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The transition zones (ecotone) between boreal forests and peatlands: Modelling water table along a transition zone between upland black spruce forest and poor forested fen in central Saskatchewan

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ABSTRACT

Close association between hydrology and ecosystem productivity in boreal transition zones requires that modelling ecosystem productivity in these zones be based on accurate modelling of water table dynamics. We hypothesize that these dynamics are driven by transfers of water through surface and lateral boundaries of transition zones, and that lateral transfers can be calculated from hydraulic gradients with external water tables at upper and lower boundaries. In this study we implement these hypotheses in the *ecosys* model to simulate water table dynamics along a boreal transition zone (ecotone) in central Saskatchewan, Canada, extending from upland black spruce forest down to a poor forested fen. Simulated water table depths were compared to measured values at upper, middle and lower ecotone positions during the dry year 2003 when peat was dried, the very wet year 2004 when peat was rewetted, and the hydrologically average year 2005 when peat remained wet. These hypotheses enabled *ecosys* to simulate declines in water table depth with declines in elevation along the ecotone that matched well those observed during each of the three years. Observed:expected plots of modelled vs. measured water table depths at all positions indicated reasonable goodness of fit with slopes (with respect to 1:1 line) and R^2 of 0.92 and 0.53 in 2003–2005 period, 0.90 and 0.28 in 2003, 0.81 and 0.51 in 2004, 0.97 and 0.46 in 2005, confirming that our hypotheses enabled changes in water table depths along boreal transition zones to be properly modelled during successively dry, wet and normal years.

1. Introduction

Boreal forests, found through most of Canada, Russia and Scandinavia, play an important role in global carbon (C) cycling, being the second largest terrestrial biome on Earth with 1/3 of the total forest C, 1/3 of the total forest area, and roughly 1/4 of the total soil C (Pan et al., 2011; Gates, 1993). In vast boreal regions soil drainage governing water table (WT) is a main determinant of soil C storage (Rapalee et al., 1998), and extensive peatlands have developed on waterlogged areas (Bauer et al., 2009). Consequently, forested peatlands and wetlands occupy a substantial part of boreal landscapes with a global area of roughly 2.5×10^8 ha (Gorham, 1991; Lugo et al., 1990). Many boreal forests adjacent to peatlands are also poorly drained (Bond-Lamberty and Gower, 2007), with black spruce/bryophyte plant communities (Turetsky, 2003; O'Neill, 2000) and poorly understood hydrological controls on C sequestration (Zoltai and Martikainen, 1996). These forests often have characteristics of transitional ecosystems with declining productivities caused by shallower WT and associated increases in peat depth towards peatlands, and gradients in bryophyte community structure (Bhatti et al., 2006; Hartshorn et al., 2003).

Even though lowering of WT has been reported to cause annual basal area increments of black spruce to more than double (Lieffers and Macdonald, 1990) and annual tree ring widths to increase by several times (Dang and Lieffers, 1989), little is known about how WT affects productivity gradients along the boreal forest – peatland transitional ecosystems. Thus, the main question of this study is whether we properly understand and model the WT dynamics through the complex soil and topographic gradients along these ecosystems, which is a prerequisite to understanding and modelling their productivity gradients in subsequent studies. Before addressing the main question though, we review the emerging knowledge of their significance.

1.1. Boreal ecotone between upland forest and peatlands

The limited research conducted so far in these ecotone ecosystems was mostly caused by uncertainty in considering them

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as forests or peatlands with their distinct tree components and thin organic layers towards the forest margins, and their markedly declining productivities and deep peat towards the peatland margins. The transitional nature of these ecosystems has been recognized since the beginning of the XX century in Scandinavia (Korpela and Rainikainen, 1996a,b) as in different national peatland classifications they were described as “mire margin forests”, “forested mires”, “moist forests” or “swamps” (Locky et al., 2005). Recently, Bauer et al. (2009) described boreal transition zones in Canada as “peat margin swamps”, based on the “swamp” definition in Canadian System of Wetland Classification stating that “swamp is a wetland influenced by minerotrophic groundwater and dominated by tall woody vegetation” (Warner and Rubec, 1997). Furthermore, Bauer et al. (2009) discriminated between “dry” and “wet” parts of the peat margin swamps, respectively towards their forest and peatland margins.

Even though these transitional ecosystems could be classified as peatlands with organic layers often >40 cm deep, they do not fit comfortably into “swamp” or another recognized wetland category (National Wetlands Working Group, 1997) with their hybrid nature of conduits for fluxes of material and energy between different systems (Ewel et al., 2001). Instead, we refer them as transition zones with pronounced gradients of productivity, peat-mineral soil profiles and WT depths that exist between rarely flooded (unlike many swamps), extremely productive forest margins (often more productive than adjacent upland forests) and well-waterlogged peatland margins (Webster et al., 2008a,b; Bhatti et al., 2006; Hartshorn et al., 2003). We also refer them as ecotone ecosystems with associated gradients in bryophyte community structure from brown and feather mosses to *Sphagnum* mosses (Yarrow and Marín, 2007).

Geographical importance of boreal transition zones, as common landscape mosaics of peat-upland complexes, can be inferred from the fact that black spruce, their main tree component, is one of the most widely distributed forest types in boreal North America (Longton, 1992), with roughly ~75% of black spruce sites growing on organic layers >40 cm (Halliwell and Apps, 1997), and peatlands covering ~20% of boreal North American landscape (Zoltai et al., 1988). The very few recent pioneering studies in these ecotone ecosystems revealed mainly four types of transition between boreal forests and peatlands in North America, i.e. forest–rich (minerotrophic) fen, forest–poor (acidic) fen, forest–bog, bog–forest, as described in greater detail by Bhatti et al. (2006) and Hartshorn et al. (2003). Forest–rich fen, forest–poor fen and forest–bog transition zones usually follow the main topographic gradient between upland black spruce (*Picea mariana*) or mixed black spruce – tamarack (*Larix lariciana*) stands and lowland forested or open fens and continental bogs. Bog–forest transition zones usually connect raised bogs of mixed stunted conifers at upper topographic locations with black spruce or Sitka spruce (*Picea sitchensis*) stands at lower topographic locations, following the gradient from organic to mineral soils overlain by *Sphagnum* and other peat-forming mosses and ericaceous shrubs.

1.2. Modelling water table dynamics in forest and peatlands

As productivities of peatlands and many forest ecosystems are strongly affected by changes in WT depths, proper modelling of WT dynamics is a prerequisite for reliable estimates of ecosystem productivity and C balance (Grant et al., 2012; Ju et al., 2006). A number of ecosystem models have been developed and applied for forest and peatland ecosystems in recent decades, with different complexity of their hydrological modules (Dimitrov et al., 2011; Ju et al., 2006). Many earlier ecosystem models either do not simulate WT dynamics (Kucharik et al., 2000; Garnier et al., 1997; Haxeltine and Prentice, 1996; Sellers et al., 1996) or require WT as an input to simulate ecosystem productivity and respiration (St-Hilaire et al., 2010; Frolking et al., 2002). Other models simulate WT from balancing simple (1D) hydrological schemes (Kennedy and Price, 2004; Potter et al., 1993; Oostindie and Bronswijk, 1992; Bronswijk, 1988), thereby omitting lateral water fluxes. Recent complex ecohydrological models, such as *ecosys* (Grant et al., 2012; Dimitrov et al., 2010a), BEPS (Sonnentag et al., 2008; Chen et al., 2005, 2007), InTEC (Ju et al., 2006), ORCHIDEE (Krinner et al., 2005), LPJ (Sitch et al., 2003; Prentice et al., 2000), simulate both vertical and lateral water fluxes, and thereby are capable of modelling hillslope WT dynamics based on spatial (3D) hydrological schemes.

1.3. Rationale of modelling water table dynamics along boreal transition zones

In this study we use the model *ecosys*, which couples hydrological to biogeochemical and ecosphysiological mechanisms in ecosystems, in order to simulate dynamically changes in C and energy fluxes through the soil–vegetation–atmosphere continuum by linking WT depth to productivity through O_2 effects on nutrient cycling driven by microbial redox reactions and root uptake (Grant et al., 2012; Dimitrov et al., 2010c, 2011). *Ecosys* has already simulated successfully forest and peatland hydrology at a site scale in the course of the year by simulating near-surface soil water contents (θ) in boreal black spruce site (Grant, 2004) and WT and θ at various depths in northern fens (Grant et al., 2012) and bogs (Dimitrov et al., 2010a). These earlier studies in peatlands demonstrated that seasonal changes in WT at a coupled hummock-hollow terrain could be simulated from water exchanges across the model surface boundary (precipitation vs. evapotranspiration) and lateral subsurface boundaries (discharge vs. recharge), as the lower subsurface boundary is assumed zero for wetlands.

The main objective of this study is to model and better understand the ecotone hydrology. To accomplish this objective, we extended our previous modelling work from a site to a landscape scale by modelling daily and seasonal changes in WT along a transect representing the boreal transition zone between a black spruce upland forest and a lowland poor fen. Unlike the site-scale WT in bogs that are largely independent from watershed hydrology or in fens that are usually focal water-gathering positions for the surrounding watersheds, the WT along transition zones are strongly dependant on watershed hydrology through complex hydraulic gradients acting at their forest and peatland margins (Bauer et al., 2009). Therefore, lateral subsurface boundary conditions need to be well defined in the model to simulate properly WT dynamics along boreal transition zones. Lateral water exchanges in *ecosys* were governed by the depth of and distance to an assumed external WT (WT_{ext}) through recharging/discharging water in/out of the site soil profile when WT at lateral subsurface boundaries moved below/above WT_{ext}. Subsurface water in *ecosys* flows down topographic gradients within the saturated zone of the model transect. Thereby, watershed hydraulic gradients can be created in *ecosys* by allowing the elevations of WT_{ext} at different lateral subsurface boundaries to vary with their topographic positions. We hypothesize that these different WT_{ext} elevations, which may be set from hydrological characteristics of the watershed independently of the model, together with surface boundary conditions can simulate and explain seasonal and interannual variability of WT at the different landscape topographic positions with different organic–mineral soil profiles, during alternating hydrologically diverse years.