Near-Surface Hydrology and Soil Properties Drive Heterogeneity in Permafrost Distribution, Vegetation Dynamics, and Carbon Cycling in a Sub-Arctic Watershed

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Discontinuous permafrost environments exhibit strong spatial heterogeneity in subsurface thermal states, vegetation cover, and carbon fluxes, with sharp transitions that occur at scales too small to be driven by weather forcing or to be captured by Earth System Models. Here we analyze – using field observations and an ecosystem model – the effects of observed spatial heterogeneity in soil and vegetation properties, hydrology, and thermal dynamics on ecosystem carbon dynamics in a watershed on the Seward Peninsula in Alaska. First, we quantify the controls on soil thermal regimes across the watershed using a dense network of distributed temperature profiling systems (DTP). The DTP data indicates that the soil thermal regimes are primarily driven by snow depth and co-vary with vegetation type with near-surface permafrost and talik present under graminoid and shrub covered area, respectively. Further, we evaluate the mechanisms driving this co-variability and its impact on carbon dynamics by applying a Morris global sensitivity analysis (GSA) to a process-rich, successfully tested terrestrial ecosystem model, *ecosys*. The GSA outputs cover the observed ranges of soil temperatures, soil moisture, and surface CO_2 fluxes observed in the watershed and confirm that landscape heterogeneity has a strong impact on soil temperatures, permafrost distribution, and vegetation composition. Snow depth, O-horizon thickness, and near-surface water content control the soil thermal regime more than an air temperature gradient corresponding to a 140 km north-south distance. High shrub productivity is simulated only in talik (perennially unfrozen) soils with high nitrogen availability Through these effects on PFT and permafrost dynamics, landscape heterogeneity impacts ecosystem productivity. We find that model runs with near-surface taliks have higher microbial respiration (by 78.0 gC m^{-2} yr^{-1}) and higher net primary productivity (by 104.9 gC m^{-2} yr^{-1}) compared to runs with near-surface permafrost, and simulations with high shrub productivity have outlying values of net carbon uptake. We explored the prediction uncertainty associated with ignoring observed landscape heterogeneity and found that watershed net carbon uptake is three times larger when heterogeneity is accounted for. Our results highlight the complexity inherent in discontinuous permafrost environments and demonstrate that missing representation of subgrid heterogeneity in TEMs could bias predictions of high-latitude carbon budget.