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Boreal permafrost thaw amplified by fire disturbance and precipitation increases

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ENVIRONMENTAL RESEARCH
LETTERS

Boreal permafrost thaw amplified by fire disturbance and precipitation increases

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Supplementary material:

The NEST model

The Northern Ecosystem Soil Temperature model (NEST) is a process-based one-dimensional model developed to quantify ground thermal conditions and permafrost and their changes with climate and disturbances in high latitudes (Zhang et al., 2003). NEST integrates the effects of key factors on ground thermal dynamics, including atmospheric climate, vegetation, snow, soil composition and ground condition, soil moisture, thawing and freezing and associated changes in liquid water (Figure S1). The model uses time steps of 30 minutes so that the heat calculation is stable.

Mosses, lichen, forest floor and peat layers are all treated as organic layers with different physical and hydraulic properties. The ground profile is divided into 40 layers with thickness increasing from 0.1 m near the surface to 4.8 m at the bottom at the depth of 120 m. Ground temperature dynamics are simulated by solving the one-dimensional heat conduction equation. The upper boundary conditions (the ground surface or snow surface when snow is present) are determined based on energy balance, and the lower boundary conditions (at 120 m depth) are defined based on the geothermal heat flux. The thickness of the snowpack is determined based on snow density and the amount of snow on the ground (water equivalent), calculated as the cumulative difference between snowfall and snowmelt. The snow density profile is simulated considering compaction and destructive metamorphism. The snowpack is also divided into about 0.1 cm layers, and the number of snow layers and the thickness of the snowpack are updated on the basis of snow dynamics. Soil water dynamics are simulated considering water input (rainfall and snowmelt), output (evaporation and transpiration, and), and redistribution among soil layers. Thawing and freezing and the associated changes in the fractions of ice and liquid water in a soil layer are determined based on energy conservation (Zhang et al., 2003). The model explicitly simulates vertical exchanges of heat and water, but with parameterized lateral water flows and snow drifting (Zhang et al., 2012; Zhang et al., 2002).

The model includes the effects of topography on solar radiation (Zhang et al., 2013), and fire disturbance (Zhang et al., 2015). Vegetation influences energy and water exchanges between ground and the atmosphere, and influences soil moisture conditions. The plant canopy is modelled as a single layer whose energy balance (or energy conservation) includes the change of heat contained in the whole vegetation layer. The heat capacity of the canopy is estimated on the basis of plant biomass and its water content. The net solar radiation intercepted by the canopy is estimated on the basis of leaf area index. Latent heat flux of canopy is estimated on the basis of Penman-Monteith equation using canopy resistance instead of surface resistance. Canopy aerodynamic resistance is a function of canopy height.

The model has been validated against measurements of surface energy fluxes, snow depth, thaw depth, soil temperature, and spatial distributions of permafrost across Canada (Chen et al., 2003; Ou et al., 2016, Zhang et al., 2005; 2006; 2008; 2012; 2013; 2015; Way et al., 2018).

The inputs of the model include climate data, soil and ground conditions, vegetation, fire disturbance and parameters for lateral water flows and snow drifting (Zhang et al., 2002). The climate data include daily minimum and maximum air temperature, precipitation, solar radiation, vapour pressure, and wind speed. Soil and ground conditions include moss layer thickness, organic layer thickness, organic matter content, degree of decomposition, the texture of mineral soil, fraction of rock in soil, depth to bedrock, thermal conductivity of bedrock, and geothermal heat flux at the lower boundary. Vegetation conditions include type, height, biomass and leaf area index (LAI). Input data on fire disturbance include the year of fire, immediate effects on LAI, top organic layer, albedo and their post-fire recovery. The output of the model includes ground temperature, thawing and freezing depths, snow depth, and soil moisture.

Model calibration

For model parameters, the surface albedo was reduced by half immediately after fire (Yoshikawa et al., 2002). The depth of bedrock was assumed as 5 m (Wolfe et al., 2011). The thermal conductivity of bedrock was 2.6 W m^{-1} $°C^{-1}$ (Brown, 1973), and heat flux at the bottom of the ground profile was assumed as 0.07 W m^{-2} (Majorowicz and Grasby, 2010). Based on the gently sloping terrain of the sites, we assumed no lateral water input or output for black spruce sites (BS, MS-U, MS-B). For the birch forest site in Boundary Creek (BB), we assumed that the water table was reduced by 5% every day when it was above 20 cm depth. No snow drifting and topographic effects on solar radiation were considered.

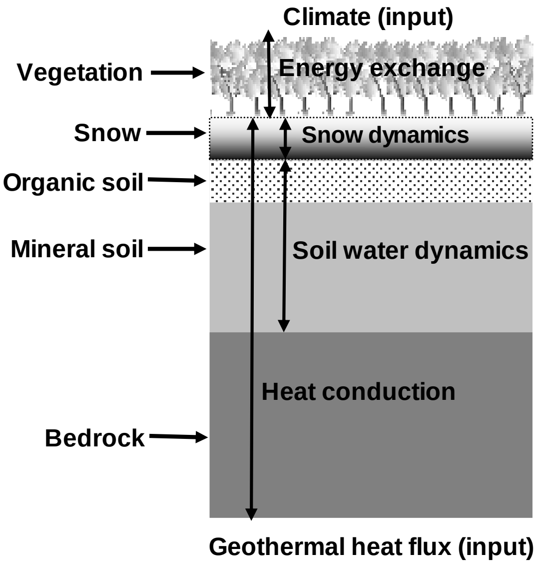

Figure S1. The structure of the NEST model (Zhang et al., 2003). Note that mosses are included as specific layers in the organic soil layer. Reproduced with permission from Zhang et al. (2003). John Wiley & Sons. Copyright 2003 by the American Geophysical Union.

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