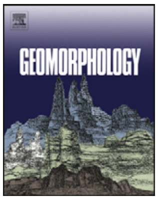
Geomorphology 206 (2014) 87–96

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph



Dynamics of active layer in wooded palsas of northern Quebec

Mélanie Jean, Serge Payette *

NSERC Northern Research Chair, Centre d'études nordiques, Université Laval, Québec, QC G1V 0A6, Canada

ARTICLE INFO

Article history:
Received 21 January 2013
Received in revised form 23 September 2013
Accepted 1 October 2013
Available online 9 October 2013

Keywords:
Palsa
Permafrost
Boreal forest
Active layer
Climate change

ABSTRACT

Palsas are organic or mineral soil mounds having a permafrost core. Palsas are widespread in the circumpolar discontinuous permafrost zone. The annual dynamics and evolution of the active layer, which is the uppermost layer over the permafrost table and subjected to the annual freeze–thaw cycle, are influenced by organic layer thickness, snow depth, vegetation type, topography and exposure. This study examines the influence of vegetation types, with an emphasis on forest cover, on active layer dynamics of palsas in the Boniface River watershed (57°45′ N, 76°00′ W). In this area, palsas are often colonized by black spruce trees (*Picea mariana* (Mill.) B.S.P.). Thaw depth and active layer thickness were monitored on 11 wooded or non-wooded mineral and organic palsas in 2009, 2010 and 2011. Snow depth, organic layer thickness, and vegetation types were assessed. The mapping of a palsa covered by various vegetation types and a large range of organic layer thickness were used to identify the factors influencing the spatial patterns of thaw depth and active layer. The active layer was thinner and the thaw rate slower in wooded palsas, whereas it was the opposite in more exposed sites such as forest openings, shrubs and bare ground. Thicker organic layers were associated with thinner active layers and slower thaw rates. Snow depth was not an important factor influencing active layer dynamics. The topography of the mapped palsa was uneven, and the environmental factors such as organic layer, snow depth, and vegetation types were heterogeneously distributed. These factors explain a part of the spatial variation of the active layer. Over the 3-year long study, the area of one studied palsa decreased by 70%. In a context of widespread permafrost decay, increasing our understanding of factors that influence the dynamics of wooded and non-wooded palsas and understanding of the role of vegetation cover will help to define the response of discontinuous permafrost landforms to changing climatic conditions.

1. Introduction

Throughout the circumpolar north, permafrost shows signs of increased degradation closely associated with warming over the last 100 years (Jorgenson et al., 2001; IPCC, 2007; Walker, 2007; Tarnocai et al., 2009). In the discontinuous permafrost zone, where permafrost temperature is close to 0 °C, minor changes in soil temperature or active layer thickness may have dramatic consequences on ecosystems (Osterkamp and Romanovsky, 1999; Jorgenson et al., 2001, 2010). Palsas and peat plateaus are organic or mineral soil mounds with a permafrost core, which are largely distributed in the discontinuous permafrost zone (Seppälä, 1972; Washburn, 1983; Harris et al., 1988). Because of their exposed shape, palsas are vulnerable to changes in climate such as increases in temperature and precipitation that affect soil temperature (Vallée and Payette, 2007; Thibault and Payette, 2009). As a result, palsas can be used as indicators of large-scale changes of active layer thickness and permafrost stability.

Climate is the main factor influencing permafrost aggradation, distribution, and stability. More precisely, permafrost is usually found in areas where the mean annual air temperature (*MAAT*) is below 0 °C (Washburn, 1979). At the landscape scale, topography, type and thickness of organic layer, soil moisture, snow depth, and vegetation cover influence permafrost stability and active layer thickness (Seppälä, 1982; Washburn, 1983; Seppälä, 1986; French, 2007). The active layer corresponds to the uppermost layer of material above the permafrost table that is subjected to the annual freeze–thaw cycle (Washburn, 1979). When dry, the organic or peat layer in the upper soil profile has a very low thermal conductivity, whereas saturated or frozen peat has much higher thermal conductivity that is closer to that of ice (Brown, 1963; French, 2007). Thus, peat reduces heat penetration in the ground during summer and enables the loss of latent heat from the ground during winter (Brown, 1963; Seppälä, 1982; Kanigan et al., 2009). Thick and low-density layers of snow have a low thermal conductivity and reduce the loss of latent heat from the ground, keeping the soils warmer; however, a late snowmelt delays ground heating in spring (French, 2007; Yi et al., 2007; Burn and Kokelj, 2009). The type of vegetation also influences active layer dynamics because of differences in albedo, shading and snow accumulation. The albedo of tundra vegetation is higher than that of a conifer forest (Burn and Kokelj, 2009). However, the albedo differences between tundra and forest seem to be compensated by forest shading, which reduces ground solar radiation (Bonan and Shugart, 1989; Burn and Kokelj, 2009). In addition to reducing ground heating, the shading of conifer trees allows

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* Corresponding author. Tel.: +1 418 656 7538; fax: +1 418 656 2043.
E-mail address: serge.payette@bio.ulaval.ca (S. Payette).

0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.10.001

ground colonization by feather mosses. Moss biomass per unit volume is only 30%, with the remaining space filled with air, provides insulation to the underlying soil (Yoshikawa et al., 2003; French, 2007; O'Donnell et al., 2009; Blok et al., 2011). A dense forest cover, such as that found in northern Manitoba, intercepts snow precipitation and maintains a thin snow cover (Zoltai and Tarnocai, 1971; Zoltai, 1972). Greater snow accumulation occurs in open forests where the trees slow wind velocity, therefore behaving as efficient ground snow traps (Couillard and Payette, 1985; Allard and Séguin, 1987; Kanigan et al., 2009; Cyr and Payette, 2010). A thinner active layer is generally found in areas where there is a dense tree cover and a thicker active layer develops in forest openings colonized by shrubs and lichens (Zoltai and Tarnocai, 1971; Kanigan et al., 2009). Detailed spatial analyses are needed to better evaluate changes of active layer thickness within and between sites, and its relationships to climate, vegetation, soil and snow (Hinkel and Nelson, 2003; Wright et al., 2009).

In North America, wooded palsas are sometimes colonized by black spruce trees (*Picea mariana* [Mill.] B.S.P.) because of drier conditions prevailing at their surface than in the surrounding wetland areas (Cyr and Payette, 2010; Quinton et al., 2011). The periods of formation of wooded palsas have been determined in the Boniface River area (northern Quebec) to be 1500–1000 cal. BP and 650–200 cal. BP (Cyr and Payette, 2010). In Siberia and North America, most forested areas occurring on permafrost soils are found in the discontinuous permafrost zone and on relatively flat ground possessing a hummock–hollow microtopography (Van Cleve et al., 1990; Yoshikawa et al., 2003; Cyr and Payette, 2010). To our knowledge, wooded palsas are found only in North America and they are estimated to represent 5% of the permafrost mounds in the treeline region in northeastern Canada (Cyr and Payette, 2010). Wooded palsas are absent in Scandinavia and Finland, and it is not known if the "woody mires over permafrost" found in Siberia correspond to wooded palsas (Botch and Masing, 1983; Cyr and Payette, 2010). Wooded palsas are unique ecosystems that persist because of a fragile equilibrium between climate, soil, and ecosystem properties (Cyr and Payette, 2010). Therefore, understanding the spatiotemporal dynamics of wooded palsas and comparing it to that of the more abundant non-wooded palsas may give insights into permafrost stability and active layer dynamics at a larger scale. This is of particular interest in North America where approximately 20% of Canada and 30% of the Quebec-Labrador Peninsula are underlain by permafrost (Payette, 2001).

The aim of this study was to evaluate the impact of the forest cover on the ground thermal regime of wooded palsas in northern Quebec. More specifically, our objectives are to compare the changing active layer thickness among palsas of different soil and vegetation types according to interannual climatic variations. We also mapped the spatial distribution of thaw depth and active layer thickness across a palsa according to local site factors. We hypothesized that the forest cover will retain more snow resulting in a warmer soil during winter, although a delayed snowmelt in the spring may retard soil thaw. The forest cover will intercept more solar radiation and maintain a cooler soil in summer, hence a thinner active layer. We suppose that active layer thickness will be strongly determined by organic layer thickness, with thicker peat inducing a thinner active layer. Moreover, the active layer should be thicker close to the borders of palsas where snow and soil moisture are greater.

2. Study area

The study area is located in the Boniface River watershed (northern Quebec, 57°45′ N, 76°00′ W; Fig. 1), approximately 30 km east of Hudson Bay and 10 km south of tree line. *MAAT* in Inukjuak, the weather station situated 130 km northwest of the study area, is −7 °C. The coldest month is February with a mean air temperature of −25.8 °C and the warmest month is July with a mean air temperature of 9.4 °C. Annual precipitation totals 460 mm of which 45% fall as snow (Environment Canada, 2012). The physiography of the study area is characterized by alternating low hills and valleys with altitudes ranging between 100 and 250 m above mean sea level. The vegetation landscape of the Boniface River area is part of the forest tundra ecotone. Black spruce is the main tree species, and dwarf birch (*Betula glandulosa* Michx.) dominates the shrub layer. Hilltops are covered by lichens and small shrubs typical of tundra vegetation whereas moss- and lichen-spruce stands are distributed in valleys and sheltered areas (Arseneault and Payette, 1997).

The Boniface River watershed lies within the discontinuous permafrost zone (Fig. 1A, zone b). Permafrost is distributed across about 50% of the area, with the greatest occurrence in fens (Vallée and Payette, 2007). Thick clay deposits susceptible to frost-heaving are found in the valleys as a result of the Tyrrell Sea transgression (Bhiry et al., 2007). Organic and mineral palsas are distributed in wetlands underlain by these clay deposits. In the Boniface River watershed, the palsas are generally circular or elongated in shape when they are found in narrow valleys. Their average diameter and height vary between 20 and 70 m and 2 and 9 m, respectively. The vegetation covering palsas ranges from bare ground and lichens (*Cladonia* spp.) to shrubs (mostly dwarf birch and Labrador tea (*Rhododendron groenlandicum* ([Oeder] Kron and Judd)) and forest stands (feather mosses and lichen black spruce stands). The topography of these palsas is usually uneven, and organic layer thickness, snow depth, vegetation types and tree height are heterogeneously distributed.

3. Methods

3.1. Site selection and description

Satellite images (Worldview-1, July 2008), aerial photographs (1:40,000; July 1957), and field validation were used to select 11 palsas and peat plateaus in 2009 (Fig. 1B). Sampling sites were selected according to accessibility, soil and vegetation types, and represented a variation in palsa size and homogeneity of vegetation cover. We selected a total of 35 main sampling sites to include four palsa types: wooded organic palsas, wooded mineral palsas, non-wooded organic palsas and non-wooded mineral palsas (Fig. 1C–L). Because of their similarity, the palsas and the peat plateaus will not be distinguished in this study (Zoltai, 1972; Payette et al., 1976; Payette, 2001; Cyr and Payette, 2010). A soil profile was dug and described next to each sampling site in October 2010. The thickness of organic, sand, and gyttja deposits were measured as well as depth to clay deposits. Plant surveys were conducted at each site according to structural groups (e.g. trees, shrubs, mosses and lichens) in 1 m^2 plots using the line intercept method (Mueller-Dombois and Ellenberg, 1974). At each site, snow depth was inferred from black spruce growth forms and the change of color of spruce needles (Lavoie and Payette, 1992). The snow depth measurements were validated in the field in March 2010.

The studied palsas were formed in minerotrophic peatlands where peat thickness is approximately 130 cm (Lavoie and Payette, 1997) and in riparian mineral deposits exposed to periods of low water levels (Vallée and Payette, 2007). The palsas varied in area and height from 156 to 9570 m^2 and 1.1 to 8.72 m, respectively (Table 1). The 35 sampling sites also showed a large range of soil types, from mineral soils devoid of an organic layer to 120 cm thick organic layers (Table 1). In the sites that showed a thin organic layer (less than 50 cm), sand deposits 11–186 cm thick were located at the contact between the organic layer and the clay deposit.

The vegetation types at all sites were defined using K-means clustering from the vegetation surveys. This method was chosen because of its non-hierarchical structure and objectivity in determining the number of groups using the Calinski–Harabasz criterion (F statistic) (Milligan and Cooper, 1985; Legendre and Legendre, 1998). Five vegetation types were defined based on K-means cluster analysis: moss spruce stand, lichen spruce stand, forest opening, shrub, *Sphagnum* and