobic decomposition which predominates within the anoxic zone below the water table (Anshari et al. 2010). In addition, the drainage and cultivation of peatlands stimulates soil organic matter (SOM) mineralization, which substantially increases CO₂ emissions from soils (Grønlund et al. 2008).

Further on, the impacts of land use conversion are not only limited to carbon loss but also on the physical and chemical properties of peat. Land use conversion results in changes in peat physical properties over time, through a combination of physical collapse of peat structure following drainage, and decomposition (Tonks et al. 2017). For example, changes in bulk density are an indicators of peat degradation in which the increase of peat bulk density may suggest peat oxidation (Krüger et al. 2015) and removal of lignified root biomass (Tonks et al. 2017). Likewise, continuous decomposition alters organic matter components and chemistry due to the rapid decrease in polysaccharide, tannin, hemicellulose, and cellulose contents (Yonebayashi et al. 1994). Prior studies have shown that conversions and drainage of peatlands have resulted in the alteration of other peat chemical properties such as pH, C/N ratio and nitrogen (Anshari et al. 2010; Frank et al. 2014; Könönen et al. 2015).

The Leyte Sab-a Basin Peatland (LSBP) has been deforested and drained for conversion into other land uses such as grassland and peatland with cultivation which has resulted in a decline of peat forest cover. Such conversion may have resulted in the loss of complex vegetation structures and replaced with grassland and monoculture crops which deposits far less carbon. Likewise, land use conversion may have also resulted in the alteration of physico-chemical properties of peat soil. Despite these, knowledge about the impact of land use conversion on carbon stocks and physico-chemical properties of peat soil in a tropical peatland particularly in the Philippines is very limited. In addition, to the best knowledge of the authors, no previous studies have been conducted in the peatlands of the country that directly evaluate such impacts of land use conversion. Thus, this study aims to assess the aboveground carbon stocks, belowground carbon stocks and physico-chemical properties of peat soil

in relation to land use conversion in the LSBP. The specific objectives of the study are (a) to determine the aboveground carbon stocks (standing trees, understory/grasses, leaf litters, and downed wood), belowground carbon stocks (tree roots, and peat soil), selected peat physico-chemical properties (gravimetric water content-GWC, volumetric water content-VWC, dry bulk density-DBD, total porosity-TP, organic matter-OM), and their differences across the different land use conversion classes (peat swamp forest, grassland, and peatland with cultivation) in LSBP; and (b) examine inter-relationships among peat physico-chemical properties across the different land use conversion classes using multivariate analyses such as regression and Principal Component Analysis (PCA).

Materials and Methods

Study Area

The LSBP has the second most significant peat soil deposit in the Philippines, next to Agusan Marsh of Mindanao (Fig. 1). It is an elongated basin with an area of 3,088.00 ha (Association of Southeast Asian Nations-ASEAN Peatland Forests Projects 2018) but recent estimates suggest that the peatland has an area of about 2,108.00 ha (Garcia et al. 2021). The peatland is situated in the northeastern portion of Leyte Island, which covers the municipalities of Alangalang, Sta. Fe and San Miguel.

On the eastern flank, the LSBP is bordered by ultramafic outcrops known as the Tacloban Ophiolite Complex (TOC). The underlying sediments of the peatland are composed of alluvial deposits derived from ultramafic rocks and sedimentary sequences (Suerte et al. 2005). The peatland is being fed by water coming from surface runoffs and streams. On the other hand, the peatland is being drained by two major river systems (Mainit River and Bangon River) and artificial outlets created by blasting a portion of the bordering hill.

During the 1970's, the Philippine government has initiated a project funded by National Food Authority and Philippine Coconut Authority to drain the LSBP for agricultural development along with provisions of land ownership. In this government project, the previous forested LSBP was deforested and canals and an artificial water outlets were made for drainage purposes. However, these areas were abandoned after a few years due to poor yield and now dominated with extensive sedges and grasses. And therefore, this has resulted in the significant reduction of forest cover and probably the degradation of the peatland. The remaining unutilized peatland of 1,288.00 ha in the northern part of the basin consists of small remnant areas of peat swamp forest (ASEAN Peatland Forests Projects 2018). The remaining

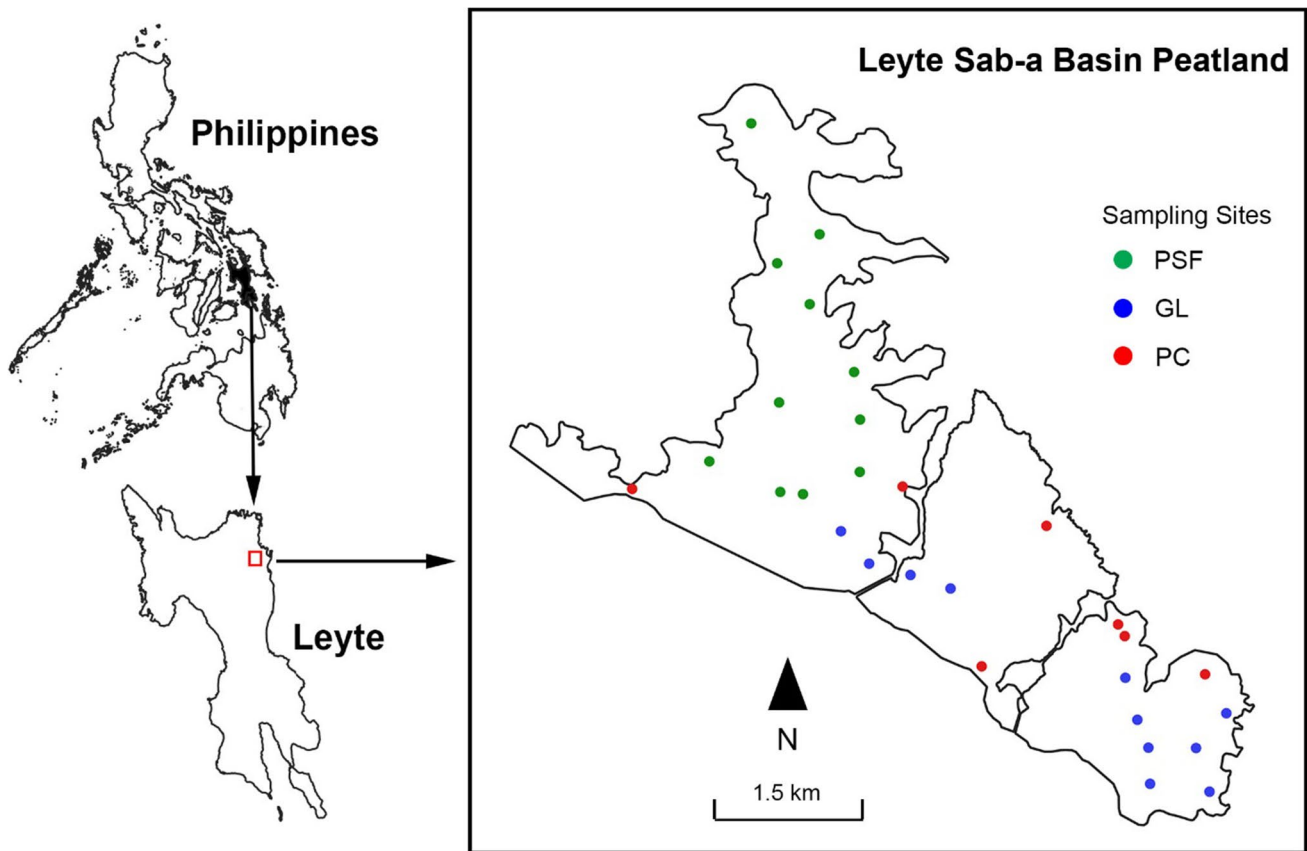


Fig. 1 Map of the Leyte Sab-a Basin Peatland (LSBP) and locations of study plots in Northeastern Leyte, Philippines. PSF–peat swamp forest, GL–grassland, PC–peatland with cultivation

forested portion of the peatland is dominated by tree species like *Ilex cymosa* Hassk.

Under the Modified Corona's Climate Classification System, the study area has a Type IV climate which is characterized by the absence of dry season and more or less evenly distributed rainfall throughout the year. The warmest month is April with an average temperature of 28.10 °C and the pronounced wetness occurs in the months of November, December, and January with rainfall of 279.00 mm, 305.30 mm, and 281.17 mm, respectively (Quiñones and Asio 2015).

Study Sites

Peat Swamp Forest

The remaining forest portions of the peatland are located at the northern part which represents original peat swamp forests. It is characterized by the presence of medium size trees dominated by *I. cymosa* and often covered by very thick vines. The understorey layer is usually dominated by *Mapania sumatrana* (Miq.) Benth. and *Scleria scrobiculata* Nees & Meyen, and a climbing fern species *Stenochlaena*

palustris (NL Burm.) Bedd. Although these swamp forest areas had no history of clear cutting and draining, these have been subjected already to some minor disturbances such as collection of wood for construction and fuel, fishing and wildlife poaching. Though, few of the forest plots established in this study were located in areas of remnant original peat swamp forest surrounded by secondary peat swamp forests. In addition, these areas still harbour some important wildlife species such as wild pigs and giant fruit bats.

Grassland

The extensive grassland and sedges with occasional shrubs and trees in the LSBP were actually abandoned croplands. The notable vegetations are sedges such as *S. scrobiculata* and *Fimbristylis globulosa* (Retz.) Kunth. with occasional trees of the species *Nauclea orientalis* (L.) L. These areas were previously cleared and drained for rice production and other agricultural crops. This happened when the major portion of the peatland has been converted to agriculture by the defunct Leyte Sab-a Development Authority, however was abandoned due to poor yield. There were large and small canals that could still be observed, however already covered

with vegetation which probably stopped the process of draining. These grasslands are subjected to fire disturbance with only the vegetation being burned during the periods of the year with minimal rainfall. Compacted peat soils can be observed indicating decomposition and mineralization. The water table was still closer or above the peat surface as the study was conducted during the months of pronounced wetness but most likely the water table is located deeper into the peat during the months with lesser precipitation.

Peatland with Cultivation

The peatlands with cultivation are situated in or surrounded by grassland and sedge areas along the peripheries of the peatland, but only the portions with cultivation were included in the study. Peatland with cultivation considered in this study were predominantly productive rice fields, though many patches of cultivated areas were non-productive or have shown attempts of cultivation. One of the dominant vegetation in these areas is a crop species (*Oryza sativa* L.) and many other grass species. These rice field areas are cultivated at least once a year and receive fertilization such as nitrogen, phosphorus and potassium. In some instances, remnants of logged or cut trees could still be observed. These are characterized by the presence canals ranging from 1.30 to 1.70 m wide and 0.25 to 0.80 m deep which were constructed to lower the water table and for irrigation purposes. As a result of a long history of cultivation, some interlayers of mineral soils could be observed in soil profiles. These ricefield areas tend to be maintained with sufficient water in most parts of the year.

Plot Establishment and Sampling

Reconnaissance surveys were conducted first prior to the sampling. There were 11, 11, and 7 sampling locations that were randomly selected in the peat swamp forest, grassland and peatland with cultivation, respectively. The geographic location of each sampling station was determined using a handheld Global Positioning System (GPS) (Model eTrex). All the field samplings took place between November 2020 to February 2021.

Aboveground Carbon Stocks

Standing Trees In every sampling location for each land use classification, a 20 m x 20 m (400 m²) plot was established to sample aboveground carbon stocks for trees. All the standing live trees with a diameter-at-breast height (DBH) of ≥ 5 cm inside the plot were counted and measured in terms of DBH and height. The height of the tree was visually determined through the use of a 2-m long calibrated pole (Madeira et al. 2009, Decena et al. 2020). In addition,

each of the tree individuals sampled were identified up to species level whenever possible using the pictorial Handbook on Peat Swamp Flora of Agusan Marsh, Mindanao of Tandang et al. (2014), and web database specifically the Co's Digital Flora by Pelsler et al. (2011) and other published literatures (Aribal and Fernando 2014; Aribal and Fernando 2018). Samples were collected as voucher specimens. The same procedures in the identification were also applied to understory/grasses.

Presently, no local site-or-species-specific allometric equation is available to estimate tree biomass. In the absence of validated and accurate local equations, the new pan-tropical equations developed by Chave et al. (2014) are more reliable than local equations which formulated using limited samples and DBH range (Manuri et al. 2014). The allometric equation is as follows:

$$AGB = 0.0673 \times (DBH^2 \times WD \times H)^{0.976}$$

Where AGB is aboveground biomass (kg), DBH is diameter at breast height (cm), WD is wood density (g cm⁻³), and H is the total tree height (m). The wood density for each of the tree species was derived from the Global Wood Density Database of Zanne et al. (2009). In case for trees that were not identified up to species level or in the absence of wood density data for species, the average wood density of the genus or family was used in the computation. The individual tree biomass values were computed using the above biomass allometric equations and were summed to give the total tree biomass stock. The biomass stock is then divided by the area sampled (400 m²) to give a value in kg m⁻². This value was converted into Mg ha⁻¹ by multiplying it by 10. Since the study area belongs to the tropical region, the tree biomass stock was converted to carbon stock density by multiplying with the default carbon value of 0.47 of the Intergovernmental Panel on Climate Change (IPCC) (2006).

Understory/Grasses To sample carbon stocks for understory and grass layers, three 1 m x 1 m smaller plots were randomly established inside the main plot. All the herbaceous, grasses and woody vegetation with a DBH < 5 cm inside the plot were sampled through a destructive method by harvesting with the use of machete. The total fresh weight of the bulk samples was determined using an electronic weighing scale with an accuracy of ± 5 g. Then, a subsample of about 300 g was weighed using the same instrument and was placed in labelled plastic bags and transported to the laboratory. The subsample was then re-weighed at the laboratory with an electronic balance (accuracy: 0.01 g). The subsamples were oven-dried at 80 °C until constant weight was achieved. The oven-dry-to-wet mass ratio of the subsample

was then used to convert the total wet mass to oven dry mass. The biomass stock of understorey/grasses was computed with the following formula;

$$UG = \frac{W_{ffs}}{A} \times \frac{W_{ods}}{W_{fs}} \times \frac{1}{100}$$

where UG is the understorey and grasses biomass stock (Mg ha^{-1}), W_{ffs} is the fresh weight of the field samples, W_{ods} is the oven-dry weight of the subsample and W_{fs} is the fresh weight of the subsample. The carbon content of the understorey and grasses was then determined by multiplying the biomass with the IPCC (2006) default carbon fraction of 0.47.

Leaf Litter To sample leaf litters, a 0.50 m x 0.50 m smaller plot was randomly marked inside the 1 m x 1 m sampling frames. All the leaf litter materials inside the plot were manually collected by hands and were placed in a labelled plastic bag. Often, the total fresh weight of the leaf litters sampled in the plot did not exceed 300.00 g, thus all the samples were just brought to the laboratory for oven-drying. The samples were oven-dried at a temperature of 80 °C until weights of the samples became constant. The oven-dried leaf litter biomass was divided by the area sampled to get a value in g m^{-2} , then, the value was divided by 100 to get a value in Mg ha^{-1} . Lastly, the leaf litter biomass was multiplied with the IPCC (2006) default carbon fraction of 0.47 to obtain carbon content.

Downed Wood The planar intercept method was employed to sample downed wood (≤ 7.6 cm diameter) (Brown 1974) by establishing four 12 m transects extending from the center of the 20 m x 20 m plot, oriented at 45° in four directions (NW, NE, SE, SW). The downed wood with a diameter ≤ 7.6 cm was tallied according to size classes along the subsections of the sampling plane: < 0.62 cm, 2 m sampling plane; 0.62 – 2.54 cm, 5 m plane; 2.54 – 7.62 cm, 10 m plane. Whereas downed wood with a diameter of > 7.62 cm was measured in actual diameter (cm) along a 12 m sampling plane and further noted in terms of decay status whether sound or rotten. About 8 to 40 collected samples of each size class were measured to determine specific gravity (wood density). The wood specific gravity (g cm^{-3}) was first determined through oven drying (105 °C) and then using the water displacement method. Now, the downed wood biomass (Mg ha^{-1}) was computed using the volumetric equations of Brown (1974) combined with site-specific data on particle diameters and wood specific gravity (wood density) by size class obtained in this study. To obtain the downed wood carbon stocks from downed wood biomass, a conversion factor of 0.474 was used (Martin and Thomas 2011).

Belowground Carbon Stocks

Belowground Root Carbon Stocks

The use of allometric relationships is the most practical and cost-effective alternative to estimate belowground root biomass/carbon stocks (Dayathilake et al. 2020). The belowground biomass for trees was estimated using the allometric equation developed by Cairns et al. (1997). This model has been developed using the root to shoot ratio for tropical trees. The allometric equation is as follows;

$$\text{BGB} = \exp(-1.0587 + 0.8836 \times \ln \text{AGB})$$

Where BGB is the belowground biomass (kg) and AGB is the above ground biomass (kg). Similarly, to the computation of the aboveground biomass, the belowground biomass for each tree individual was computed using the above allometric equation and then summed up to give the total belowground biomass. The same extrapolations were also performed to derive a value in Mg ha^{-1} . Finally, to derive the belowground root carbon stock, the biomass stock was multiplied with a factor of 0.39 (Murdiyarsa and Kauffman 2015; Dayathilake et al. 2020).

Soil

Inside each main plot, a peat core sample of 100 cm in length was taken using a bi-partite gouge auger (Eijkelkamp, Netherlands) with a 60 mm in diameter. In case of peat sampling in the forest sites, samples were taken at least 1 m from a tree since the presence of the roots could prevent the extraction of samples. Before the peat samples were extracted, sedges and grasses were removed with the use of machete. However, peat augering was discontinued whenever the auger encountered large living roots and very hard undecomposed tree trunks buried in the peat or when some samples were lost during lifting of the auger. The extraction of peat samples was only limited to 1 m since it was often no longer possible to extract undisturbed peat samples beyond this depth especially at forest sites. On site, the core samples were cut at 10 cm intervals resulting in a total of 290 soil samples, and were placed in labelled ziplock bags. However, some portions/layers of the peat core samples particularly from the peatland with cultivation had very obvious mineral materials, consequently these were excluded in the analysis (Leifeld et al. 2020). Peat samples were brought to the laboratory for further analysis.

In each sampling location, the water table height of the peatland relative to the peat surface was measured up to 0.50 m accuracy using a ruler or meter stick. It was measured either from the peat surface to the water surface if positive, or if negative from the surface down to the water

table via the core sampler borehole. The peat depth was also measured by inserting a single gouge auger or long bamboo or wooden pole especially in areas with very thick peat deposit usually exceeding 5 m.

The soil carbon stock (CS) in Mg ha^{-1} was determined for each depth layer using the equation, $\text{CS} (\text{Mg ha}^{-1}) = [\text{DBD} (\text{g cm}^{-3}) \times \text{Peat layer depth} (\text{cm}) \times \text{OC} (\%)] \times 100$ (Alibo and Lasco 2012). The organic carbon (OC) was derived from OM using a conversion factor of 1.724 (Agus et al. 2011). The values for DBD were derived from the succeeding determinations/calculations of peat physico-chemical properties.

Peat Physico-chemical Properties

All the peat samples were analysed for gravimetric water content (GWC), volumetric water content (VWC), dry bulk density (DBD), total porosity (TP), and organic matter (OM). The GWC and DBD were determined by oven drying the sample at 105°C for 24 h. The peat samples were spread thinly as much as possible in the container before oven drying. The TP was derived from DBD and an average particle density for peat of 1.40 g cm^{-3} (Rowell 1994). The OM content was determined by loss on ignition (LOI) through combustion of sieved peat samples in a box furnace (Cole-Parmer Box Furnace, United States) at 550°C for 5 h. The mass lost during the combustion process represents the organic matter (Rahgozar and Saberian 2015). The GWC, VWC, DBD, TP, and OM were calculated using Eqs. (1), (2), (3), (4), and (5).

$$\text{GWC}(\%) = \frac{\text{WS}(\text{g}) - \text{DOW}_{105(\text{g})}}{\text{DOW}_{105(\text{g})}} \times 100 \quad (1)$$

$$\text{VWC}(\text{g cm}^{-3}) = \text{DBD} \times \frac{\text{GWC}(\%)}{100} \quad (2)$$

$$\text{DBD}(\text{g cm}^{-3}) = \frac{\text{DOW}_{105(\text{g})}}{\text{SV}(\text{cm}^3)} \quad (3)$$

$$\text{TP}(\%) = 1 - \frac{\text{DBD}(\text{g cm}^{-3})}{\text{PD}(\text{g cm}^{-3})} \times 100 \quad (4)$$

$$\text{OM}(\%) = \frac{\text{DOW}_{105(\text{g})} - \text{AW}_{550(\text{g})}}{\text{DOW}_{105(\text{g})}} \times 100 \quad (5)$$

Where WS is the wet sample weight, DOW_{105} is the constant weight after drying at 105°C for 24 h, and SV is the sample volume, PD is the particle density of 1.40 g cm^{-3} , and AW_{550} is the ash residue weight after combusting at 550°C for 5 h.

Data Analysis

Kruskal-Wallis ANOVA was applied to determine any difference in aboveground carbon stocks (standing trees, understorey/grasses, leaf litter, downed wood, and total aboveground carbon stocks) and belowground root carbon stocks between land use conversion classes. Post-hoc tests were performed whenever there were significant variations at $p \leq 0.05$ using pairwise comparisons. In this study, analyses in the difference in soil carbon stocks as well as the peat soil physico-chemical properties between land use conversion and depth classes was only limited up to 1 m depth of peat. The Generalized Linear Mixed Models (GLMMs) were applied to test any difference in peat carbon stock and peat soil properties across the different land use conversion classes, peat depth classes and their interaction. The GLMMs analysis used normal distribution with identity link function or gamma distribution and log link function as the procedure involved continuous data. In this analysis, sampling depth (layer) was included as a random factor in the model to account for dependence among samples of the same core. The relationships among peat physico-chemical properties across the different land use were examined using regression analyses. In addition, Principal Component Analysis (PCA) was also applied to further evaluate the relationships between peat soil properties with land use. PCA was performed with Z-score transformed data ($Z \text{ score} = (X_i - X_{\text{avg}})/X_{\text{std}}$; where X_i is a given value of a variable in a sample, X_{avg} is the average of that variable and X_{std} is its standard deviation). The analyses including Kruskal-Wallis ANOVA, GLMMs and regression were carried out in SPSS version 20.0 for Windows, and the PCA was performed using PAST 3.22 (Hammer et al. 2001).

Results

Plant Species Inventory and Structure

In this study, a total of 773, 10 and 6 tree individuals were inventoried in the peat swamp forest, grassland, and peatland with cultivation, respectively. The greatest number of tree species was recorded in the peat swamp forest (31) which was dominated by *I. cymosa* representing 65.85% of the total inventoried trees. Other abundant tree species found in the peat swamp forest were *Ficus cf. virgata* Reinw. ex Blume and *Syzygium zeylanicum* (L.) DC. On the other hand, very few species were recorded in the grassland (2) and peatland with cultivation (1) of which *N. orientalis* generally dominates. Trees found in the peatland with cultivation were generally larger with an average DBH value of $15.60 \pm 2.99 \text{ cm}$, and then followed by 11.00 ± 0.23 and $8.89 \pm 2.04 \text{ cm}$ for trees in the peat swamp forest and grassland,

respectively. Taller trees were found in the peat swamp forest with an average height of 5.96 ± 0.06 m, followed by 5.17 ± 0.75 and 3.81 ± 0.52 m for peatland with cultivation and grassland, respectively. Meanwhile, the peatland is home for high diversity of understorey and grass species wherein a total of approximately 63 different species were documented. The understorey layer of the peat swamp forest was usually dominated by *M. sumatrana* and *S. palustris*, grassland was dominated *S. scrobiculata* and *F. globulosa*, while the peatland with cultivation was represented crop species (*O. sativa*) and many other grasses.

Aboveground Carbon Stocks

The carbon stocks for standing trees differed significantly among land use conversion classes (Table 1; Fig. 2a), with higher values for peat swamp forest (29.78 ± 4.79 Mg ha⁻¹) compared to grassland (0.20 ± 0.14 Mg ha⁻¹) and peatland with cultivation (0.49 ± 0.42 Mg ha⁻¹). Peat swamp forest had significantly higher understorey and grass carbon stocks (5.98 ± 0.43 Mg ha⁻¹) than peatland with cultivation (2.54 ± 0.22 Mg ha⁻¹) but not with grassland (4.70 ± 0.89 Mg ha⁻¹) (Table 1; Fig. 2b). The carbon stocks associated with leaf litter was significantly higher in peat swamp forest (0.64 ± 0.17 Mg ha⁻¹) compared to grassland (0.24 ± 0.06 Mg ha⁻¹) and peatland with cultivation (0.11 ± 0.03 Mg ha⁻¹) (Table 1; Fig. 2c). Similarly, downed wood carbon stocks were higher in peat swamp forest (2.16 ± 0.67 Mg ha⁻¹) than the other land use conversion classes (0.02 ± 0.01 Mg ha⁻¹ and 0.54 ± 0.50 Mg ha⁻¹ for grassland and peatland with cultivation, respectively) (Table 1; Fig. 2d). Also, the combined aboveground carbon stocks were significantly higher in peat swamp forest with a value of 38.56 ± 4.58 Mg ha⁻¹ than in grassland and peatland with cultivation (Table 1; Fig. 2e).

Belowground Carbon Stocks

Belowground root carbon stocks differed significantly among land use conversion classes (Table 1; Fig. 3a). Likewise, with standing tree carbon stocks, root carbon stocks

Table 1 Results of the Kruskal-Wallis ANOVA on aboveground carbon stocks (standing trees, understorey/grasses, leaf litter and downed wood) and belowground carbon stock (roots) between land use conversion classes

Variables	N	Kruskal-Wallis H	df	p
Standing trees C (Mg ha ⁻¹)	29	21.30	2	<0.001
Understorey/grasses C (Mg ha ⁻¹)	29	15.53	2	<0.001
Leaf litter C (Mg ha ⁻¹)	29	17.07	2	<0.001
Downed wood C (Mg ha ⁻¹)	29	18.29	2	<0.001
Total aboveground C (Mg ha ⁻¹)	29	20.58	2	<0.001
Root C (Mg ha ⁻¹)	29	21.77	2	<0.001

were higher in peat swamp forest (5.05 ± 0.64 Mg ha⁻¹) than grassland (0.03 ± 0.02 Mg ha⁻¹) and peatland with cultivation (0.09 ± 0.07 Mg ha⁻¹). The GLMMs analyses revealed that peat carbon stocks in the surface (0–30 cm) and middle layer (30–60 cm) increased across all the land use conversion classes (Table 2; Fig. 3b). Carbon stocks in the surface layer were 34.83 ± 1.38 , 49.79 ± 2.54 , and 61.27 ± 3.07 Mg ha⁻¹ for peat swamp forest, grassland, and peatland with cultivation, respectively. Also, the carbon stocks in the middle layer were 27.56 ± 0.89 , 37.93 ± 1.46 , and 55.70 ± 2.29 Mg ha⁻¹ for peat swamp forest, grassland, and peatland with cultivation respectively. In the deepest layer (60–100 cm), carbon stock did not differ significantly between peat swamp forest and grassland but was highest in the peatland with cultivation (45.28 ± 2.25 Mg ha⁻¹).

Peat Properties

Thick peat soil deposits mostly occurred at forest sites ranging from 190.00 to 1143.00 cm with an average of 670.09 ± 103.64 cm. The average peat deposit in the grassland (405.82 ± 91.41 cm) was lower than in peat swamp forest although the greatest peat deposit was documented here with a peat depth of 1150.00 cm. On the other hand, shallowest peat deposits were observed in the cultivated areas which were located at the peripheries of the peatland (Fig. 4a). The position of the water table relative to the peat surface during the collection of the peat samples were 15.05 ± 3.58 , 12.55 ± 4.57 , and 6.64 ± 10.07 cm for peat swamp forest, grassland, and peatland with cultivation respectively (Fig. 4b). The positive values indicated water surface being above the peat and this also suggests that the water table decreases towards the more disturbed land use conversion classes (e.g., grassland and peatland with cultivation).

As reflected from the water table position, gravimetric water content decreased across land use conversion classes in both surface (1514.48 ± 70.61 , 1111.94 ± 76.86 , and $578.05 \pm 83.94\%$ for peat swamp forest, grassland, and peatland with cultivation respectively) and middle layer (1956.01 ± 68.70 , 1638.45 ± 75.88 , $826.48 \pm 83.79\%$ for peat swamp forest, grassland, and peatland with cultivation respectively) (Table 2; Fig. 5a). It is also important to note that gravimetric water content significantly increased with peat depth. Main differences in peat volumetric water contents among land use conversion occurred at surface and middle layer. The volumetric water content of surface peat was significantly higher in peat swamp forest (1.04 ± 0.03 g cm⁻³) and grassland (1.05 ± 0.02 g cm⁻³) than in peatland with cultivation while water content in the middle layer was highest at grassland (1.11 ± 0.01 g cm⁻³). However, the volumetric water content did not differ significantly between depth classes (Table 2; Fig. 5b). The peat dry bulk density significantly differed among

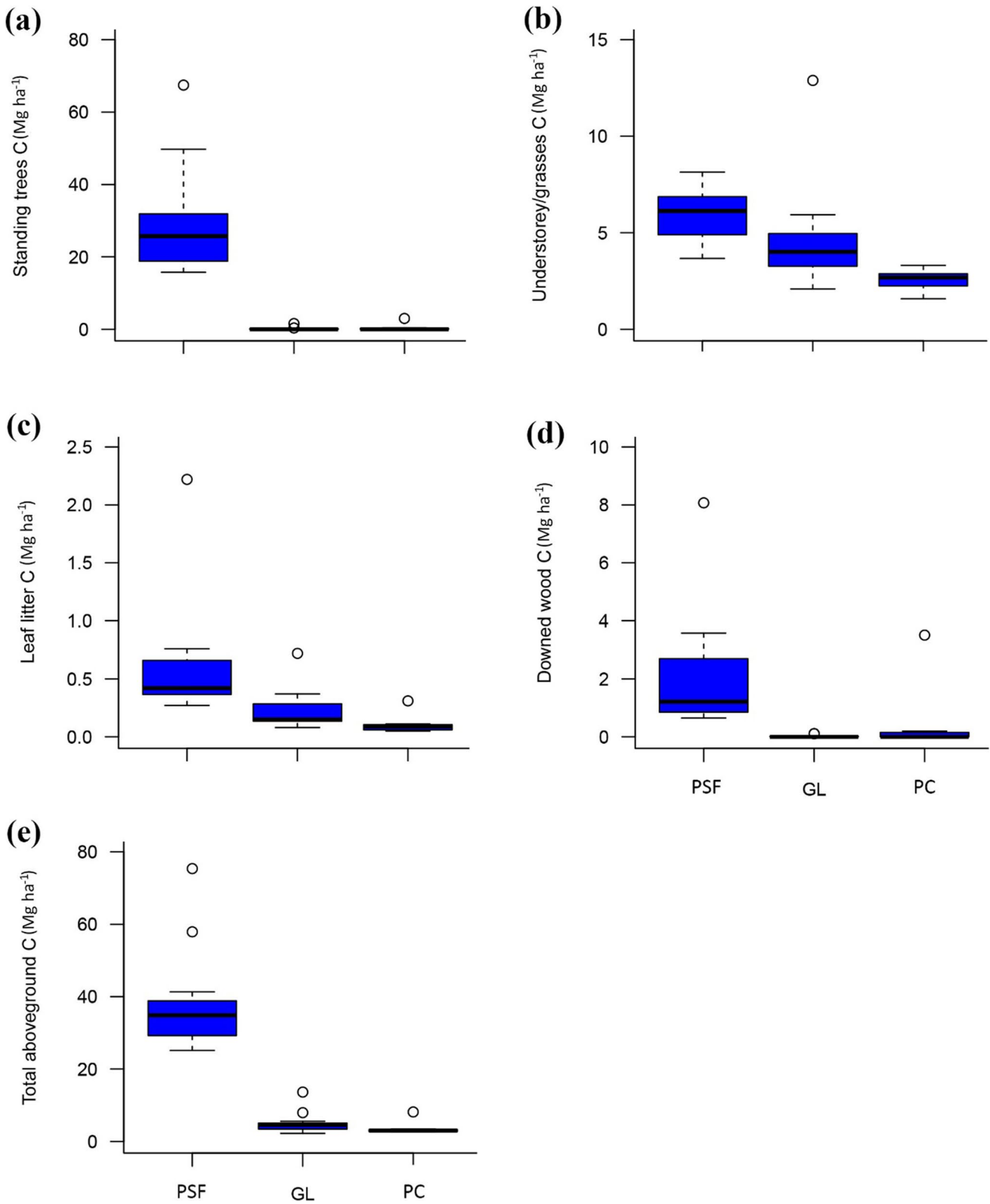


Fig. 2 Aboveground (a) standing trees, (b) understorey/grasses, (c) leaf litter, (d) downed wood, (e) total carbon stocks in the peat swamp forest, grassland, and peatland with cultivation in the LSBP in North-

eastern Leyte, Philippines. Average values for land use conversion classes and standard error bars are shown. PSF–peat swamp forest, GL–grassland, PC –peatland with cultivation

Fig. 3 Belowground (a) root and (b) peat soil carbon stocks in the peat swamp forest, grassland, and peatland with cultivation in the LSBP in Northeastern Leyte, Philippines. Average values for land use conversion classes and standard error bars are shown. PSF–peat swamp forest, GL–grassland, PC –peatland with cultivation

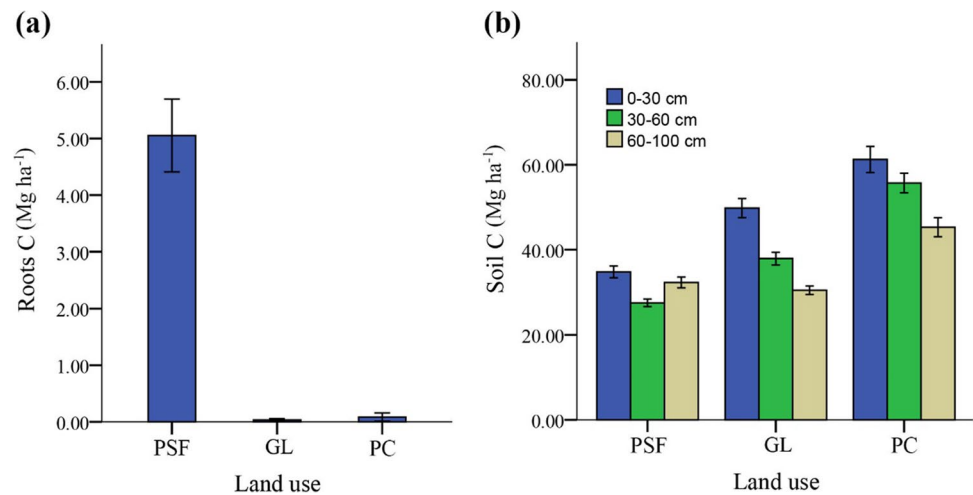


Table 2 Summary results of GLMMs analyses on peat soil carbon stock and peat physico-chemical properties (GWC, VWC, DBD, TP, and OM)

Variable	F	df	p
Soil C stock			
Land use	130.07	2,275	<0.001
Depth	26.44	2,275	<0.001
Land use x Depth	13.74	4,275	<0.001
GWC			
Land use	163.07	2,275	<0.001
Depth	29.51	2,275	<0.001
Land use x Depth	5.51	4,275	<0.001
VWC			
Land use	4.50	2,275	0.012
Depth	2.06	2,275	0.130
Land use x Depth	3.89	4,275	0.004
DBD			
Land use	137.92	2,275	<0.001
Depth	30.97	2,275	<0.001
Land use x Depth	7.96	4,275	<0.001
TP			
Land use	128.44	2,275	<0.001
Depth	30.52	2,275	<0.001
Land use x Depth	7.63	4,275	<0.001
OM			
Land use	81.10	2,275	<0.001
Depth	17.76	2,275	<0.001
Land use x Depth	1.48	4,275	0.208

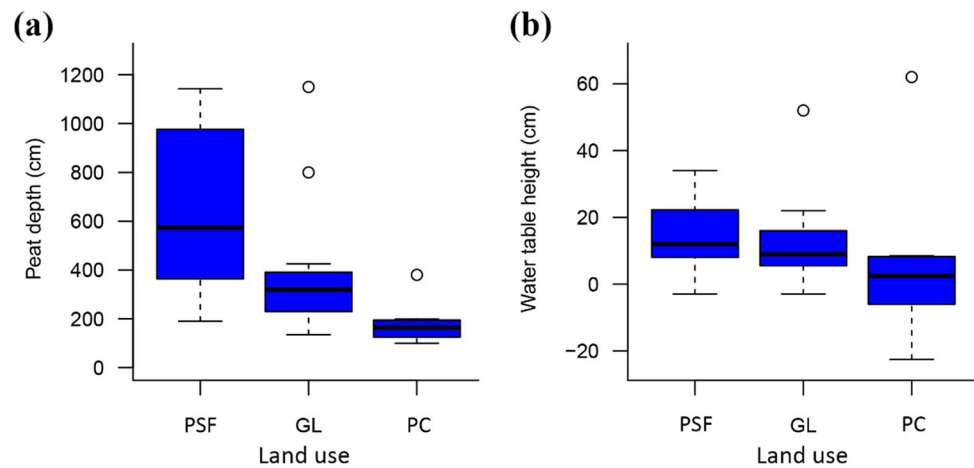
all land use conversion classes where peat soils became denser in all peat layers in more disturbed land use conversion classes. Dry bulk densities were all highest in the peatland with cultivation with a value of 0.21 ± 0.02 , 0.15 ± 0.02 , and 0.12 ± 0.01 g cm⁻³ for surface, middle and

deepest peat layer, respectively (Table 2; Fig. 5c). The total peat porosities were found to be high in all land use conversion classes wherein the highest porosities occurred at peat swamp forest with a value of 94.73 ± 0.30 and $96.11 \pm 0.15\%$ for surface and middle peat layer, respectively (Table 2; Fig. 5d). Peat porosities were observed to decrease from peat swamp forest to peatland with cultivation. The peat organic matter differed significantly among land use conversion and depth classes (Table 2; Fig. 5e). Organic matter in peat swamp forest ($87.39 \pm 0.74\%$) and grassland ($88.75 \pm 0.71\%$) was significantly higher than in the peatland with cultivation. Lastly, organic matter increased with peat depth with significantly higher values in the middle ($85.33 \pm 1.37\%$) and deepest peat layer ($86.29 \pm 1.09\%$).

The regression analyses showed significant relationships between peat physical properties and peat organic matter. Organic matter showed a positive S-curve relationship with gravimetric water content (Fig. 6a) and positive linear relationship with volumetric water content (Fig. 6b). Peat bulk density had a negative exponential relationship with organic matter (Fig. 6c) while total porosity exponentially increased with organic matter (Fig. 6d).

PCA was applied to further explore the associations between peat physico-chemical properties and land use. The relationships between peat physico-chemical properties and land use are shown in the PCA biplot (Fig. 7) with two principal components explaining 92.07% of the total variance. The first principal component accounted for 70.66% of the total variance with higher positive loadings for gravimetric water content (0.50), total porosity (0.54), and organic matter (0.52), and negative loading for dry bulk density (-0.43). The positive loading for gravimetric water content, porosity and organic matter indicated strong associations with and increases towards peat swamp forest and grassland whereas negative loading of bulk density

Fig. 4 The measured (a) peat depth and (b) water table height in the peat swamp forest, grassland, and peatland with cultivation in the LSBP in Northeastern Leyte, Philippines. PSF—peat swamp forest, GL—grassland, PC—peatland with cultivation



suggests inverse relationships with the latter peat properties and strongly associated with peatland with cultivation. In addition, the second principal component accounted for the 21.41% of the total variance with high positive loading for volumetric water content (0.98), and this peat property is also associated with peat swamp forest and grassland as indicated in the PCA biplot.

Discussion

Changes in Aboveground Carbon Stocks

Tropical peatland forests provide numerous ecosystem services including carbon storage, and thus they are important for climate change mitigation (Murdiyarso et al. 2009; Novita et al. 2021). However, in this study, it was found that aboveground carbon storage of peatland forest particularly in standing trees was significantly altered by land use conversion. The carbon storage of standing trees was extremely low in grassland ($0.20 \pm 0.14 \text{ Mg ha}^{-1}$) and peatland with cultivation ($0.49 \pm 0.42 \text{ Mg ha}^{-1}$) compared to the peat swamp forest ($29.78 \pm 4.79 \text{ Mg ha}^{-1}$). Such loss in carbon storage is attributed to the removal of vegetation mainly for the purpose of agricultural production (Anshari et al. 2010). In the LSBP, a large portion of the peat swamp forest has been deforested and converted to agriculture (primarily for rice production) but later abandoned due to poor yield leaving extensive grasslands (ASEAN Peatland Forests Projects 2018) which stores far less carbon. In other tropical peatland forests especially in Indonesia and Malaysia, the removal and conversion of forests have been associated mainly from the establishment of oil palm plantations and logging (Miettinen and Liew 2010; Tonks et al. 2017; Jaafar et al. 2020) which subsequently resulted in the significant carbon loss. Hergoualc'h and Verchot (2011) were able to estimate the carbon loss in vegetation associated with the

conversion of virgin peat swamp forest into other land uses in Southeast Asia. When converted to logged forest, mixed croplands and shrublands, rice field, and oil palm plantation, the carbon loss are estimated at 116.9 ± 39.8 , 204.1 ± 28.6 , 214.9 ± 28.4 , and $188.1 \pm 29.8 \text{ t ha}^{-1}$, respectively (Hergoualc'h and Verchot 2011).

In addition, the potential for carbon storage of the peatland forest under study should not be underestimated for its relatively higher average carbon stock of $29.78 \pm 4.79 \text{ Mg ha}^{-1}$ with a range of 15.74 to 67.45 Mg ha^{-1} . The average standing tree carbon stock observed in this study was higher when compared to the average carbon stock of standing trees in the intermediate forest (14.42 Mg ha^{-1}) but lower compared to the tall pole forest (87.01 Mg ha^{-1}) of the Caimpugan peatland of Agusan Marsh in Mindanao Island, Philippines (Alibo and Lasco 2012). When compared to the estimates in previous studies in other parts of the world, it was comparable to the average tree carbon stock of Thalawathugoda and Kolonnawa peatlands of Colombo Sri Lanka ($30.38\text{--}47.99 \text{ Mg ha}^{-1}$, Dayathilake et al. 2020) and mangrove forest at Sofala Bay, Central Mozambique ($28.02 \pm 9.20 \text{ Mg ha}^{-1}$, Siteo et al. 2014) but was lower than in riverine wetlands (peat swamp) of Encrucijada Biosphere Reserve, Mexico ($95.1 \pm 15.7 \text{ Mg ha}^{-1}$, Adame et al. 2015), Indonesian mangrove forest (64.40 Mg ha^{-1} , Murdiyarso et al. 2009) and Micronesian mangrove forest ($104.4 \pm 12.9\text{--}169.20 \pm 28.2 \text{ Mg ha}^{-1}$, Kauffman et al. 2011).

Similar to the pattern of carbon stocks of trees, carbon stocks associated with understory and grass layer generally decreased with land use conversion which was highest in the peat swamp forest ($5.98 \pm 0.43 \text{ Mg ha}^{-1}$) and lowest in the peatland with cultivation ($2.54 \pm 0.22 \text{ Mg ha}^{-1}$). The greater understory and grass layer carbon stock in the peat swamp forest can be directly associated with the presence of a thick layer of sedges mainly composed of *M. sumatrana* and *S. scrobiculata*, and a fern species *S. palustris*. The observed

average carbon stocks for understorey in peat swamp forest was higher compared to that of understorey carbon stocks of forest areas (0.66–2.33 Mg ha⁻¹) in Caimpugan peatland of Agusan Marsh, Mindanao (Alibo and Lasco 2012). In the study of Dayathilake et al. (2020), it was pointed out that the contribution of understorey species to the overall aboveground and belowground carbon stock in peat swamp forest may be insignificant. However, the present investigation demonstrated that understorey and grass layers accounted for a relatively larger percentage of the total aboveground carbon even at forest sites ($17.79 \pm 2.39\%$), indicating the significance of its contribution to the overall aboveground carbon stock. Whereas, the low carbon stock in the peatland with cultivation can be explained by the fact that these areas are dominated crop species (e.g. *O. sativa*) and other grasses which are either subjected to harvesting or cultivation. The cultivation process can slow down the growth or immediately remove vegetation and they store carbon in a relatively much shorter period of time than those in the peat swamp forest or grassland.

Litter materials such as leaves and woody debris are important components of aboveground carbon stocks where the decompositions of these materials serve as an important control on carbon accumulation in tropical peatlands (Hoyos-Santillan et al. 2015). However, land use conversion results in the disappearance of the litter layer and a decrease in the rate of litter fall (Hairiah et al. 2006). Such effects on litter are evident in this study where leaf litter and downed wood carbon stocks decreased significantly from peat swamp forest through peatland with cultivation. The study of Upton et al. (2018) showed that litter inputs determined carbon storage in tropical peatlands where there were greater litter inputs and organic carbon accumulations in mixed forest and mangrove forest. Therefore, the reduction in leaf litter and downed wood carbon stocks in LSBP would directly mean a reduction on carbon accumulation in peat soils in much disturbed land uses (peatland with cultivation and grassland) as compared to peat swamp forest. In addition, the reduced accumulation in litter biomass and carbon stock in the study area can be directly associated also with the accelerated decomposition due to exposure of moist litter materials to air brought about by the decline in the water table. Instead of accumulating, plant organic matters turn into gasses and dissolved organic acids and substances (Anshari et al. 2010).

Finally, the combined aboveground carbon stocks in the LSBP have declined significantly where the conversion of peat swamp forest to grassland and peatland with cultivation had resulted in carbon loss of as much as 86.59 and 90.45%, respectively. The overall average aboveground carbon stock in peat swamp forest (38.56 ± 4.58 Mg ha⁻¹) in the present study was similar to that of the carbon stock in the intermediate forest of Caimpugan peatland, Philippines

(31.16–43.40 Mg ha⁻¹, Alibo and Lasco 2012) and mangrove forest at Sofala Bay, Central Mozambique (33.30 Mg ha⁻¹, Siteo et al. 2014) although lower than in the peat swamp of Tanjung Puting National Park, Indonesia (~200.00 Mg ha⁻¹, Murdiyarso et al. 2009) and in intact peat forest of Central Kalimantan, Indonesia (73.48 Mg ha⁻¹, Petrova et al. 2008). The finding implies a greater need for the preservation of the remaining forested portion of the peatland as carbon sink.

Changes in Belowground Carbon Stocks

As expected, belowground root carbon stocks were significantly higher in peat swamp forests (5.05 ± 0.64 Mg ha⁻¹) as compared to grassland and peatland with cultivation. It can be speculated that carbon loss in roots is directly associated with the forest removal in the LSBP. However, caution must be taken into account in interpreting this finding of the study, that perhaps there is still the presence of undecomposed tree roots in the grassland and peatland with cultivation areas forming the belowground carbon pool. The observed belowground root carbon stock of the peat swamp forest in the present study was comparable to that found in Thalawathugoda and Kolonnawa peatlands of Colombo Sri Lanka (4.87–7.44 Mg ha⁻¹, Dayathilake et al. 2020) but lower than in the mangrove forest of Sofala Bay, Central Mozambique (25.22 ± 5.30 Mg ha⁻¹, Siteo et al. 2014). Root systems should be considered as they are an important part of the total forest biomass and eventually carbon storage (Verwer and van der Meer 2010) where belowground root carbon accounted for $11.49 \pm 0.50\%$ of the total biomass carbon for peat swamp forest in this study. Apart from that, roots have been found to be crucial in the peat formations in tropical peat swamp forest (Verwer and van der Meer 2010, Hoyos-Santillan et al. 2015).

Peat soil carbon stocks within 1 m depth increased along with land use conversion classes (Fig. 3b) despite the lower peat organic matter/carbon in the peatland with cultivation areas of LSBP (Fig. 5e). This finding corroborated with the result of the study of Bader et al. (2018) where carbon stocks in managed peat soils (1 m depth) was significantly higher in peatland with cultivation than those in grassland and forest. This pattern can be explained by the higher overall average peat bulk density in peatland with cultivation (0.15 ± 0.01 g cm⁻³) which can be the result of mixing with mineral soils (Murdiyarso et al. 2009) and compaction due to the use of heavy machineries for cultivation. However, when the total peat depth is taken into consideration in the determination of carbon stock, it would most likely turn out that the peat swamp forest would have the greatest carbon storage than grassland or peatland with cultivation as indicated in peat depth data (Fig. 4a). As part of the limitation for this study, as much as it was desired to sample the whole peat profile,

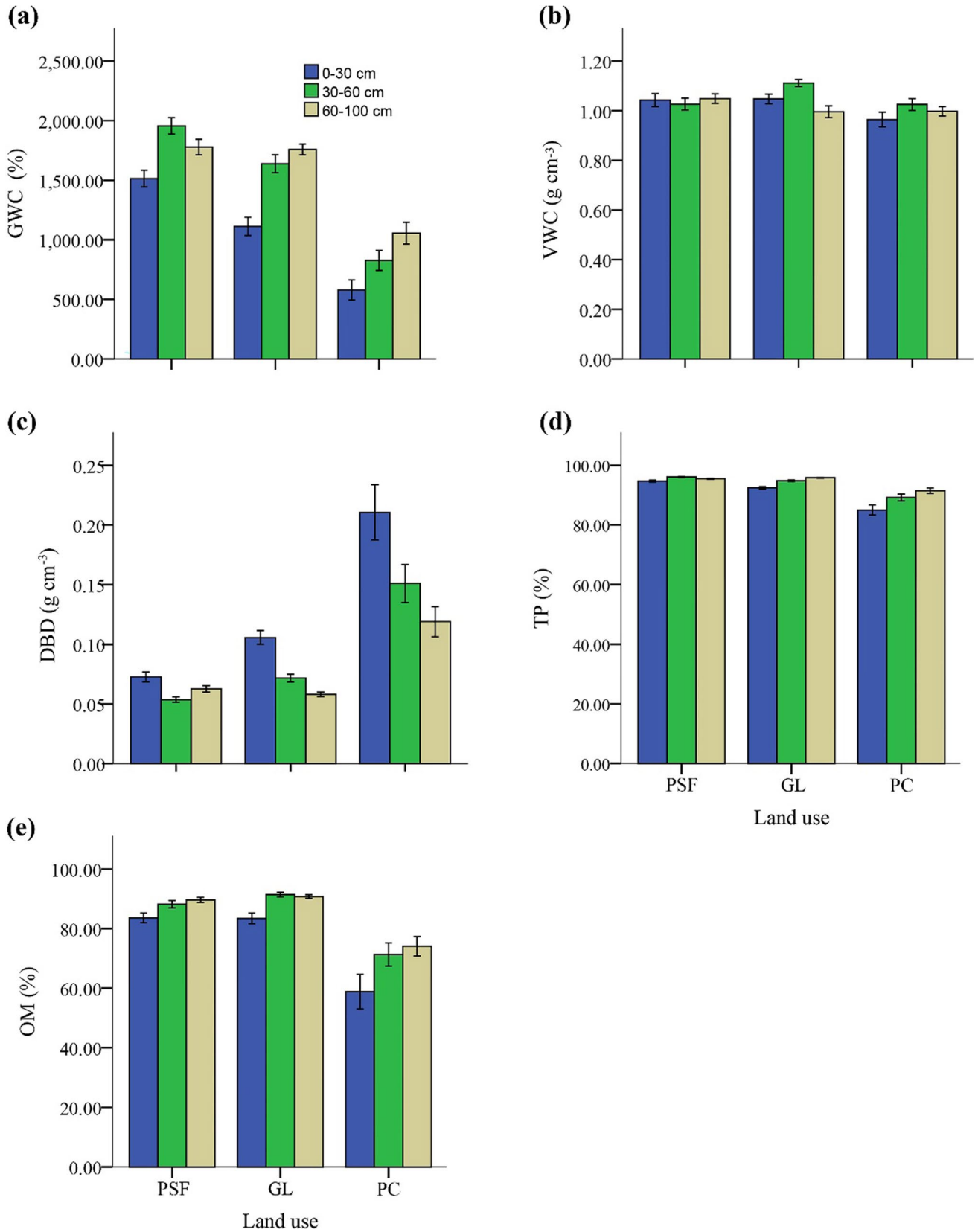


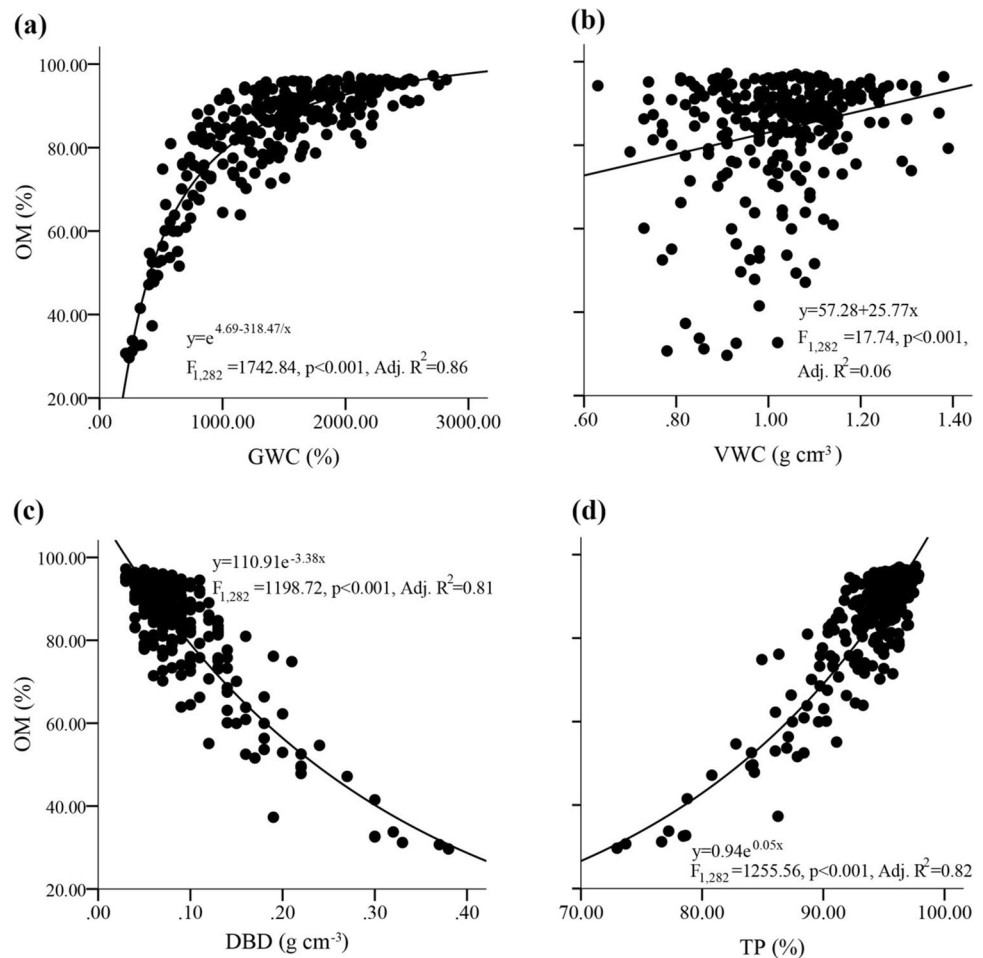
Fig. 5 The difference in (a) gravimetric water content, (b) volumetric water content, (c) dry bulk density, (d) total porosity, and (e) organic matter in peat soils in the peat swamp forest, grassland, and peatland with cultivation in the LSBP in Northeastern Leyte, Philippines. Average values for land conversion classes and standard error bars are shown. PSF—peat swamp forest, GL—grassland, PC—peatland with cultivation

it was only possible to extract a complete and undisturbed core samples up to 1 m depth with the kind of peat sampler used. Nevertheless, to have an overview on the potential peat carbon stock for all the land uses in LSBP, approximate carbon stock was computed for each location using the peat depth data and the overall average value for organic carbon and bulk density for each land use classification. The estimated carbon stocks were 2050.48 ± 317.15 , 1655.74 ± 372.95 , and 1100.57 ± 213.35 Mg ha⁻¹ for peat swamp forest, grassland and peatland with cultivation, respectively. These estimated values imply that LSBP especially in peat swamp forest stores significant amount of carbon in peat.

Changes in Peat Physico-chemical Properties

The water content of peat in the peat swamp forest was higher than the reported values in the tropical peatland forest of Southeast Asia (Anshari et al. 2010, Tonks et al. 2017). The peat moisture content decreased from forest to peatland with cultivation along with the decreasing trend of water table height (Fig. 4b) which can be linked to compaction from farm machinery (Tonks et al. 2017). Peat bulk densities in the peat swamp forest areas (0.05 ± 0.002 – 0.07 ± 0.004 g cm⁻³) of this study were comparable to tropical peatland forests of SE Asia ranging from 0.07 to 0.15 g cm⁻³ (Anshari et al. 2010, Lampela et al. 2014, Könönen et al. 2015, Tonks et al. 2017) although lower than in other studies (0.46–0.69 g cm⁻³) (Murdiyarso et al. 2009, Aribal and Fernando 2018). Peat bulk densities in this study linearly increased with land use conversion that was highest in the peatland with cultivation and which indicates peat degradation or decomposition (Krüger et al. 2015, Guillaume et al. 2016). High peat bulk density in the peatland with cultivation can be a consequence of compaction linked to pressure applied on the peat by agricultural equipment, and shrinkage that

Fig. 6 The relationships between (a) gravimetric water content and organic matter, (b) volumetric water content and organic matter, (c) dry bulk density and organic matter, (d) total porosity and organic matter. The significant regressions lines and their equations, R², F and p-values are presented in the figures



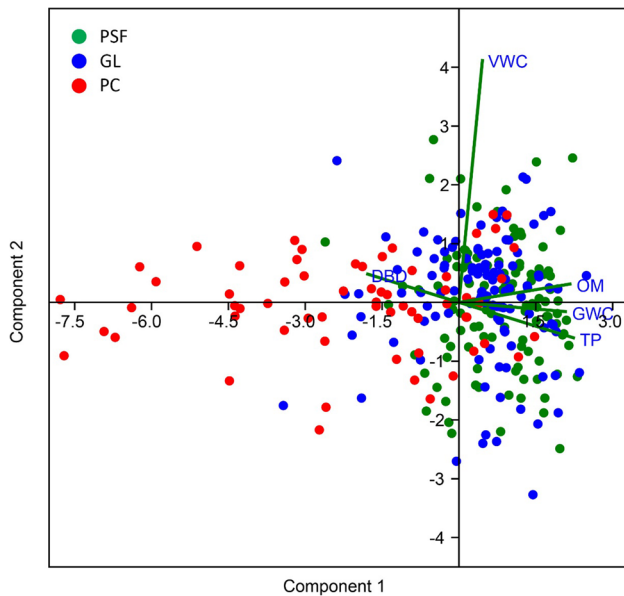


Fig. 7 Principal Component Analysis (PCA) biplot showing the relationships between peat soil physico-chemical properties and land use. PSF—peat swamp forest, GL—grassland, PC—peatland with cultivation

occurs through the contraction of organic fibers when drying (Hooijer et al. 2012). Those above-mentioned processes might as well explain why peatland with cultivations have very shallow peat. Similar to the finding of this study, high bulk densities were observed for converted peat in mature oil palm plantations (Anshari et al. 2010). In addition, aside from the possible effect of compaction from equipment, low porosities in peatland with cultivation are an indication of peat decomposition which reduces the proportion of large pores by breaking down plant debris into smaller fragments (Rezanezhad et al. 2016), thereby reducing the water-holding capacity of peat soil.

The observed organic matter in the peat swamp forest ($87.39 \pm 0.74\%$) of the present investigation was comparable to North Selangor Peat Swamp Forest (NSPSF), Malaysia as reported by Tonks et al. (2017) with a value of $94.1 \pm 1.5\%$ but slightly higher than in Caimpugan peat swamp forest on Mindanao Island, Philippines (65.74–73.70%, Aribal and Fernando 2018). The reduction of organic matter particularly in the surface peat in the peatland with cultivation area provides evidence on peat decomposition (Tonks et al. 2017). Enhanced peat decomposition follows after drainage, which is characterized by microbial respiration and peat oxidation, and as well the application of fertilizer, induce organic matter losses (Anshari et al. 2010, Leifeld et al. 2020). Such influence of drainage on organic matter loss is depicted by the observed direct positive relationships between water content and organic matter (Figs. 6a and b and 7) which was exactly observed also in the study of Tonks et al. (2017). Moreover, the loss of

organic matter due to land use conversion was observed to be explained by increasing peat bulk density (Anshari et al. 2010, Hooijer et al. 2012) as found also in this study (Fig. 6c).

Conclusions

Tropical peatland forest may contribute significantly to climate change as a consequence of the increasing trend of degradation and deforestation (Andriess 1988). Indeed, the present investigation has demonstrated that land use conversion of tropical peatland forest has resulted in carbon loss. It turned out that conversion of peatland forest into other land uses such as to grasslands and peatland with cultivations reduced carbon storage in vegetation in both aboveground and belowground. Peatland with cultivation had the highest carbon stocks in peat (1 m deep) due to high peat bulk density may be as a result of compaction. However, it was the peat swamp forests that potentially store the greatest carbon due to very thick peat deposits. In addition, land use conversions also have further negative effects on peat physico-chemical properties such reduction in peat water content and organic matter, and compaction as reflected by denser peat soils, all of which are indicators of peatland degradation. Taking altogether the results of this study, to keep the function of the LSBP as a significant carbon sink and to preserve its ecological integrity, there should be an impetus to develop and implement effective conservation and management plans.

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Data Availability Interested party may request data and materials from the corresponding author.

Code Availability Not applicable.

Declarations

Conflicts of Interest/Competing Interests There are no conflicts of interest to disclose.

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

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