

## Article

# Above-and-Belowground Carbon Stocks in Two Contrasting Peatlands in the Philippines

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**Abstract:** Although tropical peatlands are huge carbon reservoirs, they are threatened by climate change and anthropogenic disturbances. Here, we assessed two contrasting peatland sites in the Philippines in terms of aboveground biomass and carbon content, soil carbon stock, and CO<sub>2</sub> fluxes in the soils. The Caimpugan peatland in Agusan del Sur was considered the ‘undisturbed’ site, while the Bambanin peatland in Mindoro Oriental was the ‘disturbed’ site. The aboveground biomass at the undisturbed site was  $35.8 \pm 30.0 \text{ Mg ha}^{-1}$  while at the disturbed site, it was  $2.0 \text{ Mg ha}^{-1} \pm 1.9 \text{ Mg ha}^{-1}$ . The aboveground C content at the undisturbed site varied from  $1.29 \text{ Mg C ha}^{-1}$  to  $37.2 \text{ Mg C ha}^{-1}$ , while the disturbed site only ranged from  $0.1 \text{ Mg C ha}^{-1}$  to  $2.1 \text{ Mg C ha}^{-1}$ . A trend of increasing soil carbon content as the soil gets deeper was observed in both sites. At the undisturbed site, the average soil carbon content was  $750 \pm 710 \text{ Mg ha}^{-1}$  and  $595 \pm 406 \text{ Mg ha}^{-1}$  at the disturbed site. In terms of soil carbon emission, the undisturbed site had  $3.6 \pm 3.0 \text{ g C m}^{-2}\text{d}^{-1}$  and was only one-third the emission rate at the disturbed site ( $11.2 \pm 6.4 \text{ g C m}^{-2}\text{d}^{-1}$ ). Our study highlights the dire condition of a disturbed peatland in terms of vegetation/soil carbon dynamics. We underscored the need to address the pressing issues on peatland drainage, agricultural activities, and human settlement within the peatland sites geared towards effectively managing this important carbon reservoir in the Philippines.

**Keywords:** soil respiration; soil carbon; biomass; Philippine peatlands



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## 1. Introduction

Peatlands areas are where partially decayed organic materials accumulate over time and where litter deposition exceeds anaerobic decomposition. These sites are important reservoirs of biodiversity, carbon, and water [1,2]. Globally, peatlands only cover three percent of the Earth’s land area yet store 2000 Gigatons of CO<sub>2</sub> [3], equivalent to 30% of terrestrial carbon (75% of all carbon in the atmosphere) or twice the carbon stored in the forests [4]. About 8% of the global peatland areas are found in the tropics [5]. Tropical peatlands are important terrestrial carbon pools storing 40 to 90 Gt C [6,7] and account for one-third of the world’s soil C pool [8]. In Southeast Asia, peatlands are primarily found in Sumatra, the Malay Peninsula, Borneo (Kalimantan, Sarawak, and Brunei), and New Guinea [9].

Although tropical peatlands are huge carbon reservoirs, they are threatened by climate change and anthropogenic disturbances [10,11]. Land-use change and water management in the oil palm production in Malaysia intensify peat degradation affecting CO<sub>2</sub> fluxes from peatlands [12,13]. Human activities such as dam construction across drainage canals in

Indonesia increased the decomposition rate of the peat and CO<sub>2</sub> emission [2,14]. Degraded drained peatlands store globally ~80.8 Gt soil C and release ~1.91 Gt CO<sub>2</sub>-eq yr<sup>-1</sup> [15]. Other anthropogenic disturbances such as land cultivation, human settlement, forest harvesting, forest fires, and drainage have negatively impacted peatland ecosystems [16–18] and consequently contribute to global warming [19].

Peatland disturbance negatively impacts the ecosystem, altering the surface drainage and reducing site productivity [20]. Soil organic matter vulnerability to decomposition increased with an increasing level of disturbance and a decreasing soil organic content (SOC), indicating positive feedback mechanisms [21]. Land-use change, drainage, and agricultural cultivation alter the peatlands' hydrological and biogeochemical processes, e.g., by enhancing mineralization of the soil organic matter (SOM) [22], turning peatlands into hotspots of greenhouse gas (GHG) emissions from soils [23,24].

The Philippines have 10,700 hectares of peatland area out of the 29 million hectares of peatland existing in Southeast Asia [9]. However, the identification of more peatland sites in the country is ongoing. Like most Southeast Asian peatland sites, the Philippine peatland forests were also disturbed due to the growing population and increasing demand for forest products and services.

Ironically, in much literature for Asian peatland assessments [7], the Philippine peatlands are seldom included in many synthesis studies. Therefore, it is imperative and urgent to publish recent reports on Philippine peatland assessments so that the unique features and estimates can be incorporated in regional peatland studies and contribute to the growing demand for peatland literature in Southeast Asia. Improved knowledge and understanding of the tropical peatland, including the Philippines, is crucial given the rapid exploitation across the tropics, especially in Southeast Asia, the home of vast peatland sites.

One of the heavily disturbed peatland sites in the Philippines is the Bamanan peatland in Mindoro Oriental, located in the western part of the archipelago. This site is mainly affected by agriculture, forest harvesting, and human settlement. In contrast, one relatively undisturbed peatland in the country is the Caimpugan peat area in Agusan Marsh, north-eastern Mindanao. However, expanding land conversion for agriculture and ecotourism has threatened this peatland site.

A few studies were conducted in these peatland sites of the Philippines, but the focus was more on peatland plant species diversity [25], socio-economic aspects [26], peat physico-chemical properties [27]. Existing literature needs updating as this was conducted a decade ago [28]. The necessity to assess the present carbon dynamics of the above-mentioned disturbed and relatively undisturbed peatland sites in the Philippines prompted us to conduct this study. The focus of this report is not to directly compare the two sites as they differ in many aspects but to report current ground measurements on aboveground biomass and carbon content, soil carbon stock, and CO<sub>2</sub> fluxes in the soils from each peatland site. This report is only an initial part of the long-term peatland management program of the Department of Environment and Natural, Philippines. Our study responds to the growing demand for peatland literature. It provides insights to simulate better peatland vegetation dynamics and carbon fluxes in many land surface and global vegetation models. Our study supports the growing concern for peatland conservation and restoration locally and globally.

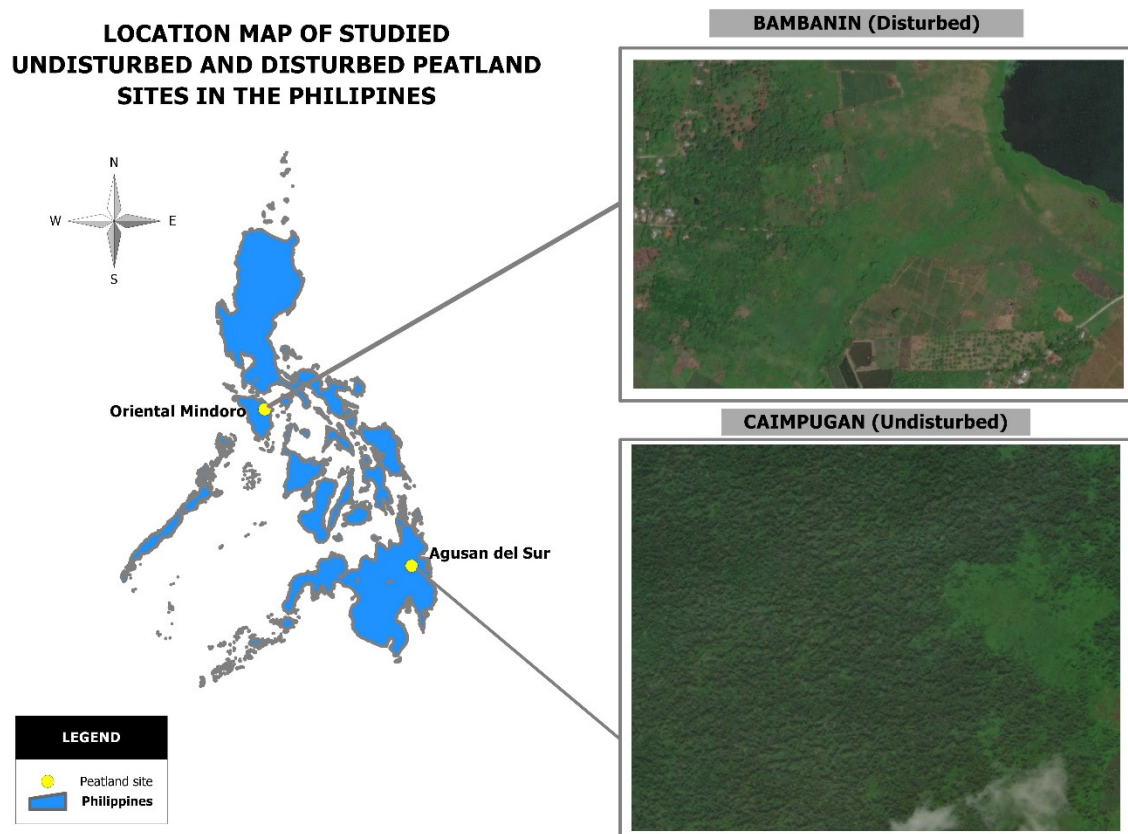
## 2. Materials and Methods

### 2.1. The Study Sites

#### 2.1.1. The Undisturbed Site

The undisturbed peatland site is located in New Visayas within the Caimpugan peatland in San Francisco, Agusan del Sur, Philippines (Figure 1). This peatland is part of the Agusan Marsh Wildlife Sanctuary, covering an area of 5630 ha. A tall forest can be observed 1.2 km from the river, and the substrate was confirmed to be peat [28]. This tall peat swamp forest is characterized by stilted rooted species predominantly of *Tristanopsis* [25]. The forest was open enough to allow a relatively thick growth of *Pandanus* sp. of up to 3 m

high and the climbing fern *Stenochlaena palustris*. The canopy height was 25–30 m [25]. Peat dome, developed between Hobong and Agusan Rivers, was observed in Caimpugan peatland [28]. The typical peat dome in Caimpugan peatland is a product of terrestrialization, where the forest is mostly intact [29]. This peatland has constantly been subjected to flooding by the river, and the input of water is relatively high in nutrients. Flooding by flowing water in the areas close to the river may have reduced the build-up of peat. A small portion of mineral soils on the western side of the Hibong River have been mostly cleared for rice production. Before site clearing for rice culture, the area was a freshwater swamp forest. Adjacent to the river and rice paddies were isolated patches of swampy areas characterized by *Terminalia copelandii* [25].



**Figure 1.** Location map of studied undisturbed and disturbed peatland sites in the Philippines.

Major issues at the Caimpugan peatland site include gradual land conversion for agriculture (ricefields and cash crops); the establishment of oil palm plantations along the periphery of the peatland within the alienable and disposable (A & D) lands; wildlife hunting (deer, birds, wild boar, monkey), and timber poaching [29].

The average temperature in this undisturbed peatland site is 27.84 °C, and the annual rainfall of 4600 mm [28]. Three levels of soil decomposition were reported at this site. These include fibric (early stage of decomposition), hemic (moderate/intermediate decomposition), and sapric (most advanced decomposition). These decomposition levels were based on the US Department of Agriculture [30].

#### 2.1.2. The Disturbed Site

Bambanin peatland site (hereinafter referred to as ‘disturbed site’) is located in the municipality of Victoria, Mindoro Oriental, Philippines. It has a total land area of 546.7 hectares [18]. Bambanin peatland is part of the Naujan Lake National Park (NLNP). Prior to the proclamation as Naujan Lake National Park in 1956, these areas were already classified as Alienable and Disposable land since 1924 [29]. Some portions of NLNP, in-

cluding this peatland site, were issued a land title and developed as an agricultural area. Although after the proclamation as a National Park, applications for the land titles were not anymore entertained by the Philippine Bureau of Lands since the area was reverted to a national park. However, settlers remained in their positioned area and continued developing and converting the land [29].

Site evaluation of existing land use within the Bambanin peatland showed expanding settlement areas. This peatland site is also subjected to indiscriminate land-use conversion for agriculture and agroforestry. Further, there has been a significant increase in the areas planted to fruit-bearing trees. These findings were based on changes in vegetative cover, as areas previously mapped as forest are now extensively grown to perennial crops. Areas mapped in 1985 as forests were noted to have changed significantly based on a recent ground survey [29].

This site has a tropical climate with an average temperature of 27.2 °C and an average annual rainfall of 2093 mm. The driest month is March, and the wettest is July, with rainfall amounts of 39 mm and 288 mm, respectively [18].

The soil acidity at the disturbed peatland site ranged from pH values of 4.3 to 5.5 [18], which is a characteristic of peatland sites [31]. This disturbed peatland site has networks of drainage canals measuring between 0.5 to 1.5 m deep such that peat soils can be used for agriculture purposes.

## 2.2. Aboveground Biomass Measurement

This study was conducted between January 2018 and December 2021. Following the methods from Alibo and Lasco (2012) [28], six 50 m × 20 m randomly distributed rectangular plots were established for each disturbed and undisturbed site. Although in this paper, we modified the plot analysis only to include all trees having a diameter at breast height (dbh) of >5 cm. We did not perform canopy stratification into tall, intermediate, and pygmy forests as Alibo and Lasco (2012) [28] did, considering the small number of plots established within each site.

Biomass was estimated using allometric equations. As local species-or-site-specific biomass equations were absent, the study used Brown's (1997) general biomass equation for wet tropical forests [32]. The biomass equation formula was:

$$Y = 21.297 - 6.953 (D) + 0.740 (D^2)$$

where Y is the biomass per tree (in kg), and D is the diameter-at-breast height (dbh, in cm).

The total aboveground biomass stock in the sampled area was calculated as the summed biomass values of individual trees. The total aboveground tree biomass was multiplied with the average C content of wood (default value of 45%) to calculate for aboveground C stock [33].

## 2.3. Soil Samples Collection

One soil sample per each of the 6 plots per site was collected from randomly selected sampling points on each plot. At each sampling point, a core sample was taken with a steel open-faced peat auger with a 1 m extension handle. Five 4 cm subsamples were collected, representing depth intervals 0–15 cm, 15–30 cm, 30–50 cm, 50–100 cm, and 100–300 cm. Soil samples were initially air-dried and then oven-dried at 60 °C for at least 24 h or until weight became stable. Soil samples were brought to the Department of Agriculture—Regional Soil Laboratory in Caraga Region for soil organic matter content determination.

The soil bulk density and carbon content were determined using the following formula [34]:

$$\text{Soil bulk density (g cm}^{-3}\text{)} = \frac{\text{Ovendry sample mass (g)}}{\text{Sample volume (m}^3\text{)}}$$

$$\text{Soil carbon content (g cm}^{-2}\text{)} = \text{bulk density (g cm}^{-3}\text{)} \times \text{soil depth interval (cm)} \times \% \text{ C}$$

The total soil carbon pool was determined by summing the carbon mass of each of the sampled soil depths extrapolated into per hectare basis ( $\text{Mg C ha}^{-1}$ ).

#### 2.4. Soil Carbon Flux Measurement

Measurement of  $\text{CO}_2$  emissions was done quarterly each year on the sampling plots for both disturbed and undisturbed sites. In situ analysis of  $\text{CO}_2$  was done using the LI-8100A (Licor, Lincoln, NE, USA). This instrument is a closed chamber-based soil gas exchange measurement system that is temporarily closed over the soil surface. A gas analyzer measures  $\text{CO}_2$  concentration over time. The amount of  $\text{CO}_2$  was measured at a 1-min interval for 3 min.

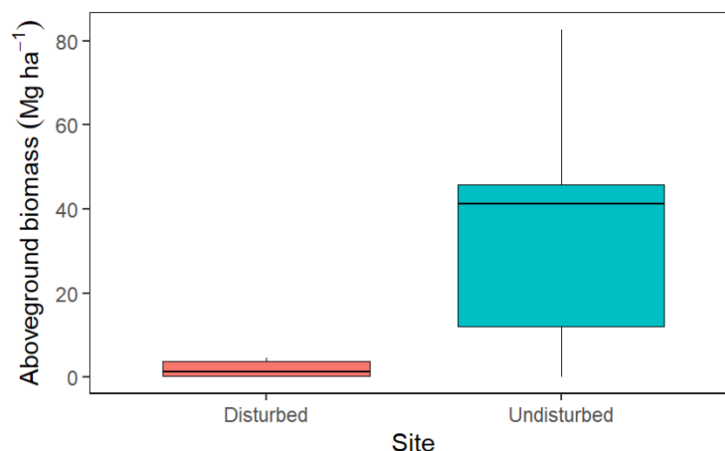
#### 2.5. Data Analysis

We tested the significant differences of the soil carbon stock at different levels in the soil profile separately for each site using Tukey's HSD Test and tested the level of significant differences at a 95% confidence level. Boxplots and bar plots were carried out using the *ggplot2* package [35]. Contour plots were used to present a 2-dimensional surface by plotting the aboveground C as contours in the *x*-axis (latitude) and *y*-axis (longitude). Contour plots were generated using *plotly* [36], *tidyverse* [37], and *reshape2* [38] packages. All analyses were processed in R version 4.1.1 [39].

### 3. Results

#### 3.1. The Aboveground Biomass at the Sites

The average aboveground biomass at the undisturbed site was  $35.8 \pm 30.0 \text{ Mg ha}^{-1}$  (Figure 2). However, the variability was very high at the undisturbed site as the biomass ranged from  $0.1 \text{ Mg ha}^{-1}$  to  $82.0 \text{ Mg ha}^{-1}$ .



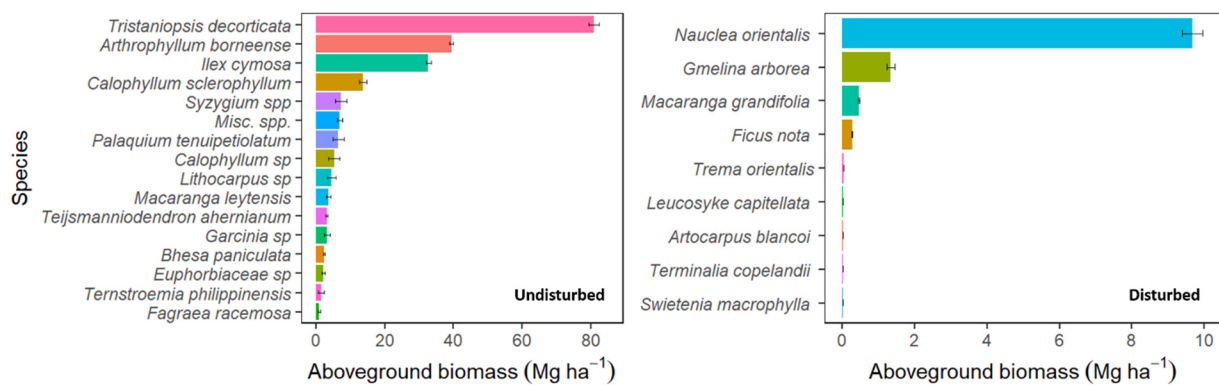
**Figure 2.** Average aboveground biomass at the disturbed and undisturbed peatland sites. In the boxplots, the thick horizontal line shows the median; the box extends to the upper and lower quartiles, and the thin vertical line outside the box indicates the nominal range.

On the other hand, the average aboveground biomass at the disturbed site was  $2.0 \pm 1.9 \text{ Mg ha}^{-1}$  (Figure 2), which varied from  $0.2 \text{ Mg ha}^{-1}$  to  $4.6 \text{ Mg ha}^{-1}$ .

#### 3.2. The Aboveground Biomass per Species

The disparity between the species with the highest biomass and the rest in either undisturbed or disturbed peatland sites was huge. For example, the species with the highest biomass at the undisturbed site was *Tristaniopsis decorticata* (Merr.) Peter, with an aboveground biomass of  $80.8 \text{ Mg ha}^{-1}$ , yet, the species with the second-highest aboveground biomass had only  $39.4 \text{ Mg ha}^{-1}$ . Whereas, the remainder of the species had  $1.7$  to  $32.7 \text{ Mg ha}^{-1}$  (Figure 3).





**Figure 3.** The aboveground biomass of important tree species at the undisturbed (left panel) and disturbed (right panel) peatland sites. The horizontal line indicates  $\pm$  standard deviation.

Similarly, the highest aboveground biomass at the disturbed site was *Nauclea orientalis* (L.) L. ( $9.67 \text{ Mg ha}^{-1}$ ), while the species with the second-highest aboveground biomass only had  $1.34 \text{ Mg ha}^{-1}$ , and the rest had below  $1.0 \text{ Mg ha}^{-1}$  (Figure 3).

### 3.3. The Aboveground Carbon Content

The aboveground C content at the undisturbed site ranged from  $1.29 \text{ Mg C ha}^{-1}$  to  $37.2 \text{ Mg C ha}^{-1}$  (Figure 4a). The contour plot showed that plots 1 and 6 were within the upper range of the aboveground C stock estimates ( $21.1 \text{ Mg C ha}^{-1}$ – $32.7 \text{ Mg C ha}^{-1}$ ) characterized by tall pole forest. Plots 2 and 5 had an aboveground C stock from  $17.8 \text{ Mg C ha}^{-1}$ – $19.3 \text{ Mg C ha}^{-1}$ , classified into an intermediate forest. The aboveground C at plots 3 and 4 were surprisingly low compared with other plots ( $0.06 \text{ Mg C ha}^{-1}$ – $1.29 \text{ Mg C ha}^{-1}$ ). These plots (3 and 4) were characterized by smaller tree structures akin to a pygmy forest and possibly were located in the peat dome. Differences in aboveground C in the study plots indicate the topographic and hydrologic variability within the peatland site.

At the disturbed site, the aboveground C content ranged from  $0.1 \text{ Mg C ha}^{-1}$  to  $2.1 \text{ Mg C ha}^{-1}$  (Figure 4b), and the variability among plots was relatively low.

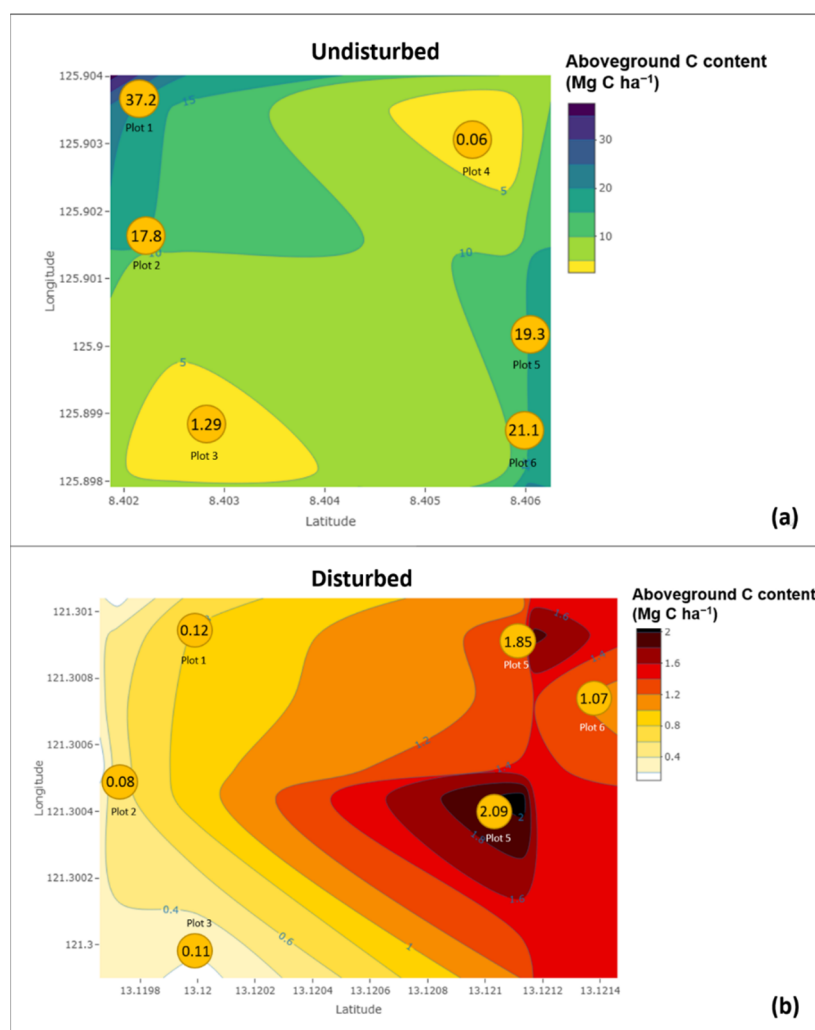
### 3.4. Soil Carbon Content

The overall average soil C content at the undisturbed site was  $750 \pm 710 \text{ Mg ha}^{-1}$ . As the soil profile gets deeper, the soil C content becomes higher. This trend was evident in our undisturbed site, where an increasing soil C stock was observed from  $217 \pm 65 \text{ Mg ha}^{-1}$  at a soil depth of 0–15 cm to  $2181 \pm 908 \text{ Mg ha}^{-1}$  at 50–100 cm depth ( $p < 0.05$ ; Figure 5).

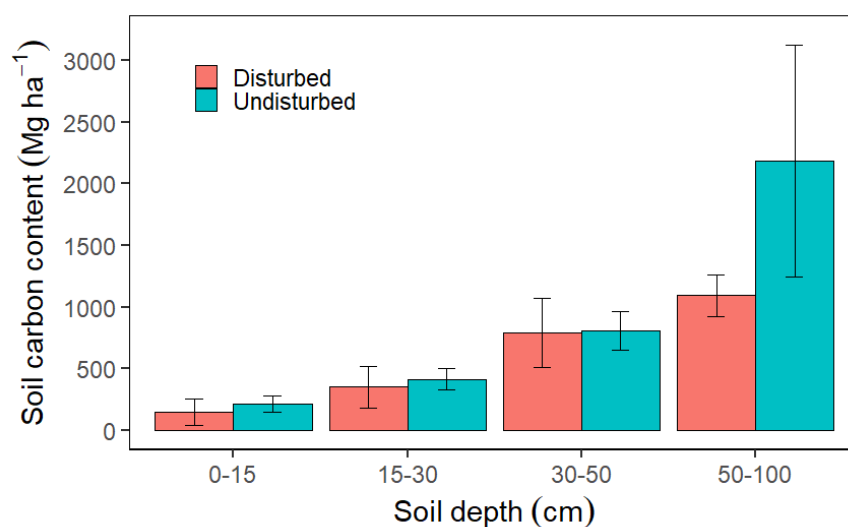
At the disturbed site, the overall average soil C content at all depth levels was  $595 \pm 406 \text{ Mg ha}^{-1}$ . At 0–15 cm soil depth, the average soil C content was  $149 \pm 104 \text{ Mg ha}^{-1}$ , increasing the soil C stock up to  $1092 \pm 165 \text{ Mg ha}^{-1}$  at a soil depth of 50–100 cm ( $p < 0.05$ ; Figure 5).

### 3.5. Soil Carbon Fluxes

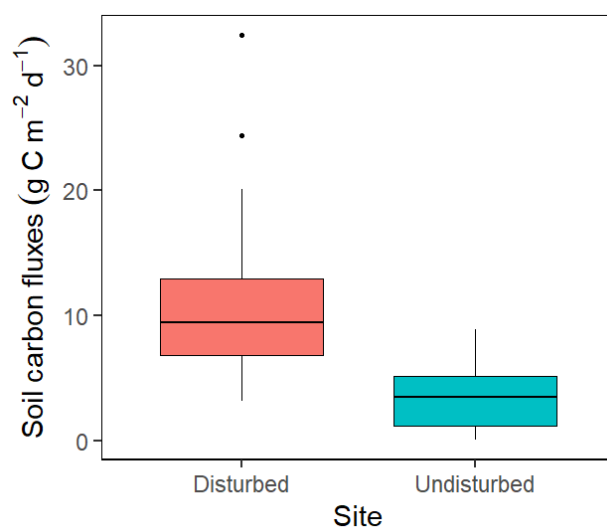
At the undisturbed site, the soil carbon emission was  $3.6 \pm 3.0 \text{ g C m}^{-2} \text{ d}^{-1}$ . The soil emission rate at the disturbed site was  $11.2 \pm 6.4 \text{ g C m}^{-2} \text{ d}^{-1}$  (Figure 6). Suppose we set aside all aspects of differences from both sites and consider them comparable; the soil carbon emission from the undisturbed site was only one-third of the emission rate at the disturbed site. However, direct comparisons need to consider the considerable differences in site condition, climate, and vegetation.



**Figure 4.** Map of the variations in aboveground C content as a function of site coordinates in (a) undisturbed peatland site in Caimpugan, Agusan del Sur and (b) disturbed peatland site in Bambanin, Mindoro Oriental, all in the Philippines. Yellow circles represent sampling plots in both undisturbed and disturbed plots. Values within each circle are the average aboveground C in each plot.



**Figure 5.** Average soil carbon content per soil depth classes at the disturbed and undisturbed peatland sites. Vertical lines depict  $\pm$  standard deviation.



**Figure 6.** Average soil carbon fluxes at the disturbed and undisturbed peatland sites. In the boxplots, the thick horizontal line shows the median; the box extends to the upper and lower quartiles, and the thin vertical line outside the box indicates the nominal range.

#### 4. Discussions

##### 4.1. The Aboveground Biomass at the Sites

Alibo and Lacson, 2012 [28], in their study within Caimpugan peatland (the undisturbed site) 10 years ago, found aboveground biomass ranging from 1.2 Mg ha<sup>-1</sup> to 87.0 Mg ha<sup>-1</sup> with an average of 34.2 Mg ha<sup>-1</sup>. This aboveground biomass from that study is close to an average of 35.8 Mg ha<sup>-1</sup> (ranged 0.1 Mg ha<sup>-1</sup> to 82.0 Mg ha<sup>-1</sup>) we found in our research. Our result is also relative to the aboveground biomass observed in Leyte Sab-a basin peatland in the Philippines with 38.5 Mg ha<sup>-1</sup> [27]. Our undisturbed site was within the range reported for the Thalawathugoda and Kolonnawa peatlands of Colombo, Sri Lanka, with 30.38–47.99 Mg ha<sup>-1</sup> [40].

The slight decrease in the aboveground biomass in our study compared with other peatland sites in the Philippines suggests that despite the threats of land conversion and timber poaching [29] at this undisturbed peatland site, it did not lower the aboveground biomass estimates considerably for over a decade. However, it must be noted that there has been no significant increase in forest tree density or productivity over the years, given only a slight change in aboveground biomass. It might be that these peatland-damaging activities may have been isolated cases, and the area affected may not be huge enough to alter the peatland vegetation.

A lower aboveground biomass estimate in our cultivated peatland (0.2 Mg ha<sup>-1</sup> to 4.6 Mg ha<sup>-1</sup>) as compared to other aforementioned peatland sites above indicates that land conversions, vegetation removal, and other disturbances such as drainage construction for agricultural production negatively impact the aboveground biomass of the site. In Indonesia and Malaysia, land conversions associated with oil palm plantation establishment and logging [13,41,42] have resulted in a significant aboveground biomass decline.

Although we caution that our sampling plots cannot represent the entire peatland site, that may question our sites' current aboveground biomass estimates.

##### 4.2. The Aboveground Biomass per Species

What is driving *Tristania decorticata* and *Nauclea orientalis* to dominate in our undisturbed and disturbed peatland sites, respectively, is a question that entails further investigation. Some possible factors leading to the dominance of a particular species can be ascribed to its aggressive vegetative growth causing depression of adjacent species; its effective seed dispersal modes and superior germinability characteristics; or possible allelopathic effect on the germination of other plants [43]. Further study is needed to prove these speculations.



*Tristaniopsis decorticata* is the dominant species with the highest biomass in our undisturbed site. *T. decorticata* has been previously reported to dominate in the Caimpugan peat swamp forest [25]. *T. decorticata* also showed greater dominance in the peat swamp forest of Sumatra and eastern Borneo [44] and low open woodland peat swamp forest on the Panch Peninsula of Sumatra [45].

Little has been known about the *T. decorticata* growing in the peatland sites in the Philippines. Although *T. decorticata* occurs in peat swamp forests, they generally occur in permanent waterlogged heath forests like in basins of the Pueh Forest Reserve in West Sarawak, Bionio River Basin, and Meruruong Plateau in central Sarawak [46].

*T. decorticata* is an evergreen small to medium-sized tree growing 10–20 m tall, 40–60 cm in diameter with no buttresses. The tree is harvested from the wild for the commercial use of its wood. This species is endemic to the Philippines and occurs in lowland to lower montane, up to 1300 m elevation. Increasing habitat loss through logging and shifting cultivation has led to this species' considerable population decline. It has been classified as 'vulnerable' in the IUCN Red List of Threatened Species [47]. This underlines the need to protect undisturbed peatland areas such as the Caimpugan swamp forest, also under a biodiversity conservation aspect.

On the other hand, *N. orientalis* is predominantly occurring at the disturbed site with the highest aboveground biomass among the species. *N. orientalis* is found in Sri Lanka and Indo-China to New Guinea and Australia [48]. In the Philippines, it is called Bangkal. This species prefers alluvial soils along river and stream banks and adapt well in the swamp ecosystem, peatlands, forest, flowing rivers, and flooded areas [49,50]. *N. orientalis* belongs to the Family Rubiaceae and is a sub-canopy, perennial tree growing up to 25 m tall, with a cylindrical bole diameter of 50 cm. The seeds of *N. orientalis* can germinate readily. *N.orientalis* has high tolerance limits to the pH range of the habitat and can accumulate contaminants [50]. This species adaptive capacity to low pH (acid), toxicity to heavy metals, and resistance to permanent or periodic swamp inundation [51] made the species a dominant species in disturbed peatland sites.

In Tinambalan peat in Maguindanao, Mindanao, Philippines, *N. orientalis* also dominates in that site. This peatland site near a lake is also highly-drained and cultivated, such as our disturbed site [52].

Examining the dominant species which dictates the canopy structure and diversity level in a particular site is crucial. Thus, evaluating the genetic, structural, and physiological characteristics of these dominant species is imperative to understanding vegetation dynamics at undisturbed and disturbed sites. They can be considered as indicator species and help to identify the disturbance status of peatlands at larger scales.

#### 4.3. The Aboveground Carbon Content

Plots 3 and 4 (Figure 4) in the undisturbed site with lower soil organic matter content may occupy the peat dome areas characterized by stunted growth forest. Based on satellite images, a stunted forest can be observed but is surrounded by a ring of the taller forest [29]. Therefore, plots 3 and 4 could have possibly been located in a peat dome. According to a report, stunted forests are nutrient-deficit deeper peat [28] and represent a unique, rare and fragile ecosystem, thus explaining a lower aboveground C content at plots 3 and 4. Accordingly, the most important limiting factors in peatlands are peat's hydrology and nutrient status, which determines the condition of the forest growing upon it [53].

Our observed aboveground C stock at the undisturbed site ( $1.29 \text{ Mg C ha}^{-1}$  to  $37.2 \text{ Mg C ha}^{-1}$ ) was lower than a report in another study conducted within the undisturbed peatland a decade ago, spanning up to  $52.3 \text{ Mg C ha}^{-1}$  [28]. Although we conducted our analysis within the vicinities of the peatland sites as the previous report we cited here (but not on the exact location), our results must be interpreted with caution since we are only using six plots randomly distributed with lesser area coverage. However, the necessity to release this initial report of our Long-term Peatland Program for peatland stakeholders,

local and national policymakers, and the academe justifies the urgency to report current findings in undisturbed and disturbed peatland sites in the Philippines.

The aboveground C content of  $0.1 \text{ Mg C ha}^{-1}$  to  $2.1 \text{ Mg C ha}^{-1}$  at the disturbed found in our study was close to that reported for a cultivated peatland forest in the Leyte Sab-a basin peatland in the Philippines with  $0.49 \text{ Mg C ha}^{-1}$  [27].

Overall, our aboveground C in both undisturbed and disturbed sites was lower than the average  $150 \text{ Mg C ha}^{-1}$  to  $250 \text{ Mg C ha}^{-1}$  for tropical peatlands [54]. Our result indicates that our disturbed or undisturbed peatland sites are experiencing dwindling ecosystem productivity and thus ecological drawbacks, most especially at the disturbed site. This phenomenon is quite a concern. Further study is needed to monitor the vegetative performances amidst this environmental crisis.

A huge difference in aboveground C between undisturbed and disturbed peatland sites in our study indicates that land conversion and establishment of drainage structures for agricultural purposes causes a significant reduction in above-and-belowground carbon content. Therefore, attention must be focused on protecting and conserving remaining peatland ecosystems with a high carbon stock before they begin losing a huge amount of C. Moreover, a continuing effort to restore disturbed peatland sites is needed as hydrologic forcing and climate change could shift the carbon balance trajectory of this important C storage.

#### 4.4. Soil Carbon Content

Our study showed that soil carbon storage in peat (average of  $750 \text{ Mg ha}^{-1}$  in undisturbed site and  $595 \text{ Mg ha}^{-1}$  in disturbed area) is an order of magnitude greater than the aboveground C content ( $\sim 37.2 \text{ Mg ha}^{-1}$  in undisturbed site and  $2.1 \text{ Mg ha}^{-1}$  in disturbed site). This finding is not surprising since peatland soils have stored huge amounts of carbon for over a millennium. In Indonesian peatland, the aboveground biomass in peat swamp forest was  $100\text{--}150 \text{ Mg ha}^{-1}$ , whereas soil carbon was  $2772 \text{ Mg ha}^{-1}$  [9].

An increasing soil C content in our study as the soil profile gets deeper was also observed in other studies [27,55]. Our belowground soil carbon estimates, which increased from  $217 \pm 65 \text{ Mg ha}^{-1}$  to  $2181 \pm 908 \text{ Mg ha}^{-1}$  as the soil profile gets deeper at the undisturbed site and  $149 \pm 104 \text{ Mg ha}^{-1}$  to  $1092 \pm 165 \text{ Mg ha}^{-1}$  at the disturbed site, were within the range reported for tropical peatlands of  $\sim 250$  to  $>5000 \text{ Mg ha}^{-1}$  [54,56].

Studies investigating soil carbon dynamics in the Philippine peatland sites are less explored. Hence, they must be examined closely. Our study conforms to the common notion that tropical peatlands are huge peat carbon stores. Thus, attention must be given to promoting policies for avoiding deforestation and further exploitation to preserve and conserve the remaining peatlands in the Philippines.

#### 4.5. Soil Carbon Fluxes

Suppose we consider all things equal except for the level of disturbance at both undisturbed and disturbed, a soil emission rate that is three times higher at the disturbed site than at the undisturbed peatland suggests that soil respiration may enhance faster as the disturbance continues.

It is difficult to compare our results with other peatland sites experiencing peatland disturbances due to scarce literature on soil carbon fluxes in the peatland ecosystem in the tropics. Here, we present some studies in various ecosystems showing how any form of disturbances could severely affect the soil carbon fluxes. A study in a peatland forest in Indonesia found that fluvial organic carbon flux from disturbed peat swamp forest is about 50% larger than that from intact peat swamp forest [57]. Another study in Germany found that respiration rates of bog peat increased more strongly with an increasing degree of disturbance than those of fen peat [21]. A soil warming experiment (to mimic the future warmer climate) in a forested peatland in Japan found that soil respiration was enhanced by 82% when the soil was warmed  $3^\circ\text{C}$  higher than the ambient temperature [58]. Peatland fire also enhances soil respiration in a peatland area of the United Kingdom [59]. Land-use

change also increased soil respiration rates in a Micronesian tropical peatland [60] and in mixed-forest in Japan [61]. In a study in North Carolina, USA, hydrologic stress and drought enhanced soil respiration when the natural wetland forest was converted into plantation forest [62]. Indeed, forest soils are vulnerable to any form of disturbances that calls for the urgent need to protect peatland forests from further destruction.

The disturbed forest is characterized by low soil carbon content, strong evidence of water table drawdown, and substantial land cultivation or simply vast grassland areas. Relative to this, lower soil respiration has been found in cultivated and grassland sites than in forested peatland sites [18], indicating that soil carbon emissions from low C organic soils are high [24].

The country's peatland sites are threatened by anthropogenic disturbances, which cause the mineralization of deeper peat layers due to nutrient and dissolved organic matter leaching. Peatland drainage and cultivation hastens peat oxidation and decomposition, prompting mineralization of the oxic portion of peat soils, resulting in increased soil carbon emission. Water table drawdown also exposes organic soil materials, thereby enhancing decomposition and releases of soil C in the atmosphere. When peatland is disturbed, mixing organic soil with mineral soil occurs, and new soil horizons may develop to alter the microbial community composition [63]. This mixing of organic and mineral soil when peatland is drained and cultivated increases the vulnerability of soil organic matter to decomposition [21]. This condition was also observed in other field and laboratory studies [21,23]. Peatland cultivation also increased nutrient availability due to fertilization, thus enhancing soil respiration rates [64,65]. Overall, the reasons behind the relatively high CO<sub>2</sub> emissions in disturbed peatlands are still under debate [21,58]. Changes in peat properties after water level drawdown and organic matter quality may affect microbial activities. These changes led to high soil respiration at disturbed/drained peatland sites [14,16,66,67], which may disrupt the regional and eventually global carbon cycling [68].

#### 4.6. Global Importance of Tropical Peatlands

Deforestation and land conversions of Asian peatlands are proceeding at 2–9% per year in Borneo [69] and other locations. It was estimated that some 106,000 km<sup>2</sup> (43%) of the tropical peatland in Southeast Asia had been drained, deforested, and converted to some other uses [70]. These disturbances are tantamount to at least 29 Gt of peat carbon being released into the atmosphere [7]. This emission rate from tropical peatland is unlikely to be reduced considering that equatorial zones will experience less rainfall and more significant seasonality leading to lower peatland water tables, enhancing peat decomposition, and increased forest fire frequency, just as predicted in the Amazonian peatlands [71].

Since tropical forests play a significant role in regulating global carbon fluxes and stocks, especially in peatland [2], even a minimal alteration to carbon balance in a biome could significantly affect atmospheric greenhouse gases, especially in peatland carbon dioxide [70]. Globally, however, deforestation and forest degradation threaten forest CO<sub>2</sub> sequestering function of peatland forests [71], and deforestation and degradation account for approximately 12% of global GHG emissions [72].

#### 4.7. Implications for Peatland Management

Land-use change in peatland areas in the Philippines is expanding. What aggravated the situation is that some peatland areas in the country are alienable and disposable lands, which may exacerbate the vulnerability of these peatland sites to a massive release of soil CO<sub>2</sub> to the atmosphere that may be accelerated by global warming. This is what we observed in our disturbed peatland study site.

A study in central Kalimantan (southern Borneo) reported the relationships between peat drainage and increased fire frequency [53]. This study revealed that peatland fires, and the subsequent changes in vegetation, have significant impacts on the carbon cycle by releasing much larger amounts of CO<sub>2</sub> into the atmosphere. It also affects various ecosystem

services, including wide-ranging social and economic impacts [53]. CO<sub>2</sub> emissions from Southeast Asian peatland fires were equivalent to 13–40% of global fossil fuel emissions [73].

The differences in carbon emissions between our study's undisturbed and disturbed sites and the other studies presented above are alarming. Setting the site differences aside, our study's three times more intense carbon emission at the disturbed than at the undisturbed site is quite alarming. To prevent more carbon releases from peatland sites, forest managers must address the pressing issues on peatland drainage, agricultural activities, and human settlement. The Philippines must learn the lessons from Malaysia, Indonesia, and other peatland-rich countries that the benefits and profits of peatland drainage for different land-use outweigh the cost of peatland restoration and rehabilitation. The impact is so enormous that it has a long-lasting effect on regional and global carbon cycle contributing to climate change. With the advent of advanced technologies in earth observations, geological surveys, and mapping, a rigorous peatland hotspot identification and characterization must be made to efficiently manage and protect the massive release of carbon stored over a millennium.

## 5. Conclusions

Peatland studies in the Philippines are scarce. Our study supports the notion of the sensitivity of peatland to anthropogenic disturbances such as land-use change as indicated by lower aboveground-and-belowground carbon storage in cultivated/disturbed sites, unlike some undisturbed peatland sites in the Philippines and the neighboring countries.

Mixing peat with mineral soil for agricultural purposes was not a promising mitigation option as releases of CO<sub>2</sub> to the atmosphere were high at the peatland-to-agriculture-converted site. However, the substantial amount of stored C in the undisturbed peatland site connotes the necessity for its continued protection, maintaining its role in mitigating CO<sub>2</sub> emissions.

Given the continued disturbance of peatlands and our study's considerable high CO<sub>2</sub> emissions and reduction in soil carbon storage in the disturbed site, there is a need to identify hotspots that appropriately target mitigating measures on these sites. Our results contribute to the needed information in predicting future peatland scenarios. The valuable information we reported can be used to develop appropriate peatland management strategies and interventions. Our study reinforces the growing demand for more stringent policy interventions to enhance peatland conservation and restoration in the country.

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