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Open digital mapping as a cost-effective method for mapping peat thickness and assessing the carbon stock of tropical peatlands

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ABSTRACT

Tropical peatland holds a large amount of carbon in the terrestrial ecosystem. Indonesia, responding to the global climate issues, has legislation on the protection and management of the peat ecosystem. However, this effort is hampered by the lack of fine-scale, accurate maps of peat distribution and its thickness. This paper presents an open digital mapping methodology, which utilises open data in an open-source computing environment, as a cost-effective method for mapping peat thickness and estimating carbon stock in Indonesian peatlands. The digital mapping methodology combines field observations with factors that are known to influence peat thickness distribution. These factors are represented by multi-source remotely-sensed data derived from open and freely available raster data: digital elevation models (DEM) from SRTM, geographical information, and radar images (Sentinel and ALOS PALSAR). Utilising machine-learning models from an open-source software, we derived spatial prediction functions and mapped peat thickness and its uncertainty at a grid resolution of 30 m. Peat volume can be calculated from the thickness map, and based on measurements of bulk density and carbon content, carbon stock for the area was estimated. The uncertainty of the estimates was calculated using error propagation rules. We demonstrated this approach in the eastern part of Bengkalis Island in Riau Province, covering an area around 50,000 ha. Results showed that digital mapping method can accurately predict the thickness of peat, explaining up to 98% of the variation of the data with a median relative error of 5% or an average error of 0.3 m. The accuracy of this method depends on the number of field observations. We provided an estimate of the cost and time required for map production, i.e. 2 to 4 months with a cost between \$0.3 and \$0.5/ha for an area of 50,000 ha. Obviously, there is a tradeoff between cost and accuracy. The advantages and limitations of the method were further discussed. The methodology provides a blueprint for a national-scale peat mapping.

1. Introduction

Tropical peatland plays an important role in the global carbon cycle as it stores a large amount of carbon in the terrestrial ecosystem (Mitra et al., 2005). Carbon stored in peatland can be 10 times larger than its aboveground biomass (Draper et al., 2014; Rudiyanto et al., 2016a). Peatland in Indonesia was considered as marginal land and as a fuel resource prior to the year 2000 (Supardi et al., 1993). With increasing awareness of peat's large C stock and potential greenhouse gases emission (Comeau et al., 2016), accurate estimation of carbon stock of tropical peatlands becomes an important issue (Warren et al., 2017). In addition, carbon stock estimation in peatland is required to support carbon emission reduction policies (Page et al., 2011).

Indonesia, responding to the global issue of reducing CO_2 emissions, has legislation on the protection and management of the peat ecosystem. The legislation outlined conservation areas, which depends on the thickness of peat; however, the main challenge is the lack of fine-scale, accurate maps of peat distribution and its thickness. The current peatland map in Indonesia is at 1:250,000 scale with an estimated area of 14.9 million ha in Sumatra, Kalimantan and Papua (Ritung et al., 2011; Wahyunto and Subagjo, 2003; Wahyunto and Subagjo, 2004; Wahyunto et al., 2006). However there is still much uncertainty in this map (Hooijer and Vernimmen, 2013; Warren et al., 2017), and this coarse scale map cannot be used to implement conservation and management regulations.

Traditional soil mapping techniques are too costly as they require

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many field observations, and the outputs can be too subjective. Many technologies for mapping peatlands have been tested in Indonesia, including remote-sensing technologies that monitor soil from the above (e.g. ICCC, 2014; Ritung et al., 2011; Shimada et al., 2016). However many of those technologies are not cost-effective for large extent mapping. This paper aims to demonstrate and validate a digital mapping methodology, which utilises open data in an open-source environment, as a cost-effective and accurate method for mapping peat thickness and estimating carbon stock for a large extent area.

Considerable attempts have been carried to develop methods that produce accurate maps of peat thickness. Kriging interpolation is often used (Akumu and McLaughlin, 2014; Altdorff et al., 2016; Bauer et al., 2003; Jaenicke et al., 2008; Keaney et al., 2013; Proulx-McInnis et al., 2013; van Bellen et al., 2011; Weissert and Disney, 2013); however to produce a fine resolution map, it needs a large number of observations evenly spread throughout the area. Spatial models were also used to predict peat thickness, such as regression analysis from terrain attributes (e.g., elevation and slope) (Holden and Connolly, 2011; Parry et al., 2012); a peat thickness inference model (Holden and Connolly, 2011); a power function of the distance to a river (Hooijer and Vernimmen, 2013); an exponential function of elevation and slope (Parry et al., 2012); an empirical function of elevation (Rudiyanto et al., 2015). These models only consider few environmental factors and thus the prediction maps still have much uncertainty.

Remote and proximal-sensors such ground penetrating radar (GPR) (Comas et al., 2015), electromagnetic induction (Altdorff et al., 2016), gamma radiometer (Rawlins et al., 2009; Keaney et al., 2013), and light detection and ranging (LiDAR) also have been proposed for mapping peat extent and thickness (Fyfe et al., 2014; Keaney et al., 2013; Koszinski et al., 2015; Parry et al., 2014; Rosa et al., 2009). These instruments produce high-resolution data; however, they still need ground data for calibration which may not be feasible in remote areas. Furthermore, the high cost of acquiring these data does not allow a wide application in large parts of Indonesia. In particular, airborne LiDAR has been proposed as a method to map fine resolution elevation and identify deep peat soils (peat domes) (Hooijer and Vernimmen, 2013). However, LiDAR only can infer peat domes and cannot delineate peat areas.

In a recent study, Rudiyanto et al. (2016b) proposed the digital soil mapping (DSM) framework (McBratney et al., 2003) widely used in the research community for mapping carbon in mineral soils (Minasny et al., 2013), as a cost-effective method for mapping peat thickness. They demonstrated successful applications in two peatlands in Sumatra and Kalimantan. In digital mapping, field observations are coupled with multi-source remotely-sensed environmental variables. This fusion of data allows the creation of spatial prediction functions via machine-learning algorithms. This produces an objective and accurate maps in the form of rasters of prediction along with the confidence of prediction. Consequently, they significantly improved the results of peat thickness mapping (in terms of better accuracy and resolution) as compared to previous studies (e.g. Jaenicke et al., 2008).

The main objective of this study is to propose and demonstrate an open digital mapping approach, which utilises open data in an open-source computing environment, as a cost-effective method for mapping Indonesian peatlands. We validate this approach in a study area in Bengkalis island, Riau province, Indonesia, with specific objectives:

- To evaluate the efficacy of various types of environmental covariates including elevation, terrain attributes, distance to rivers and or sea, radar and optical images for digital mapping of peat thickness,
- To evaluate the accuracy of various types of machine-learning models,
- To evaluate the effect of number of observations of peat thickness on the accuracy of the models,
- To map peat thickness accurately along with its prediction confidence, at a raster resolution of 30 m,
- To estimate below ground carbon stock along with its uncertainty, and
- To provide a relationship between accuracy, cost and time requirement for peat mapping.

2. Materials and methods

2.1. Study area

The study area is located in the eastern part of Bengkalis Island (Fig. 1a and b), Riau Province, Indonesia; which covers an area of around 50,000 ha at latitudes: N1.2502° to N1.5637° and longitudes: E102.2658° to E102.5087°. This area was provided by the Indonesian Peat Prize (IPP) committee as part of its test site. Peatland in Bengkalis island was previously studied by Supardi et al. (1993). Bengkalis island is about 10 km located off the east coast of the Riau province in the strait of Malacca. Its mean annual rainfall is 2400 mm and a mean annual temperature of 27 °C.

Carbon-14 dating showed that the accumulation of this Holocene peat range from 4740 ± 200 to 5730 ± 180 year B.P. (Supardi et al., 1993) when rising sea level stabilized, which resulted in exposure of large, relatively flat areas of marine sediments (Neuzil et al., 1993). The initial 3 m of peat accumulated rapidly at an average rate of 5.1 mm year^{-1}, and the upper 5 m of peat accumulated at a slower rate of 1.2 mm year^{-1}. The peat is ombrogenic, fibric-hemic to hemic-sapric. The main land use is forestry, with some areas planted with oil palm, and others used for dry land farming. Since 2012, there has been a large land use change with conversion of primary forests, and mangroves to industrial plantations (Barus et al., 2016).

2.2. Data set

2.2.1. Data set from field observation and laboratory measurements

Peat thickness was observed in the field using a Russian-type peat corer (Jowsey, 1966) along with their geographical coordinates with a handheld global positioning system (GPS).

117 observations were obtained from the Ministry of Environment and Forestry (MOEF) Indonesia that were collected in 2015. In addition, we collected additional field data in February 2017 to fill in the geographical gaps of existing data (n = 42). Thus, overall, 159 peat thickness observations were used in this study. Fig. 1b shows point locations of peat thickness measurements. The distribution of peat thickness for all data is shown in Fig. 2. Peat thickness ranges between 0 and 12 m with a median of 6.0 m.

We also collected 34 peat samples from the depth up to 30 cm in the 2017 survey for laboratory analysis. Bulk density (BD), carbon content (C_c) were measured on those samples at the Laboratory of Soil Science in Riau University. BD was collected using a ring sampler and determined gravimetrically. Organic matter content was determined using the loss on ignition (LOI) method and converted to C content using the van Bemmelen factor of 0.58. The plot of bulk density, BD vs. carbon content, C_c with their histogram is shown in Fig. S1 (Supplementary material). The data show that there is no relationship between C_c and BD. Observed bulk density ranges between 0.12 and 0.47 g cm^{-3} with a mean and SD of 0.226 ± 0.088 g cm^{-3}. Generally, the bulk density of tropical peat is between 0.013 and 0.25 g cm^{-3} (Rudiyanto et al., 2016a). Supardi et al. (1993) reported that an average bulk density of peatland in Bengkalis Island as 0.08 g cm^{-3}. Frizdew (2012) also showed a similar result of bulk density values obtained from Bengkalis for 0–1 m of depth which is equal to 0.074 ± 0.011 g cm^{-3}. Thus, the surface bulk density obtained in the field is relatively large, which may due to surface compaction. Observed carbon content varies between 0.498 and 0.578 g g^{-1} with a mean and SD of 0.568 ± 0.016 g g^{-1}. This is in accordance with values found in the literature for tropical peat where the C content values are between 0.5 and 0.62 g g^{-1} (Rudiyanto et al., 2016a). Supardi et al. (1993) showed relatively