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Distribution and landscape controls of organic layer thickness and carbon within the Alaskan Yukon River Basin

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ABSTRACT

Understanding of the organic layer thickness (OLT) and organic layer carbon (OLC) stocks in subarctic ecosystems is critical due to their importance in the global carbon cycle. Moreover, post-fire OLT provides an indicator of long-term successional trajectories and permafrost susceptibility to thaw. To these ends, we 1) mapped OLT and associated uncertainty at 30 m resolution in the Yukon River Basin (YRB), Alaska, employing decision tree models linking remotely sensed imagery with field and ancillary data, 2) converted OLT to OLC using a non-linear regression, 3) evaluate landscape controls on OLT and OLC, and 4) quantified the post-fire recovery of OLT and OLC. Areas of shallow (<10 cm), moderate (≥10 cm and <20 cm), moderately thick (≥20 cm and <30 cm), and thick (≥30 cm) OLT, composed 34, 20, 14, and 18% of the YRB, respectively; the average OLT was 19.4 cm. Total OLC was estimated to be 3.38 Pg. A regional chronosequence analysis over 30 years revealed that OLT and OLC increased with stand age (OLT: $R^2 = 0.68$; OLC: $R^2 = 0.66$), where an average of 16 cm OLT and 5.3 kg/m^2 OLC were consumed by fires. Strong predictors of OLT included climate, topography, near-surface permafrost distributions, soil wetness, and spectral information. Our modeling approach enabled us to produce regional maps of OLT and OLC, which will be useful in understanding risks and feedbacks associated with fires and climate feedbacks.

1. Introduction

The northern circumpolar region has been estimated to contain 50% of the global belowground organic carbon pool (Tarnocai et al., 2009). Much of this soil organic carbon pool is composed of moss, litter, and woody and sedge peat (Grosse et al., 2011; Turetsky et al., 2011). The research presented here focuses on the surface soil organic layer. Specifically, organic matter and carbon content above the mineral transition and excluding buried O horizons, collectively described as organic layer thickness (OLT) and organic layer carbon (OLC) within this paper. We focus on quantifying and mapping the near-surface organic layer in the Yukon River Basin (YRB) in interior and western Alaska that is subject to seasonal freeze–thaw processes and moisture variations (Grosse et al., 2011), while recognizing that a substantial quantity of soil organic carbon is found in deeper carbon pools that contain as much, or more, organic carbon as the surface organic layer (Tarnocai et al., 2009).

Species composition, carbon dynamics, ecosystem productivity, leaf area index, albedo and permafrost condition are often fire-regulated in the boreal forest (Amiro et al., 2006; Balshi et al., 2009a; Barrett et al., 2011; Bergner et al., 2004; Goetz et al., 2007; Harden et al., 2000; Liu et al., 2005; McMillan and Goulden, 2008). Fires frequently burn deep organic layers (Kasischke et al., 2000; Turetsky et al., 2011), and concurrently burn the less dense organic surface layers, both of which are important to ecosystem functioning in terms of soil moisture and temperature (Johnstone et al., 2010a; Kasischke and Johnstone, 2005). Fires can thereby affect the active-layer depth and lead to degradation of near-surface permafrost (Harden et al., 2006; Jorgenson et al., 2010, 2013; Yoshikawa et al., 2003). The depth of the organic layer after fire also affects post-fire succession because deep organic layers generally preclude the establishment of deciduous seedlings in boreal ecosystems (Johnstone and Chapin, 2006; Johnstone et al., 2010a). The observed trend of increased fire severity and area burned in recent decades (Kasischke et al., 2010) is therefore associated with more deciduous-dominated or co-dominated regrowth because it often results in bare mineral soils or thin organic layers (Barrett et al., 2011; Johnstone and Kasischke, 2005), a pattern likely to

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Acronyms

OLT	organic layer thickness not including buried organic horizons
OLC	organic layer carbon not including buried organic horizons
DT	decision tree

continue with future warming (Johnstone et al., 2010b; Shenoy et al., 2011).

The process of vegetation succession provides feedbacks that contribute to permafrost formation and stability (Jorgenson et al., 2010). Evergreen-dominated successional processes provide resilience to permafrost and to stand self-replacement through the development of thick moss and organic layers that provide thermal insulation and resistance to deep burning (Johnstone et al., 2010a; Jorgenson et al., 2010; Kane and Vogel, 2009). This resilience may be reduced with concurrent increases in long-term deciduous forest cover (with high rates of decomposition and mineralization leading to the maintenance of a thin organic layer) associated with the increasing fire return interval and severity, and climate warming (Chapin et al., 2000; Johnstone et al., 2010b; Kasischke and Turetsky, 2006). Fire- and climate- mediated changes to the relative abundance of evergreen and deciduous forests and to OLT and OLC stocks therefore represent a potential feedback to regional and global scale climate and carbon cycles (Harden et al., 2012; Kasischke et al., 1995; Mishra and Riley, 2012; Yuan et al., 2012) and a substantial alteration to historically dominant successional pathways (Johnstone et al., 2010a,b). Moreover, these changes will likely affect the substantial soil organic carbon pools held in permafrost and peatlands (Tarnocai et al., 2009; Turetsky et al., 2002, 2011), with global climate implications.

Understanding the spatial distribution of OLC stocks in Arctic/subarctic ecosystems is critical due to their importance in the global carbon cycle and potential contribution to climate feedbacks (Grosse et al., 2011; Mishra and Riley, 2012; Yuan et al., 2012). Moreover, maps of post-fire OLT provide indications for long-term successional trajectories and susceptibility of permafrost to thaw (Barrett et al., 2011). Maps of OLT and OLC in the region remain incomplete, however, due to the landscape heterogeneity, limited number of field observations (frequently concentrated along roads), and often uncertain data quality resulting from sampling and analytical problems (Tarnocai et al., 2009). The current study extends and improves upon previous research by including a large number of field observations that are well distributed across the landscape, and spatially extrapolating these data using robust decision tree (DT) models (McBratney et al., 2003) to produce the first comprehensive quantification of OLT across interior Alaska. Given the high variability of OLT at both the microsite (pedon) and site (Landsat pixel) scales (Ping et al., 2006), we used broad depth intervals instead of continuous depth measurements to better match the scales of soil profile measurements (1 m) and the remote sensing inputs (30 m).

Our goal was to map the distribution of OLT and OLC stocks in the YRB and assess the landscape-scale factors controlling the spatial variation. Specifically, we aimed to 1) map OLT and associated uncertainty using DT models linking remotely sensed imagery with field and ancillary data; 2) estimate OLC from OLT using a non-linear regression; 3) evaluate geographic patterns in OLT and OLC in relation to various environmental factors; and 4) quantify the effects of fire, and subsequent recovery, on OLT and OLC.

2. Study area

The Alaskan Yukon River Basin comprises nine Major Resource Land Areas (MLRA; USDA, 2006) with a total land surface of approximately 500,000 km^2 (Fig. 1). The basin has eight major classes of vegetation, including upland spruce–hardwood forest, lowland spruce–hardwood forest, bottomland spruce–poplar forest, high brush, low brush-muskeg bog, alpine tundra, moist tundra, and wet tundra (Spetzman, 1963). Forests are dominated by black (*Picea mariana* Mill) and white spruce (*Picea glauca* Moench), in addition to deciduous stands consisting of Alaskan birch (*Betula neoalaskana* Sarg.), aspen (*Populus tremuloides* Michx.), and balsam poplar (*Populus balsamifera* L.) (Viereck et al., 1992). Deciduous stands are commonly associated with earlier successional communities (Van Cleve and Viereck, 1981; Van Cleve et al., 1983), and generally possess a thin organic layer and lack permafrost (Viereck et al., 1992). Black spruce stands commonly contain a continuous layer of mosses and lichens underlain by a deep organic soil layer (Kasischke and Chapin, 2008). Tundra is found in the coastal lowlands (e.g. in the Yukon Kuskokwim Delta) and in higher elevation portions of the interior. Many tundra communities possess a single canopy layer with both shrubs and herbaceous plants, underlain by mosses and lichens. Lowland tundra is dominated by wet sedge meadows often including cotton-grass (*Eriophorum angustifolium* Honck.) and water sedge (*Carex aquatilis* Wahlenb.). Upland tundra consists of *Dryas* spp., dwarf shrub, dwarf birch (*Betula nana* L.), and ericaceous shrub communities (Viereck et al., 1992). Permafrost is discontinuous through most of the study area, becoming more continuous north of the Yukon River (Jorgenson et al., 2008b). The landscape of interior Alaska is unglaciated, containing poorly developed soils, with Inceptisols, Histosols, and Gelisols composing the dominant orders (Ping et al., 2006). The unique ecological diversity and sensitivity to climatic perturbations made the basin an ideal location for this research. Also fueling this research is recent observations of permafrost degradation (Jorgenson et al., 2006), increases in the occurrence, severity, and size of fires (Kasischke and Turetsky, 2006; Kasischke et al., 2010), and a national carbon assessment effort (U.S. Geological Survey LandCarbon), all of which are directly linked with surface organics and the global carbon cycle.

3. Methods

3.1. Field data

Field measurements of OLT and OLC were collected from 1994 to 2012, by various agencies and researchers. The bulk of the measurements were collected by the National Resource Conservation Service (NRCS; e.g., Clark and Duffy, 2003) and ABR, Inc. (Jorgenson et al., 1999, 2001; Jorgenson et al., 2008a), while much of the remainder was collected from late July to early September 2012, in a collaborative effort between the U.S. Geological Survey (USGS) and the U.S. Fish and Wildlife Service. The majority of all observations were made using soil plugs, soil pits, and hand-held augers. While soil investigation approaches differed among data sources, the actual measurement of OLT (i.e. tape measure, soil profile tape measure) and OLC (i.e. bulk density tests and % C for individual organic horizons) was similar. Furthermore, while operator errors were not assessed, organic horizon designation was consistent among field teams and relatively straightforward; where organic horizons are usually visually or texturally distinct from vegetation and mineral horizons. It is important to note that OLT sampling designs (point measurements and transects averages) differed among a portion of these data sources, which could present slight biases within our estimations of OLT.

Field data obtained from the NRCS and other researchers were screened in an effort to include only complete, consistent, and accurate observations. ‘Screening’ consisted of an assessment for data entry errors (e.g. erroneous geographical location, removal of buried organic layers from total OLT), which appeared to be fairly uncommon. OLT observations were then grouped into an integrated database (~5100). Measurements that coincided with water, barren land, perennially frozen ice/snow, planted/cultivated, moss, and/or developed landcover