Tropical peatlands in North Kalimantan: characteristics, extent, and estimates of carbon stock

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Abstract. North Kalimantan Province has the third largest tropical peatlands in Kalimantan Island. Despite this, a detailed data on the characteristics, extent, and carbon stock of tropical peatlands in North Kalimantan is currently not available. Therefore, BBSLP has carried out a semi-detailed peatlands mapping on Nunukan and Tana Tidung Regencies and Tarakan City, North Kalimantan Province. Peat soil mapping refers to SNI 7925:2019, scale of 1:50,000. The study found that peatlands in North Kalimantan covered about 216.944 ha, with the majority extent in Tana Tidung Regency (71.512 ha), followed by Nunukan Regency (142.198 ha) and Tarakan City (3.233 ha). Peatlands in this area occupied fluvio-marine (B) and peat (G) landforms, with hemic and sapric decomposition levels, and a depth of 50 - < 700 cm (shallow to extra very deep). Substratum layer, i.e. mineral soils, comprised of clay to sandy clay soil texture. According to the Indonesian Soil Classification system, peat soil in the research area was categorized as Organosol Saprik, Organosol Hemik and Organosol Fibrik. Estimated carbon stock was about 328.80 M tons C, with an average of 1.516 tons ha⁻¹. With this large figure, the results emphasize the importance of peatlands for land use and spatial planning.

1. Introduction

Indonesian Peatland Map (scale of 1:250,000) [1] indicates that peatland areas cover about 14.93 M ha, of which about 6.43 M ha in Sumatra, 4.78 M ha in Kalimantan, 3.69 M ha in Papua and 23.844 ha in Sulawesi. Based on a detailed data (Indonesian peatland scale 1:50,000), however, total peatland areas in Sumatra, Kalimantan, Sulawesi, and Papua are 13,430,517 ha [2]. Largest peatlands of Kalimantan are found in Central Kalimantan Province (2,550,440 ha), while North Kalimantan Province (216,944 ha) marks the third. With this respect, a more detailed peatland map (perhaps at scale 1:50,000 or beyond) is necessary. With the role of peat soil as a C-terrestrial storage, detailed data on its distribution and characteristics would contribute to numerous aspects in public interests.

In Indonesia, peatland environments are amongst the most dynamic landscapes, which have been experiencing major land use changes influenced by economic development coupled with social, political and climatic changes. Despite this importance, paucity of information regarding spatial and temporal extent is evident. Assessments to obtain recent information about peat development at national and regional level are, therefore, crucial [3], especially when the data serve as a basis for inventories in future developments. Updated peat information (in terms of areas and depth) would fill critical gaps in accurately determining regional/global organic C stocks and informing future directions for sustainable use and management of tropical peatlands [4].
The aims of this study were to characterize peatlands and to estimate carbon stocks in North Kalimantan peatlands. The outcome could serve as a reference for peatland utilization and planning to sustain this invaluable resource.

2. Materials and methods

2.1. Study area
North Kalimantan Province is located between 1° 21’ 36” and 4° 24’ 55” N, and 114° 35’ 22” and 118° 03’ 00” E (Figure 1). In this paper, we adopted Soil Taxonomy [5] definition for peat soil, in which organic soils are classified as Histosols. To comply with Indonesian peat soils classification system, however, we also implemented a minimum thickness of 50 cm. Hence, organic soils are classified as Organosol [6].

2.2. Materials
The materials used in this study include a collection of previous surveys in 2013 [7] and verification project for peat soil mapping in 2019 covering Nunukan Regency, Tana Tidung Regency, and Tarakan City, North Kalimantan Province. Selected peat samples were taken at three locations for lab-based soil analysis. Land unit maps was delineated by overlapping remotely-sensed imageries (Landsat 8 OLI, ALOS, and SPOT-6/7 images), Digital Elevation Model (DEM)/SRTM with spatial resolution of 30 m, and geological maps of Malinau, Tarakan, and Sebatik sheets (scale 1:250,000) [8, 9]. All datasets were processed using PC with an Arc GIS software. Soil samples were taken using an Eijkelkamp peat auger and Belgian soil auger. In addition, this research employed altimeter, field knife, meter band, Munsell Soil Color Chart, Abney level, pH-trouch and digital pH meter, H2O2 fluids, GPS, field observation forms, plastic bags and labels during the survey.

This research also exploited legacy soil maps derived from soil databases of the Indonesian Centre for Agricultural Land Resource Research and Development (ICALRRD), including reconnaissance soil maps (scale 1:250,000) [10] and Indonesian peatlands map scale at the same scale [11].

2.3. Methods
The SNI standard (SNI 7925: 2019) about Peat Soil Mapping at scale of 1:50.000 [12] was adopted in this study. This consists of data collection and compilation (image interpretation), determination of land
unit map, performing survey and in-situ verification, ratification and correlation of polygon boundaries, laboratory analysis of peat samples, reinterpretation of field data and imagery, and data compilation for database and peatlands maps.

A hand operated Eijkelkamp peat auger with a 50 cm barrel and 10 m extension was used to manually extract peat cores to mineral substratum. All field observations of peat properties and their associated environment adhered technical guidance for semi-detailed soil survey and mapping programs [12]. Peat depth was divided into five classes: D1 (shallow 50 - < 100 cm), D2 (moderately deep 100 - < 200 cm), D3 (deep 200 - < 300 cm), D4 (very deep 300 - < 500 cm), and D5 (extremely deep 500 - < 700 cm).

Chemical and physical soil analyses were carried out on selected soil samples. Soil chemical analysis consisted of soil organic carbon (SOC) content (Walkley and Black), total N (Kjeldahl), soil reaction (pH H₂O and pH KCl 1:5 and pH H₂O), potential P₂O₅ and K₂O (HCl 25%), available P₂O₅ (Bray-1), exchangeable bases, cation exchange capacity (CEC) and base saturation using 1 N NH₄OAc, extraction pH 7.0, total Fe and S (HNO₃). Soil physics analysis comprised of analysis of bulk density (BD) as well as ash and fiber contents. All soil samples were analyzed in accordance to Technical Manual Guidelines for Soil, Water, Plant and Fertilizer Analysis [13]. The degree of peat decomposition was determined in the field by estimating volume of soil sample after sample was squeezed by hand. Carbon stock was calculated based on Carbon Stock equation \( C (t) = L \times D \times BD \times C \); where L is the area of peat (m²), D is the thickness of the peat (m), BD is the bulk density (g cm⁻³), and C-organic is organic carbon content [14].

3. Results and discussions

3.1. Distribution of peatlands and peat soil classification

Based on spatial analysis, North Kalimantan peatlands covered about 216,944 ha, with specific distribution is depicted in Table 1. Depth of peat layer in Nunukan and Tana Tidung Regencies varied from shallow (50 - < 100 cm) to extremely deep (500 - < 700 cm). Meanwhile, depth over Tarakan City ranged from shallow (50 - < 100 cm) to very deep (300 - < 500 cm).

| No. | District/City           | Subdistricts | Landform                  | Depth (cm) | Total Area |
|-----|------------------------|--------------|---------------------------|------------|------------|
|     |                        |              |                           | 50 - < 100 | 100 - < 200 | 200 - < 300 | 300 - < 500 | 500 - < 700 | (ha) |
| 1   | Nunukan District       | Sembakung    | Fresh water topogenous peat | 1616       | 8106       | 44765       | 33668       | 6648        | 94803 |
|     |                        | Sebuku       |                           | 808        | 4053       | 22378       | 16831       | 3324        | 47395 |
|     | **Sub total**          |              |                           | 2424       | 12159      | 67144       | 50499       | 9972        | 142198 |
| 2   | Tana Tidung District   | Sesayap      | Fresh water topogenous peat | 1951       | 3480       | 4128        | 9276        | 394         | 19227 |
|     |                        | Selayap Hilir |                           | 5305       | 9461       | 11223       | 25221       | 1073        | 52285 |
|     | **Sub total**          |              |                           | 7257       | 12841      | 13531       | 34497       | 1467        | 71513 |
| 3   | Tarakan City           | Central Tarakan | Brackish water topogenous peat | 358        | 528        | -           | -           | -           | 886   |
|     |                        |                | Florisumare plains         | 148        | -          | -           | -           | -           | 148   |
|     |                        | West Tarakan   | Brackish water topogenous peat | 364        | 27         | -           | 78          | -           | 469   |
|     |                        |                | Florisumare plains         | 40         | -          | -           | -           | -           | 40    |
|     |                        | North Tarakan  | Brackish water topogenous peat | 466        | 708        | -           | -           | -           | 1175  |
|     |                        |                | Florisumare plains         | 515        | -          | -           | -           | -           | 515   |
|     | **Sub total**          |              |                           | 1891       | 1264       | -           | 78          | -           | 3233  |
|     | **Total North Kalimantan** |            |                           | 216944     |            |             |             |             |       |

Note: D1 = shallow (50 - < 100 cm); D2 = moderate (100 - < 200 cm); D3 = deep (200 - < 300 cm); D4 = very deep (300 - < 500 cm); D5 = extra very deep (500 - < 700 cm).

Classified soil types according to Indonesian Soil Classification [6] and their equivalence, Key Soil Taxonomy [5], is presented in Table 2. Peatlands in Nunukan Regency and Tana Tidung Regency and Tarakan City are Organosol Saprik (Typic Haplosaprist), Organosol Hemik (Sapric Haplohemist and Typic Haplohemists), and Organosol Fibrik (Hemic Haplofibrists). In this research area, peat soil is dominated by Organosol Hemik (Typic Haplohemists).
### Table 2. Chemical properties of peat soil samples

| Pedons and horizons | Symbol | Depth (cm) | Soil Classification | Geographic Coordinate | pH (1:5) | KCl (1N) | HCl (25%) | Bray (mg.100 gr-1) | C (%) | N (%) | C/N |
|---------------------|--------|------------|---------------------|------------------------|----------|----------|-----------|-----------------|-------|-------|-----|
|  |  |  |  |  | H2O | KCl | cmol.kg-1 | mg.100 gr-1 | (%) |
| Tana Tidung District |  |  |  |  |  |  |  |  |  |  |  |  |
| YA-02/I Ox1 | 0-13 |  | Organosol Hemik (Typic Haplohemists) | 3° 35’ 35.03” 116° 55’ 48.36” | 4.1 | 3.0 | 0.00 2.19 | 24 | 21 | 37.6 | 37.3 | 1.01 | 37 |
| YA-02/II Ox2 | 13-38 |  |  |  | 3.6 | 2.6 | 3.12 5.70 | 7 | 13 | 11.1 | 39.9 | 1.01 | 40 |
| YA-02/III Ox1 | 38-78 |  |  |  | 4.0 | 2.9 | 3.52 3.04 | 7 | 11 | 9.9 | 49.0 | 1.09 | 45 |
| YA-02/IV Ox2 | 78-103 |  |  |  | 4.4 | 3.2 | 4.22 2.26 | 2 | 5 | 6.8 | 44.5 | 1.03 | 43 |
| YA-02/V Ox3 | 103-133 |  |  |  | 4.5 | 3.4 | 2.74 1.88 | 5 | 11 | 5.7 | 33.3 | 0.84 | 40 |
| YA-02/VI Ox4 | 133+ |  |  |  | 4.7 | 3.7 | 2.74 1.00 | 9 | 10 | 9.7 | 6.5 | 0.21 | 31 |
| SO-17/I Ox1 | 0-59 |  | Organosol Hemik (Typic Haplohemists) | 3° 38’ 53.95” 117° 8’ 15.98” | 3.4 | 2.3 | 0.00 0.31 | 18 | 48 | 57.9 | 51.1 | 1.69 | 30 |
| SO-17/II Ox1 | 59-119 |  |  |  | 3.5 | 2.4 | 0.98 7.52 | 3 | 12 | 11.4 | 47.7 | 1.53 | 31 |
| SO-17/III Ox2 | 119-185 |  | Organosol Hemik (Typic Haplohemists) | 3° 42’ 32” 116° 54’ 52” | 3.6 | 2.3 | 0.91 6.14 | 3 | 10 | 11.7 | 47.4 | 1.46 | 33 |
| SO-17/IV Ox2 | 185-225 |  |  |  | 3.7 | 2.6 | 0.86 4.15 | 2 | 5 | 5.4 | 26.0 | 0.84 | 31 |
| SO-17/V Ox3 | 235-340 |  |  |  | 3.7 | 2.6 | 2.93 7.17 | 4 | 9 | 12.1 | 45.8 | 1.46 | 31 |
| SO-17/VI Ox4 | 340-450 |  |  |  | 3.7 | 2.6 | 1.29 3.17 | 5 | 9 | 13.9 | 50.2 | 1.59 | 32 |
| CB-53/I Ox1 | 0-26 |  | Organosol Hemik (Typic Haplohemists) | 3° 42’ 32” 116° 54’ 52” | 3.6 | 2.3 | 0.91 7.52 | 3 | 12 | 11.4 | 47.7 | 1.53 | 31 |
| CB-53/II Ox1 | 26-76 |  |  |  | 3.6 | 2.4 | - - | 8 | 25 | 39.7 | 31.6 | 0.85 | 37 |
| CB-53/III Ox1 | 76-400+ |  |  |  | 3.6 | 2.3 | - - | 3 | 10 | 11.6 | 28.3 | 0.76 | 37 |
| Tarakan City |  |  |  |  |  |  |  |  |  |  |  |  |  |
| YA-11/I Ox1 | 0-21 |  | Organosol Saprik (Typic Haplouerts) | 3° 21’ 20.31” 117° 39’ 24.68” | 4.0 | 2.8 | 2.75 2.05 | 13 | 6 | 38.4 | 27.4 | 0.97 | 28 |
| YA-11/II Ox1 | 21-94 |  |  |  | 3.6 | 2.4 | 3.31 5.97 | 4 | 5 | 8.4 | 50.7 | 1.63 | 31 |
| YA-11/III Ox2 | 94-350+ |  |  |  | 3.6 | 2.4 | 9.18 2.92 | 5 | 7 | 48.9 | 15.7 | 1.57 | 31 |
| Nunukan District |  |  |  |  |  |  |  |  |  |  |  |  |  |
| UY-3/I Ox1 | 0-40 |  | Organosol Fahrik (Hemic Hapluferrals) | 3° 58’ 48.2” 117° 07’ 26.3” | 3.8 | 2.5 | 0.33 2.87 | 25 | 13 | 49.3 | 1.24 | 40 |
| UY-3/III Ox1 | 40-90 |  |  |  | 3.9 | 2.6 | 0.33 3.07 | 11 | 15 | 49.6 | 1.08 | 46 |
| UY-3/III Ox2 | 90-300+ |  |  |  | - - | - - | - - | - - | - - | - - | - - | - - |
| HK-6/I Ox1 | 0-30 |  | Organosol Hemik (Typic Haplohemists) | 3° 56’ 45.8” 117° 11’ 46.6” | 3.8 | 2.6 | 1.55 4.71 | 34 | 15 | 42.4 | 2.36 | 18 |
| HK-6/II Ox1 | 30-90 |  |  |  | 3.8 | 2.6 | 0.97 2.38 | 14 | 5 | 28.6 | 1.04 | 28 |
| HK-6/III Ox2 | 90-105 |  |  |  | 3.9 | 2.9 | 10.02 2.94 | 7 | 5 | 16.8 | 1.07 | 16 |

#### 3.2. Chemical characteristics

Chemical properties of peat soil samples were selected based on soil fertility criteria [13]. Table 2 shows that pH H2O was higher than pH KCl, indicating negatively charged peat soil. pH values in Tana Tidung data indicated acidic to very acidic level, while in Nunukan Regency and Tarakan City, very acidic level in almost all layers was discovered. Topogenous fresh water peat soil contained a higher pH than the one found in brackish water topogenous peat. Up to 100 cm deep, in almost all locations, soil pH was between 3.1 and 4.5. Soil organic carbon (SOC) and ash content value, shown in Table 2, ranged between 24.65 and 49.09% (very high), while C/N ratio spanned from 16 to 45% (high to very high), suggesting that peat decomposition degree was very low.

This research found that ash content in almost all samples were high value (> 0.25%) up to 100 cm deep, especially on surface layers. The exception, however, applied to pedon UY-3 (0.73 - 1.37%). This indicated that peatlands, either medium or very deep peat with high ash content, has been enriched by local mineral soil. As research location was a tidal area, deposited minerals were very likely to occur. This proved that both moderate and extremely deep peat soils receive mineral enrichment. Table 3 shows that CEC for all samples were categorized into moderate to very high (21.23 - 107.08 cmol.kg⁻¹). High CEC value was a result of negative charge.

Potentials P2O5 and K2O in all pedons, up to 100 cm deep, were decreased. Those properties were found at a higher quantity on the upper layer than the ones on the lower layer (potential P2O5 value 18 - 43 mg.100 g⁻¹ and potential K2O value 13 - 54 mg.100 g⁻¹). The exception was discovered on pedon YA-11 with very low value (potential P2O5 of 13 mg.100 g⁻¹ and potential K2O 6 of mg.100 g⁻¹).
### Table 3. Chemical properties of peat soil samples selected on study area (continued)

| Pedons and horizons | Symbol | Horizons | Depth (cm) | Exchangeable cations | CEC cmol kg⁻¹ | BS (% | Fiber Content | Ash Content |
|---------------------|--------|----------|------------|----------------------|---------------|------|---------------|-------------|
|                     |        |          |            | Ca       | Mg       | K      | Na      | ∑         |             |
| Tana Tidung District|        |          |            |          |          |        |         |          |             |
| YA-02/I Oa1         | 0-13   | -        | 5.72      | 4.74     | 0.42     | 0.25   | 11.13   | 11.13     | 61.95       |
| YA-02/I Oe2         | 13-38  | -        | 1.62      | 2.29     | 0.21     | 0.19   | 4.31    | 3.41       | 59.30       |
| YA-02/III Oe1       | 38-78  | -        | 1.98      | 5.59     | 0.21     | 0.72   | 8.50    | 5.91       | 59.11       |
| YA-02/IV Oe2        | 78-103 | -        | 1.13      | 7.60     | 0.18     | 0.95   | 9.86    | 6.86       | 60.84       |
| YA-02/V Oe3         | 103-133| -        | 1.09      | 6.77     | 0.14     | 1.79   | 9.79    | 4.89       | 59.11       |
| YA-02/VI Oe4        | 133+   | -        | 0.60      | 6.99     | 0.15     | 1.39   | 9.13    | 18.83      | 59.11       |
| SO-17/I Oa1         | 0-59   | -        | 5.30      | 0.69     | 0.91     | 1.35   | 8.25    | 8.25       | 103.66      |
| SO-17/III Oe1       | 59-119 | -        | 1.64      | 1.69     | 0.23     | 0.61   | 4.17    | 4.17       | 94.52       |
| SO-17/III Oe2       | 119-185| -        | 1.53      | 1.50     | 0.18     | 0.66   | 3.87    | 3.87       | 82.20       |
| SO-17/IV Oe2        | 185-235| -        | 1.42      | 1.06     | 0.10     | 0.59   | 3.17    | 3.17       | 49.04       |
| SO-17/V Oe3         | 235-340| -        | 1.44      | 1.19     | 0.17     | 0.50   | 3.30    | 3.30       | 91.39       |
| SO-17/VI Oe4        | 340-450| -        | 2.99      | 2.56     | 0.18     | 0.68   | 6.41    | 6.41       | 97.26       |
| CB-53/I Oa1         | 0-26   | -        | 0.57      | 1.37     | 1.01     | 0.27   | 3.22    | 3.22       | 107.08      |
| CB-53/II Oe1        | 26-76  | -        | 0.86      | 0.97     | 0.35     | 0.65   | 2.83    | 2.83       | 57.28       |
| CB-53/III Oe2       | 76-400+| -        | 0.55      | 0.69     | 0.10     | 0.39   | 1.73    | 1.73       | 51.61       |
| Tarakan City        |        |          |            |          |          |        |         |          |             |
| YA-11/I Oa1         | 0-21   | -        | 2.55      | 2.15     | 0.11     | 0.22   | 5.03    | 5.03       | 58.81       |
| YA-11/III Oe1       | 21-94  | -        | 1.56      | 1.82     | 0.10     | 0.70   | 4.18    | 4.18       | 98.14       |
| YA-11/III Oe2       | 94-350+| -        | 0.99      | 1.87     | 0.09     | 0.39   | 3.34    | 3.34       | 97.97       |
| Nunukan District    |        |          |            |          |          |        |         |          |             |
| UY-3/I Oe           | 0-40   | -        | 0.79      | 1.16     | 0.24     | 0.28   | 2.47    | 2.47       | 22.16       |
| UY-3/II Oe1         | 40-90  | -        | 1.07      | 1.26     | 0.30     | 0.27   | 2.90    | 2.90       | 21.23       |
| UY-3/II Oe2         | 90-300+| -        | -         | -        | -        | -      | -       | -          | -           |
| HK-6/I Oa           | 0-30   | -        | 3.41      | 3.57     | 0.21     | 0.96   | 8.15    | 8.15       | 53.75       |
| HK-6/II Oe1         | 30-90  | -        | 1.83      | 1.84     | 0.03     | 0.53   | 4.23    | 4.23       | 24.67       |
| HK-6/III Oe2        | 90-105 | -        | 1.38      | 2.30     | 0.07     | 0.81   | 4.56    | 4.56       | 56.42       |

Cation exchangeable rate varied from very low to low categories to a depth of 100 cm. The order of magnitude of cation exchangeable in the soil was Mg > Na > Ca > K. Exchanged Ca cation ranged from very low to moderate (0.57 - 5.72 cmol kg⁻¹); meanwhile, low to high were observed for exchanged Mg cation (0.69 - 7.67 cmol kg⁻¹). This research observed very low to high for exchanged K cation (0.03 - 1.01 cmol kg⁻¹) and low to very high for exchanged Na cation (0.19 - 1.79 cmol kg⁻¹). We noted that exchanged Mg cation in almost all peat soil samples reached beyond 1.0 cmol kg⁻¹. Meanwhile, exchanged Na cation spanned from moderate to very high (0.50 - 1.35 cmol kg⁻¹) in SO-17 pedon (Tana Tidung Regency) and medium to high values (0.53 - 0.96 cmol kg⁻¹) on HK-6 pedon (Nunukan District).

Base saturation (BS) on top-to-bottom layers was low (<20%) in all observed pedons. Low BS with high CEC causes availability of bases to be low. This means that availability of macronutrients at the research site was considerably low.

### 3.3. Carbon stocks

Based on an estimation model [14], this research indicated that total peat carbon stock in Tana Tidung, Nunukan and Tarakan City reached 92,978 M tons (average of 1,519 tons C ha⁻¹), 233,542 M tons (average of 1,642 tons C ha⁻¹), and 2,275 M tons (average of 785 tons C ha⁻¹), respectively. To summarize, total carbon accumulation in North Kalimantan peatlands was about 328.80 M, with an average per hectare of around 1,516 tons.
3.4. Utility and implication

The outcome of this study expands the benefit of high-resolution peatland dataset for general utilization or for land use and spatial planning. Enhancement related to characteristics, distribution, and estimates of carbon stocks in peatlands emphasizes recent geospatial references as well as improving information on estimates of carbon storage and its cycle, land use and spatial planning for research and development. It is expected that this research would help in better understanding disaster mitigation of forest and peatlands fires.

4. Conclusions

Peatlands in North Kalimantan Province were about 216,944 ha, with following distribution: 71,512 ha (32.96%) in Tana Tidung, 142,198 ha (65.55%) in Nunukan, and 3,233 ha (1.49%) in Tarakan City. Peatlands were located in fluvio-marine landform (B) in forms of fluvio-marine plain and brackish water topogenous peat, and peat landform (G) as fresh water topogenous peat. Peat soil found in fluvio-marine landform was classified as shallow peat. Meanwhile, in peat landform, peat depth varied greatly, from shallow to very deep categories.

Observed BD values were very low for hemic peat and peat maturity level, hemic (half ripe) and sapric (ripe); the most extensive was classified as hemic. Peat soils, classified as Organosol Saprik (Typic Haplosaprists), Organosol Hemik (Sapric Haplohemists and Typic Haplohemists), and Organosol Fibrik (Hemic Haplofibrist). The Organosol Hemik (Typic Haplohemists), dominated in the study area. Peat soils reaction was very acidic, with high to very high CEC and very low base saturation.

Estimated carbon stocks reached 328.8 M tons with an average of 1,515 tons C ha$^{-1}$. The results of this study are very useful for land use and spatial planning in peatland areas, to support public uses.

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