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Using forest structure to predict the distribution of treed boreal peatlands in Canada

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ABSTRACT

Mapping peatland extent in Canada would contribute important information concerning carbon balance and hydrology. While such mapping, based on air photo interpretation and remote sensing data, has recently improved, maps have been limited to 1:1 million scale. We hypothesized that forest structure information from forest inventory plots could be used to predict the presence of forested and treed peatlands in boreal Canada at the ground plot-level, and that a resulting model could be used to predict the distribution of forested and treed peatlands across Canada. Inventory ground plots from the Canadian National Forest Inventory (NFI) with organic soil depth measurements were used to create a model of the presence of treed to forested (canopy cover ranging from sparse to closed) peatlands (greater than 40 cm organic soil depth) in boreal Canada. The presence of black spruce (*Picea mariana*) or larch (*Larix laricina*), in combination with low stand height and stand age greater than 75 years, were the strongest predictors of the presence of peatlands. Bioclimatic variables related to high diurnal and annual temperature variation, consistent with a continental climate, also contributed to the increased predicted presence of treed peatlands. Both logistic and boosted regression tree models showed similar results, with ~87% accuracy in the discrimination of treed peatlands when validated against an independent set of ground plots. The boosted regression tree model was propagated across Canada using forest attribute raster data layers at 250 m resolution from the NFI along with bioclimatic layers. Estimates of treed peatland extent agreed with data points from peat cores with 85–95% accuracy in the Boreal Shield ecozone, although prediction was less accurate in the more southern boreal and Great Lakes forest areas. The resulting map can be used as an input to forest carbon modelling, and the improved knowledge of treed peatland extent will be useful in modelling wildfire or peatland drainage.

1. Introduction

Peatlands represent hotspots of carbon (C) storage in the North American boreal forest, covering 110 Mha of land with local accumulations exceeding 200 kg C m^{-2}. Peatland soils are defined as organic deposits greater than 40 cm in depth, which corresponds to the maximum rooting depth of most boreal trees (Canada Soil Survey Committee, 1978). These organic soils cover approximately 22% of the land area in Canada's boreal and subarctic regions; 97% of all peatland areas in Canada fall within these boreal and subarctic regions (Tarnocai et al., 2011). Densely forested peatlands, with a closed tree canopy and tree canopy height greater than 5 m, constitute approximately 17% of the peatland area in Canada (Zoltai and Martikainen, 1996). In such densely forested peatlands, the higher wood volume allows for wood fibre extraction (Zoltai and Martikainen, 1996), though peatland drainage and active forest management of peatlands in Canada has never extended beyond a few limited trials (Haavisto et al., 1995). However, trees also play a major role in the C balance (Wieder et al., 2009), ecology (Miller et al., 2015), and hydrology (Kettridge et al., 2013) of open-canopy treed peatlands where tree biomass is too small to economically harvest. Because of the low economic value of these peatlands, they largely remain unmapped except when found adjacent to timber extraction areas in the southern portion of the Canadian boreal forest. In Canada, many of these open treed peatlands are classified as forested lands under the Marrakesh Accord, in which a threshold of 25% crown closure and potential tree height of 5 m is used to define forested lands (UNFCC, 2002). Here, we use the term "treed" to refer to peatlands that have, at a minimum, the density of a treed peatland, but also up to and including closed-canopy densely forested peatlands.

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Mapping peatland extent in Canada originated in ecological inventory efforts, principally through the Canada Land Inventory (Pratt, 1965). Early efforts were largely limited to polygon-mapping products of 1:1 million or greater scale, although there were attempts to characterize the abundance of differing peatland types regionally (Zoltai et al., 1975). A more exact quantification of peatland area and C stock was required by the 1990s as early C budgets of northern peatlands were developed (Gorham, 1991). This effort was quickly followed by research on plot-level carbon cycling in boreal peatlands (e.g., Hogg et al., 1992; Moore and Dalva, 1993; Frolking et al., 1998).

Polygon-mapping products depicting proportional peatland area of differing classes in Canada at the 1:1 million scale have been available for some time (e.g., Tarnocai et al., 1995, 2011) and were based on air photo interpretation and manual delineation of LANDSAT imagery (Lacelle, 1998). More detailed analyses were available for selected locations, such as north-central Alberta (Vitt et al., 1995). Air photo interpretation of forested peatlands relies on two surface expressions of peatlands: forest structure and landform (Zoltai and Vitt, 1995). Forest attributes (e.g., tree height, density, volume), particularly when they indicate an open, short, conifer canopy, were used to delineate forested peatlands from upland conifer stands (Zoltai and Vitt, 1995). In addition to forest structure, landforms such as permafrost palsas, strings, flarks, and other features visible in aerial photography (approximately 100 m or larger in size) assist in the manual identification of peatlands (Zoltai and Vitt, 1995). Remote sensing approaches, including optical (e.g., Palylyk and Crown, 1984), synthetic aperture radar (Touzi et al., 2007), and composite methods involving radar and optical (Li and Chen, 2005) offer high accuracy (>80%) of peatland delineation over small spatial areas. The delineation of large, open, treeless peatlands in Canada has been available for some via the Earth Observation for Sustainable Development (EOSD) landcover product (Wulder et al., 2008). The identification of smaller, more heavily forested peatlands with little or no patterning is more difficult, as such peatlands resemble upland conifer forests. Given that peatland disturbances such as wildfire are more severe in more heavily forested peatlands (Lukenbach et al., 2015) that are associated with shallow peat (Bhatti et al., 2006), the efficient identification of these more hidden peatland areas becomes even more important for C accounting. Contemporary C accounting practices and models increasingly require high-resolution maps of soil C loads in order to accurately model emissions from disturbances such as fire (Anderson et al., 2015).

Peat depth has rarely been measured in a systematic way in Canada; notable datasets of peat depth from peat coring studies by Zoltai et al. (2000) and Riley and Michaud (1989) lack information on forest structure and only provide a cover percentage by tree species. Peat depth measurements are available alongside metrics of forest structure from the Canadian National Forest Inventory (NFI), a national network of aerial and ground forest inventory plots, spanning all provinces, territories, and forested ecozones. While not as numerous as provincial silviculture permanent sample plots that measure large merchantable trees, the NFI plots offer the advantage of representing both merchantable and non-merchantable forest stands with a harmonized methodology across Canada. The ground plots available through the NFI (913 in total to date) include at least one soil pit measuring total organic soil depth (OSD) down to 100 cm. Compared with PSP networks, the NFI dataset has the additional advantage that the deep OSD (in the form of peat) is actually measured, as are the attributes of trees as small as 1.3 m in height, which are common in forested peatlands.

Recently, forest attribute data derived from a combination of manually interpreted aerial photography and modelling, available from the 2 × 2 km photo plot database, have been interpolated between photo-plot sites using optical remote sensing data from the Moderate Resolution Imaging Spectrometer (MODIS), using a *k*-nearest neighbour (*k*-NN) interpolation approach for imagery from 2001 (Beaudoin et al., 2014). The resulting data products are 250 m resolution raster maps of numerous forest canopy attributes available from the NFI photo plots, such as stand height, merchantable volume, proportion of biomass by species, and crown closure. Measurements exclusive to ground plots, such as OSD, were therefore not included in the analysis. However, some of the forest attributes, such as open-crown, short, pure conifer stands, on the raster maps produced by Beaudoin et al. (2014) have been shown to be indicators of the presence of boreal forested peatlands (Zoltai and Vitt, 1995). This combination of a comprehensive ground plot methodology relevant to forested peatlands, coupled with complete national coverage of forest attribute layers serving to predict peatland presence, can be used to produce a spatial presence–absence model, in the same way as point count datasets for birds (Venier et al., 2004) or plants (Ohse et al., 2009) have been used.

We hypothesized that (i) forest structure information from forest inventory plots could be used to predict the presence of forested and treed peatlands in boreal Canada at the ground plot-level, and that (ii) a subset of the forest structure variables available from both ground plots and national raster datasets could be used to calibrate such a model, which could then be spatialized using the raster datasets to predict the distribution of forested and treed peatlands across Canada. Therefore, the objectives of this study were to (1) create models predicting the presence of forested peatlands using NFI ground inventory plots for which forest, soil, and climatic attributes are available; (2) spatialize these models across targeted ecozones of Canada using available national raster maps; and (3) assess the accuracy of output maps using independent validation sets of ground plots.

2. Methods

2.1. Area and input data

The spatial predictions targeted all boreal and taiga regions of Canada (Ecological Stratification Working Group, 1996) where forested peatlands are a significant landscape feature (including Taiga Shield, Taiga Plains, Hudson Plains, and Boreal Shield ecozones; and Great Lakes–St. Lawrence, Mid-Boreal Shield, Lake of the Woods, and Southern Boreal Shield ecoprovinces, the last three being subdivisions of the Boreal Shield ecozone; Fig. 1). Four hundred and fifty NFI ground plots (Gillis et al., 2005) located within these ecozones or ecoprovinces were used as input data for model calibration. Only variables available in both the NFI ground plots (400 m^2 area) and the photo plots used in the creation of the *k*-NN dataset were used in constructing the model. If data on tree cover were missing or no trees were measured in the ground plot (20 × 20 m), sites were excluded. This step eliminated treeless peatlands, such as those with only moss, sedge, and shrub cover. Sites were classified as peatlands if they had a reported OSD greater than 37.5 cm, following the 40 cm threshold used in the Canadian System of Soil Classification (Canada Soil Survey Committee, 1978). The 37.5 cm definition allows for a marginal thickness of moss cover in addition to peat cover, as the NFI ground plots group all duff, litter, and peat in measuring OSD thickness.

2.2. Model creation

Two models predicting the presence or absence of OSD greater than 40 cm were calibrated and compared to evaluate their relative merits and limitations. First, a logistic regression model of forested