Study on permafrost and ground surface conditions at the Taiga-Tundra boundary in the Indigirka River lowland, northeastern Siberia

（北東シベリアインディギルカ河川低地タイガ-ツンドラ境界における永久凍土と地表面状態に関する研究）

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**D 論の要約**

The warming trend and an increase trend of snow cover in the Arctic region are expected to cause drastic changes including permafrost degradation and vegetation shifts. There seems to be an interaction between permafrost and the ground surface conditions such as vegetation, microtopography, and snow cover in Arctic region. In this study, we conducted (1) investigation of a relationship between the ground ice and the vegetation/microtopography, and also the ground ice formation conditions, and (2) snow survey to observe the spatial distribution of snow cover, at the Taiga–Tundra boundary near Chokurdakh (70°37′N, 147°53′E) in the Indigirka River lowlands of northeastern Siberia. The stable isotopic composition of water ($\delta^{18}O$, $\delta D$, and d-excess) was used to estimate the source and freezing rate of ground ice and sublimation and re-distribution processes of snow cover.

We selected four observation sites near Chokurdakh with different densities of larch tree. This observation area is underlain by continuous permafrost and located on the Taiga–Tundra boundary. Observation (vegetation structure and composition and microtopography) and sampling (soil and soil water) data were collected at each site, especially for Kodac site (site K) which was typical Taiga–Tundra boundary ecosystem, in the periods of 9–24 July 2011 and 16–26 July 2012. Frozen soil cores down to a depth of approximately 1 m were obtained with geological data at all sites, and were sampled at intervals of less than 10 cm. The vegetation composition and landscape were investigated at each sampling point and categorized into three types: tree mounds, wet areas, and intermediate areas. Snow survey was conducted in 23–26 April 2014 and 15–17 April 2015. At each sampling point, a manual snow prove was done. Snow depth was measured and snow cover was obtained as a core, and snow density and snow water equivalent (SWE) were directly calculated using the snow depth and the weight of the snow core. For isotope analysis, water in the soil samples, river water from the Indigirka mainstream and tributaries, summer precipitation and the snowmelt water samples were obtained and kept in glass vials.

The gravimetric water content (GWC) in the frozen soil layer was significantly higher at microtopographically high elevations with growing larch trees (i.e., tree mounds) than at low elevations with wetland vegetation (i.e., wet areas). The observed ground ice (ice-rich layer) with a high GWC in the tree mounds suggests that the relatively elevated microtopography of the land surface, which was formed by frost heave, strongly affects vegetation composition. Large variations in the isotope ratios of the ground ice ($\delta^{18}O$ was from –25.7‰ to –21.8‰) were observed for the ice-rich layer with high ice content in the tree mounds. The slope of the regression line of these data in the $\delta D$–$\delta^{18}O$ plot was 6.9, suggesting a near equilibrium isotope fractionation occurred during freezing. This implies that the ice formed with sufficient time for the migration of unfrozen soil water to the freezing front (i.e., ice segregation), therefore thick ice lenses formed. In contrast, narrow variation range in the isotopic data ($\delta^{18}O$ was from –22.4‰ to –20.4‰) with low ice content of approximately 130% was observed in the wet areas. It was indicated that rapid freezing occurred under relatively non-equilibrium conditions, implying that there was insufficient time for ice segregation to occur.

The freezing rate of the tree mounds was slower than that of the wet areas due to the difference of such as soil moisture and snow cover which control underground thermal conductivity. A clear relationship between the snow cover parameters and the vegetation was observed in the study area. Snow cover was the deepest at the site covered by dense and tall shrub (69 cm in 2014 and 60 cm in 2015), while snow density was the highest on ice over a lake (0.277 g/cm$^3$ in 2014 and 0.227 g/cm$^3$ in 2015). The Snow water equivalent (SWE) was the highest at the shrub site (135 mm in 2014 and 113 mm in 2015), whereas that was the lowest at the site of sedge and/or sphagnum wetland (84 mm in 2014 and 66 mm in 2015). Since the clear relationship between SWE and vegetation type, we estimated regional SWE in observation area (10 × 10 km) using a vegetation map. The values were 111 mm in 2014 and 86 mm in 2015.

It was shown that there is an interaction between permafrost and ground surface conditions in this study area. It seems that the presence of ground ice formed microtopography which controls vegetation structure and composition at the Taiga–Tundra boundary, conversely, microtopography and vegetation affect the freezing environment of ground ice through such as soil moisture and shading effect. The microtopography and vegetation also controls the spatial distribution in snow cover at the study area, the snow cover affects the soil freezing environment such as ground temperature through the thermal conductivity. Therefore, the ground ice and the ground surface conditions affect one another. The warming and increase in snowfall predicted in the future will affect degradation of the permafrost, which can have a significant impact on the microtopography and the vegetation structure and composition. In addition, the current increases in trees and shrubs in the Taiga–Tundra boundary greatly contributes to the distribution in snow cover on a regional scale, which may suppresses the ground temperature cooling in winter. Future climate change will have a significant impact on the freezing environment of ground ice and change the ground surface conditions, then they may interact further.