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Digital mapping for cost-effective and accurate prediction of the depth and carbon stocks in Indonesian peatlands

Rudiyanto [a,b,*], Budiman Minasny [b,*], Budi Indra Setiawan [a,*], Chusnul Arif [a], Satyanto Krido Saptomo [a], Yudi Chadirin [a]

[a] Department of Civil and Environmental Engineering, Bogor Agricultural University, Indonesia
[b] Faculty of Agriculture and Environment, The University of Sydney, New South Wales 2006, Australia

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ABSTRACT

Tropical peatlands have an important role in the global carbon cycle. In order to quantify carbon stock for peatland management and conservation, the knowledge of the spatial distribution of peat and its depth is essential. This paper proposed a cost-effective and accurate methodology for mapping peat depth and carbon stocks in Indonesia. The method, based on the *scorpan* spatial soil prediction function framework, was tested in Ogan Komering Ilir, South Sumatra and Katingan, Central Kalimantan. A peat hydrological unit, where a peatland is bounded by at least two rivers, is defined as the mapping area or extent. Peat depth is modelled as a function of topography and spatial position. Four machine learning models were evaluated to model and map peat depth: Cubist regression tree, Random Forests (RF), Quantile Regression Forests (QRF) and Artificial Neural Network (ANN). Covariates representing topography and spatial position were derived from the 1 arc-second digital elevation model (DEM) of the Shuttle Radar Topography Mission (SRTM) (resolution of 30.7 m). The spatial models were calibrated from field observations. For model calibration and uncertainty analysis, the k-fold cross validation approach was used. Three models: Cubist, Random Forests, and Quantile Regression Forests models showed excellent accuracies of peat depth prediction for both areas where the coefficient of determination values range from 0.67 to 0.92 and root mean squared error (RMSE) values range from 0.6 to 1.1 m. ANN showed inferior results. In addition, QRF and Cubist showed the best account of the uncertainty of prediction, in terms of percentage of observations that fall within the defined 90% confidence interval. In terms of the best predictor, elevation comes first. Using the spatial prediction functions, peat depth maps along with their 90% confidence interval were generated. The estimated mean carbon stock for Ogan Komering Ilir is 0.474 Gt and for Katingan is 0.123 Gt. Our estimate for Ogan Komering Ilir is twice larger than a previous study because we mapped the peatland hydrological unit, while the previous study only delineated peat domes. Finally, we recommend a sampling method for peat depth mapping using numerical stratification of elevation to cover both the geographical and covariate space. We expect that the combination of an improved sampling strategy, machine learning models, and kriging will increase the accuracy of peat depth mapping.

1. Introduction

Tropical peatlands are characterized by an accumulation of partially decomposed organic matter in the water-saturated and anaerobic environment for a long period. Although the bulk density of peat is relatively low, ranging between 0.013 and 0.3 g cm^{-3} (Agus et al., 2011; Lähteenoja and Page, 2011; Rudiyanto et al., 2016), its carbon content is very high, ranging between 23 and 62% on mass basis (Farmer et al., 2014; Rudiyanto et al., 2016; Warren et al., 2012). In addition, tropical peats can accumulate up to a thickness of 20 m (Page et al., 2011). As a result, peatlands store the largest amount of terrestrial carbon per unit area, and it plays an important role in global carbon cycle as a carbon sink, although naturally, they also release two greenhouse gases (GHG) into the atmosphere: carbon dioxide (CO_2) and methane (CH_4) (Farmer et al., 2011; Sjögersten et al., 2014; Wright et al., 2011, 2013). This fact was supported by Page et al. (2011) who estimated that carbon stock in global peatlands stores between 480 and 610 Gt (Giga tonnes) or 15 to 30% of the world's carbon stock (Hugron et al., 2013), albeit global peatlands only cover between 3.8 and 4.1 million km^2, with the best estimate of 3,971,895 km^2 or about 2.5 to 3% of the whole lands of the earth (Page et al., 2011).

Within the context of Reduce Emissions from Deforestation and Degradation (REDD+), peatlands become the main concern in the measurement, reporting and verification (MRV) system which documents

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* Corresponding authors at: Department of Civil and Environmental Engineering, Bogor Agricultural University, Kampus IPB Darmaga, PO. BOX 220, Bogor 16002, Indonesia.
E-mail addresses: lupusae@yahoo.com (Rudiyanto), budiman.minasny@sydney.edu.au (B. Minasny), budindra@ipb.ac.id, budindra@yahoo.com (B.I. Setiawan).

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carbon stocks and its change. Inventory of carbon in peatlands generally is calculated from the dot product of carbon content, bulk density and peat depth (Akumu and McLaughlin, 2014; Fell et al., 2016; Holden and Connolly, 2011; Parry and Charman, 2013). Range values of carbon content and bulk density have been well studied; however peat depth shows a high spatial variation. Thus the presence of accurate peat depth map is important for reliable estimate carbon stock in peatlands. The peat depth map is also required for decision policy of sustainable peatland management (Biancalani and Avagyan, 2014) and for a better understanding of peatland development (Bauer and Vitt, 2011; Esterle and Ferm, 1994) as well as its ecosystem function (Joosten and Clarke, 2002). Recently the Indonesian government has released the Regulation No 71, 2014 on the Protection of Peat Ecosystem. This regulation states that within a peatland hydrological unit if 30% of the area has a peat depth more than 3 m (considered as a peat dome) and located in the river upstream, and then it should be considered as an area of conservation.

In Indonesia, peatland is estimated to cover 206, 950 km^2 (Page et al., 2011), while (Ritung et al., (2011, 2012)) estimated that peatlands in the 3 main islands: Sumatra, Kalimantan, and Papua, cover 149 ,056 km^2. Nevertheless, there are still much uncertainty in these figures (Hooijer and Vernimmen, 2013). Moreover, the peatlands covered a relatively large area and located at remote sites which are difficult to access. Therefore, mapping peat depth remains a big challenge.

Past studies on mapping peat depth commonly used kriging interpolation (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 high spatial resolution map, it needs a large number of observations evenly spread throughout the area. Other works used spatial models to predict peat depth from proxy environmental information such as terrain attributes (e.g., elevation and slope) (Holden and Connolly, 2011; Parry et al., 2012). Other models include: a peat depth inference model (Holden and Connolly, 2011), a power function of the closest distance to a river (Hooijer and Vernimmen, 2013), an exponential function of elevation and slope (Parry et al., 2012), and an empirical function of elevation (Rudiyanto et al., 2015). The accuracy of these published models is usually moderate.

Remote and proximal sensors such gamma radiometer, GPR, electromagnetic induction, and LiDAR have been proposed for mapping peat depth (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, and may not be feasible in remote areas, furthermore, the high cost of acquiring these data does not allow a wide application.

Digital soil mapping (DSM) has been successfully applied to map carbon content of mineral soils evidenced by a large number of publications in recent years (McBratney et al., 2003; Minasny and McBratney, 2015). The advances of DSM are mainly supported by the availability high-quality covariates as well as the development of machine learning algorithms such as: Random Forests (Breiman, 2001), Cubist tree model (Quinlan, 1992, 1993a,b), Artificial Neural Networks (Bishop, 1995; Günther and Fritsch, 2010), and regression kriging (Hengl et al., 2004; Odeh et al., 1994; Odeh et al., 1995). These models have been successfully applied in digital mapping of soil organic carbon (Aitkenhead and Coull, 2016; Aitkenhead et al., 2015; Grimm et al., 2008; Page et al., 2004; Song et al., 2016; Wiesmeier et al., 2011), soil physicochemical properties (e.g., bulk density, plant available water capacity, saturated hydraulic conductivity, pH, chemical concentration) (Malone et al., 2009; Motaghian and Mohammadi, 2011; Odgers et al., 2015), soil texture (i.e., percentage of sand, silt and clay) (Adhikari et al., 2013; Ballabio et al., 2016; Ließ et al., 2012), soil classes (Heung et al., 2016; Pahlavan Rad et al., 2014; Taghizadeh-Mehrjardi et al., 2015), soil parent material (Heung et al., 2014), etc.

This paper seeks for a cost-effective and accurate method for mapping peat depth in Indonesia. Digital mapping techniques for peatlands at a relatively high resolution (30 m) using widely available covariates were proposed. Four machine learning models: Cubist regression tree, Random Forests (RF), Quantile Regression Forests (QRF) and Artificial Neural Network (ANN) were evaluated and tested for peat depth modelling, mapping and uncertainty estimates. The models were tested in two peatlands in Sumatra and Kalimantan. The peat depth map combined with carbon density estimates were used to derive carbon stocks in these peatlands. In addition, based on important predictors found in the regression models, the best sampling strategy for peat depth mapping will be recommended.

2. Materials and methods

2.1. Study area

Tropical peatlands in Indonesia mostly can be found along the east coast of Sumatra and in parts of Kalimantan (Page et al., 2006, 2007). This study was conducted in two peatlands in the two islands (Fig. 1a). Since the formation of peatlands depends on nutrient and oxygen availability which was controlled by flooding from rivers (Anderson, 1961, 1964; Esterle and Ferm, 1994), the mapping area or extent for both peatlands was defined based on the smallest unit of a peatland, namely the hydrological peatland unit, where a peatland is bounded between two rivers or sea. This is in contrast with the mapping extent defined by Jaenicke et al. (2008) where they only delineated areas considered as a peat dome.

The first peatland is located in Ogan Komering Ilir (OKI) District in South Sumatra which covers latitude: S2°23′24.251″ to S3°25′16.313″ and longitude: E105°10′27.152″ to E106°5′37.075″. The total area is about 610,311 ha and bordered by Riding river in the west and Lumpur river in the south and Bangka strait in the northeast (Fig. 1b, left). The main landuse is forest plantation, and some parts are conserved. This area includes two peat domes studied by Jaenicke et al. (2008): Air Sugihan and Teluk Pulai. The second area is in Katingan District, Central Kalimantan and lays on S1°52′7.887″ to S2°6′50.785″ and E113°18′ 46.341″ to E113°51′39.727″. The total area is about 93,257 ha and bordered by Katingan river in the west and Rungan river in the east (Fig. 1b, right), mainly used as a conservation area. Note that, the study area in Katingan does not cover the whole peatland because field observations were only limited to parts of the area. Hereafter, we refer the two peatlands as OKI and Katingan, respectively.

2.2. Collecting field data

Field data collections were carried out between years 2007 and 2009 in OKI. Peat depth data were obtained from field surveys of drilling using the Eijkelkamp peat auger. The observations were based on transects commonly used in peat surveys with a distance between observations of about 100 to 1000 m (Fig. 1b left). Peat depth is defined as the depth from the surface until the depth where mineral soil layer is found (Agus et al., 2011; Page et al., 1999). At each location of drilling, the geographical coordinates were recorded using a global positioning system (GPS). In addition, data from South Sumatra Forest Fire Management Project (SSFFMP) collected in 2005 (Prayitno and Bakri, 2005) were also included in the Ogan Komering Ilir dataset. For Katingan, the observed peat depths were obtained from published data of Boehm and Frank (2008) where the peat drillings were done in years 2006 and 2007 (Fig. 1b right) and Shimada et al. (2001).

Fig. 2a and b shows the histogram of peat depth data for OKI and Katingan, respectively. In total, 840 observations were collected from OKI with peat depth ranging between 0 and 7.1 m with median = 1.9 m and 121 observations were obtained from Katingan ranging between 0 and 9 m with median = 1.39 m.