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## Identifying ice-rich permafrost using remotely sensed late-season subsidence

**Simon Zwieback** and Franz Meyer

University of Alaska Fairbanks, Geophysical Institute, Fairbanks, United States of America (szwieback@alaska.edu)

Despite the critical role of ground ice for permafrost ecosystems and terrain stability, we lack fine-scale ground ice maps across almost the entire Arctic. This is chiefly because ground ice cannot be observed directly from space. Here, we analyse late-season subsidence from Sentinel-1 InSAR satellite observations as a physically based indicator of vulnerable excess ground ice at the top of permafrost. The key idea is that the thaw front can penetrate materials that were previously perennially frozen at the end of a warm summer, triggering subsidence where the permafrost is ice rich. We assess the idea by comparing the InSAR observations to permafrost cores and an independently derived ground ice classification.

We find that the late-season subsidence in an exceptionally warm summer was 4 - 8 cm (5th - 95th percentile) in the ice-rich areas, while it was lower in ice-poor areas (-1 - 2 cm). The observed distributions for ice-rich and ice-poor terrain overlapped by only 2%, demonstrating high sensitivity and specificity for identifying top-of-permafrost excess ground ice.

The strengths of late-season subsidence include the ease of automation and its applicability to areas that lack conspicuous manifestations of ground ice, as often occurs on hillslopes. The biggest limitation is that it is not sensitive to excess ground ice below the thaw front and thus the total ice content. A further challenge is the sub-resolution variability in ground ice, ice-wedge polygons being a striking example, which needs to be accounted for when interpreting and validating the results.

We expect late-season subsidence to enhance the automated mapping of ice-rich permafrost terrain, complementing existing (predominantly non-automated) approaches based on largely indirect associations of ice content with vegetation and periglacial landforms. The suitability of satellite-observed late-season subsidence for mapping ice-rich permafrost can contribute to anticipating terrain instability in the Arctic and sustainably stewarding its ecosystems.