High-resolution mapping and spatial variability of soil organic carbon storage in permafrost-affected soils

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Permafrost soil sampling time-lapse video

Introduction

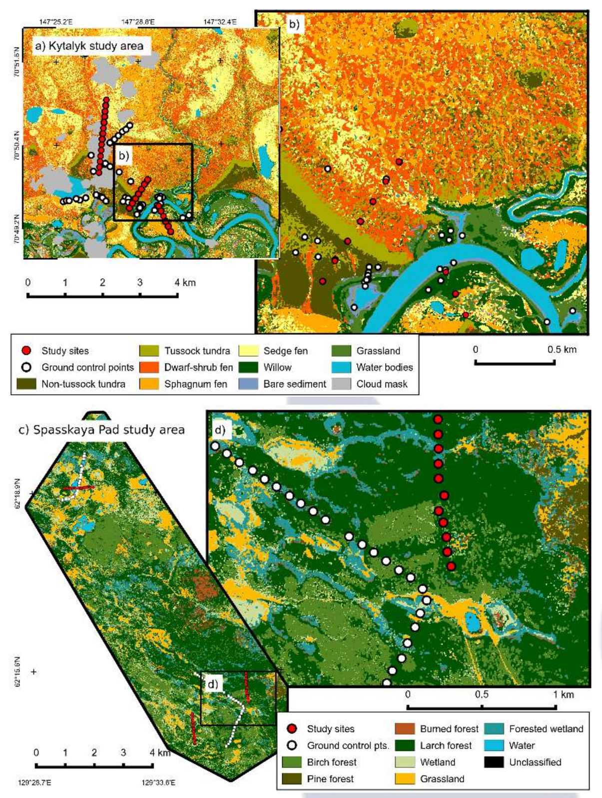
Permafrost-affected soils store large amounts of soil organic carbon (SOC). Mapping of this SOC provides a first order spatial input variable for research that relates carbon stored in permafrost regions to carbon cycle dynamics. High-resolution satellite imagery is becoming increasingly available even in circum-polar regions. The presented research highlights findings of high-resolution mapping efforts of SOC from five study areas in the northern circum-polar permafrost region.

Study 1:

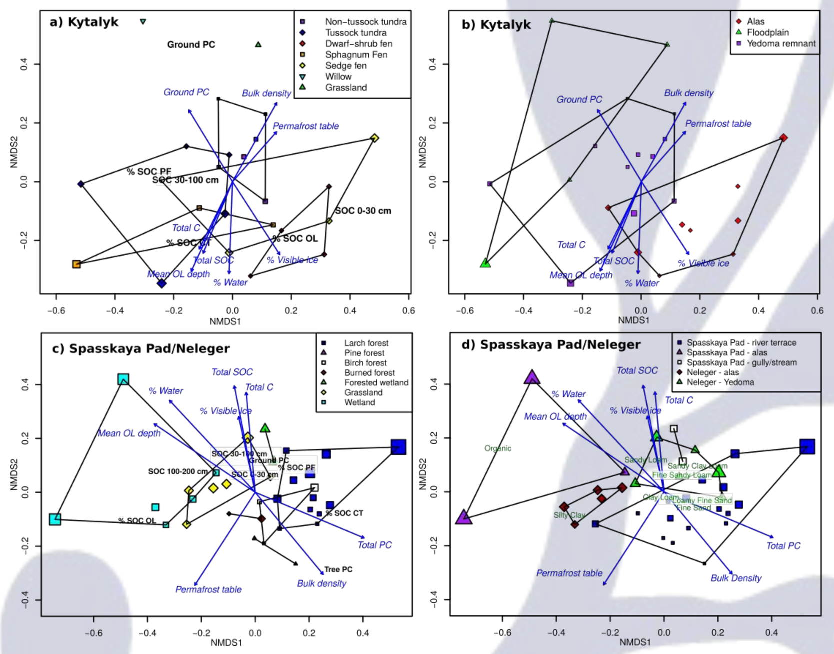
Siewert, M.B., Hanisch, J., Weiss, N., Kuhry, P., Maximov, T, Hugelius, G., 2015. **Comparing carbon storage of Siberian tundra and taiga permafrost ecosystems at very high spatial resolution: Ecosystem carbon in taiga and tundra.** JGR Biogeosciences.

Key Findings

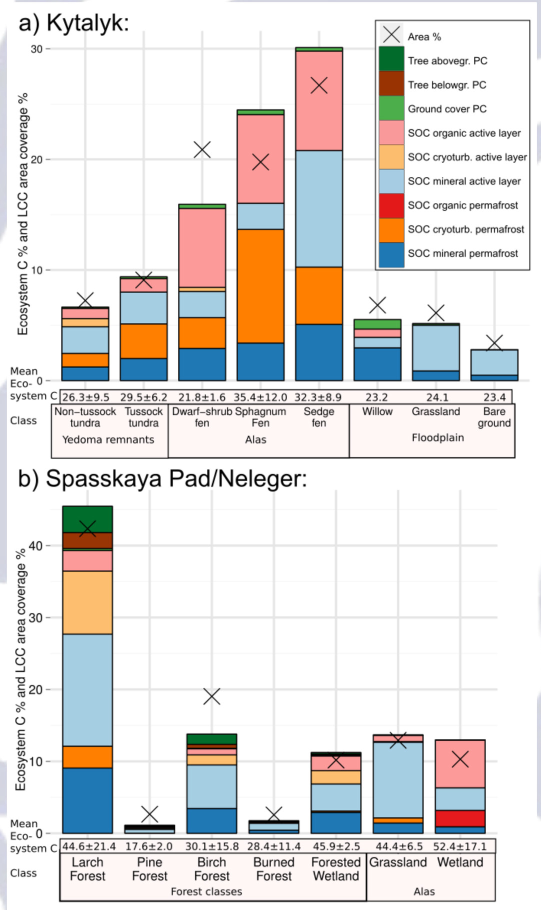
High-resolution remote sensing (2 x 2 m) delivers new detail.
Ecosystem carbon almost entirely stored in the soil (≥86%).
Yedoma and thermokarst define ecosystem carbon storage at landscape scale.
Within land cover class variability:
- **In tundra by geomorphological features.**
- **In taiga by environmental gradients.**



High-resolution land cover maps from Kytalyk and Spasskaya Pad used for thematic upscaling.



Multivariate ordination diagrams showing soil pedons and their relationship to response and environmental variables. Pedons are grouped by class (a, c) and by geomorphological units (b, d).



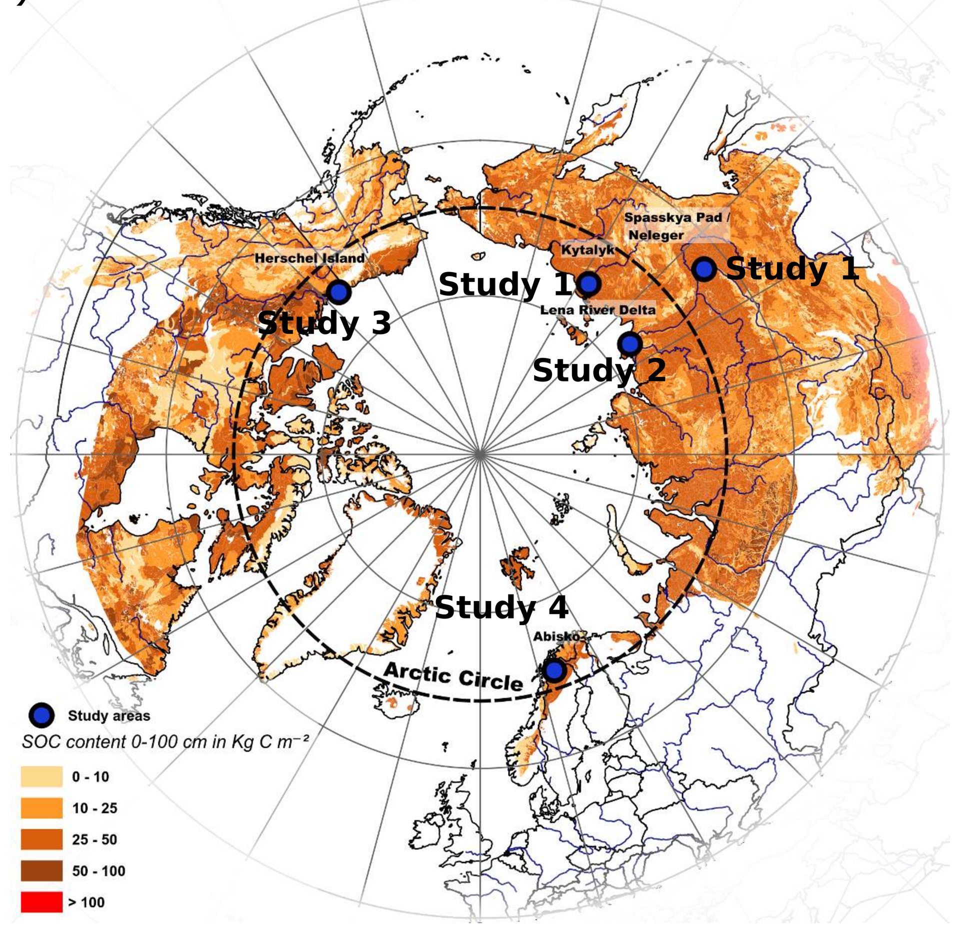
Detailed ecosystem C partitioning showing carbon storage per land cover class and area covered (x). Note the low amount of C stored in vegetation compared to soil.

Key findings and summary

Our high spatial resolution analyses show how geomorphology has a strong influence on the distribution of SOC (Study 1,2,3,4). The SOC is organized at different spatial scales. Periglacial landforms and processes dictate local scale SOC distribution due to patterned ground landforms. Such landforms are non-sorted circles and ice-wedge polygons of different age and scale (Study 1,2,3). Palsas and peat plateaus are formed and can cover larger areas in Sub-Arctic environments (Study 4). Ice-rich Yedoma sediments can dominate the local relief through thermokarst formation and create landscape scale macro environments that dictate the distribution of SOC (Study 1, 2).

A general trend indicates higher SOC storage in Arctic tundra soils compared to forested Boreal or Sub-Arctic taiga soils. Yet, due to the shallower active layer depth in the Arctic, much of the SOC may be permanently frozen and thus not be available to ecosystem processes (Study 1, 2, 4). Significantly more SOC is stored in soils compared to vegetation, indicating that vegetation growth and incorporation of the carbon into plant phytomass alone will not be able to offset SOC released from permafrost (Study 1).

High-resolution satellite imagery and advanced mapping methods such as digital soil mapping using machine-learning can significantly improve SOC estimates (Study 4). Soil pedon data represents an urgent research priority and is the limiting factor in SOC mapping (Study 1, 2, 3, 4). Statistical analyses are provided as an indication for best practice of soil pedon sampling for permafrost-affected soils (Study 2).



Study areas of this project and circumpolar distribution of soil organic carbon (Source Tarnocai et al . 2009).

Study 2:

Siewert, M.B., Hugelius, G., Heim, B., Faucherre, S., 2016. **Landscape controls and vertical variability of soil organic carbon storage in permafrost-affected soils of the Lena River Delta.** CATENA

Key findings

Great diversity of soils in the Lena River Delta.

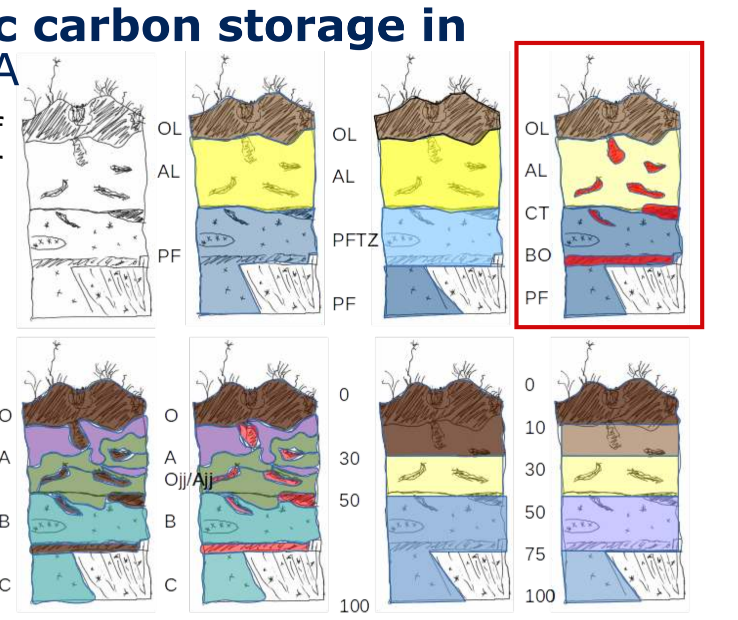
Geomorphological units explain SOC variability best.

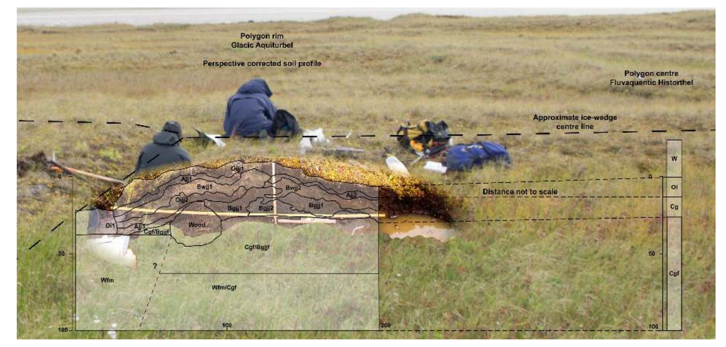
High vertical resolution is necessary to reflect SOC variability with depth.

Image classification is improved by segmentation analysis, modern classifier and data-fusion.

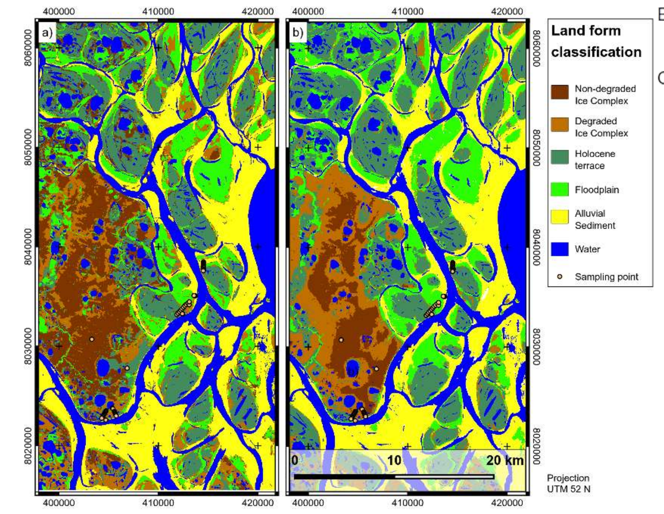
Soils should be sampled according to:
- **organic surface layer**
- **mineral active layer**
- **mineral permafrost**
- **cryoturbated and buried organic layers**

Statistical analysis of different subdivisions for permafrost-affected soils.

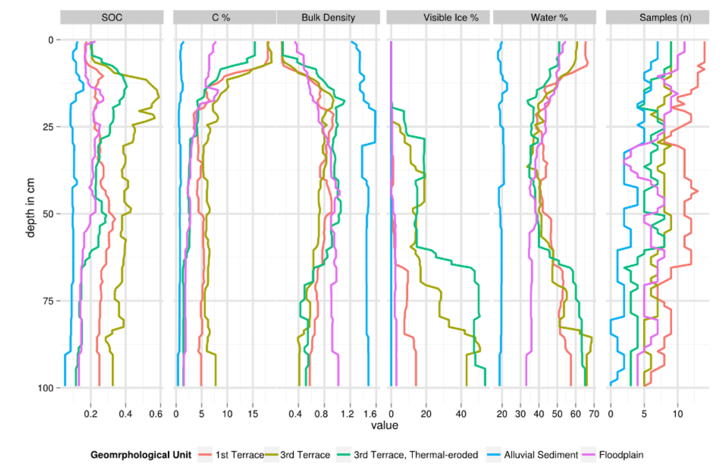




Detailed soil sampling and analsyis following soil horizons.



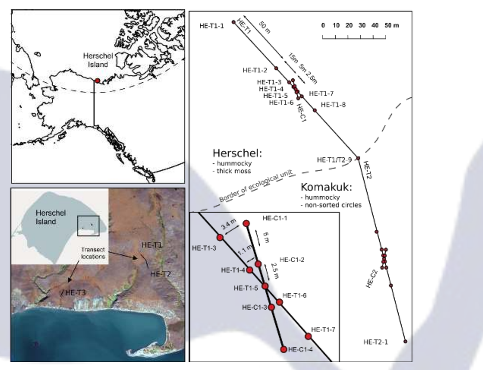
Land form classification without Digital elevation model (DEM) (a) and with DEM (b) showing market improvement using data-fusion.



High vertical variability of SOC and related key soil variables.

Study 3:

Siewert, M.B., Lantuit, H., Hugelius, G., in prep. **Spatial variability of soil organic carbon in tundra terrain at local scale.**



Nested spatial sampling sheme to investigate spatial autocorrelation

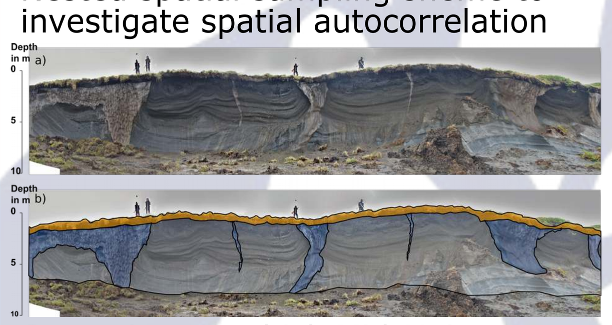
Key Findings

Issues of scale deserve special attention in permafrost environments due to repetitive patterns.

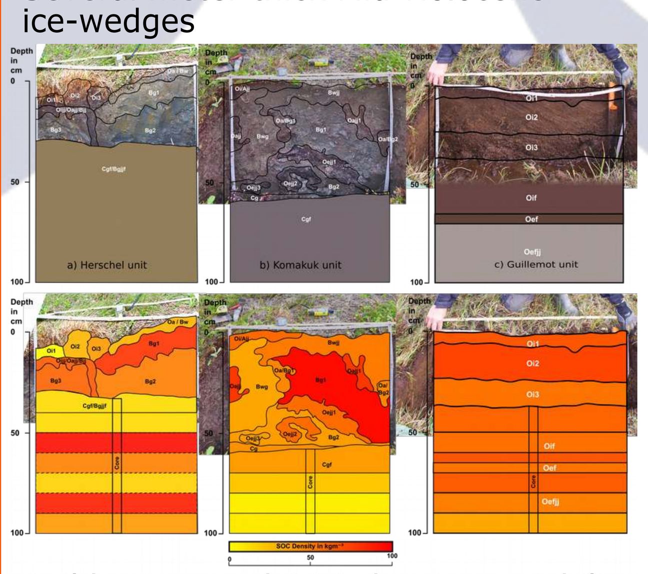
Patterns caused by landforms can have different age, controls and reactions to climate warming.

Spatial mapping should not be based on the assumption of spatial autocorrelation.

Applicable to hydrological, biogeochemical and microbiological processes.



Several meter thick Mid-Holocene ice-wedges



Soil horizon and SOC density variability for three typical tundra types.

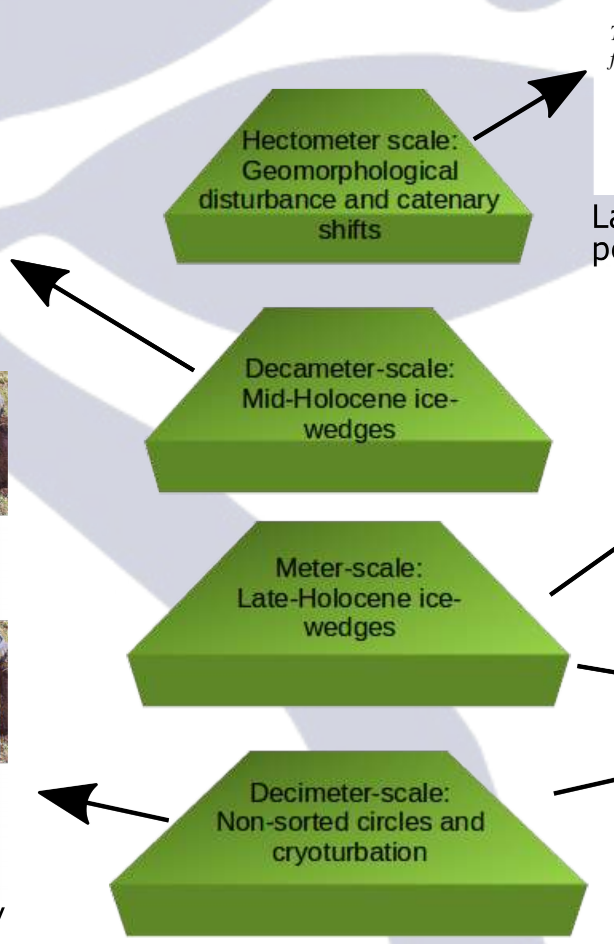
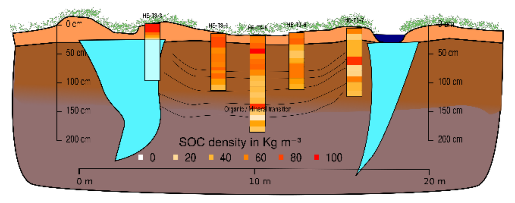


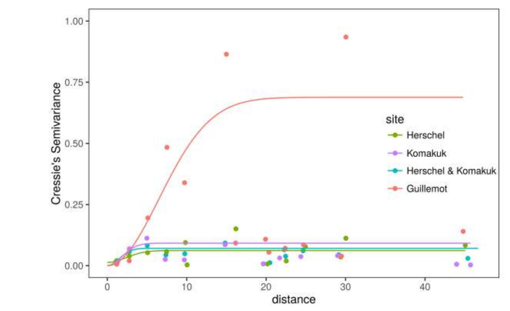
Table 2. Summary of the SOC values and active layer thickness (cm) and SOC values for several depth increments (kg m^{-2}) for the three analyzed ecological units.

Ecological Unit	Sites (n)	Active layer thickness (cm)	SOC Active layer	SOC Permafrost	SOC 0–30 cm	SOC 0–100 cm	SOC 0–100 cm (min.–max.)
Herschel	13	49.1 ± 36.9	21.4 ± 5.9	22.3 ± 6.2	11.6 ± 3.2	43.6 ± 9.7	25.7–60. 7
Komakuk	12	73.5 ± 21.2	29.1 ± 8.4	5 ± 1.4	14.6 ± 4.2	34.1 ± 7	23.7–47.7
Guillemot	11	40.5 ± 12.2	19.1 ± 5.8	20.7 ± 6.2	14.6 ± 4.4	39.8 ± 15.2	7.4–52.8

Landscape scale SOC variability from soil pedons.



SOC distribution in polygonal terrain with Late-Holocene ice-wedges.



Spatial variograms for different tundra types show no spatial autocorrelation.

Study 4:

Siewert, M.B. subm. **High-resolution digital mapping of soil organic carbon in permafrost terrain using machine-learning: A case study in a sub-Arctic peatland environment.**

Key Findings

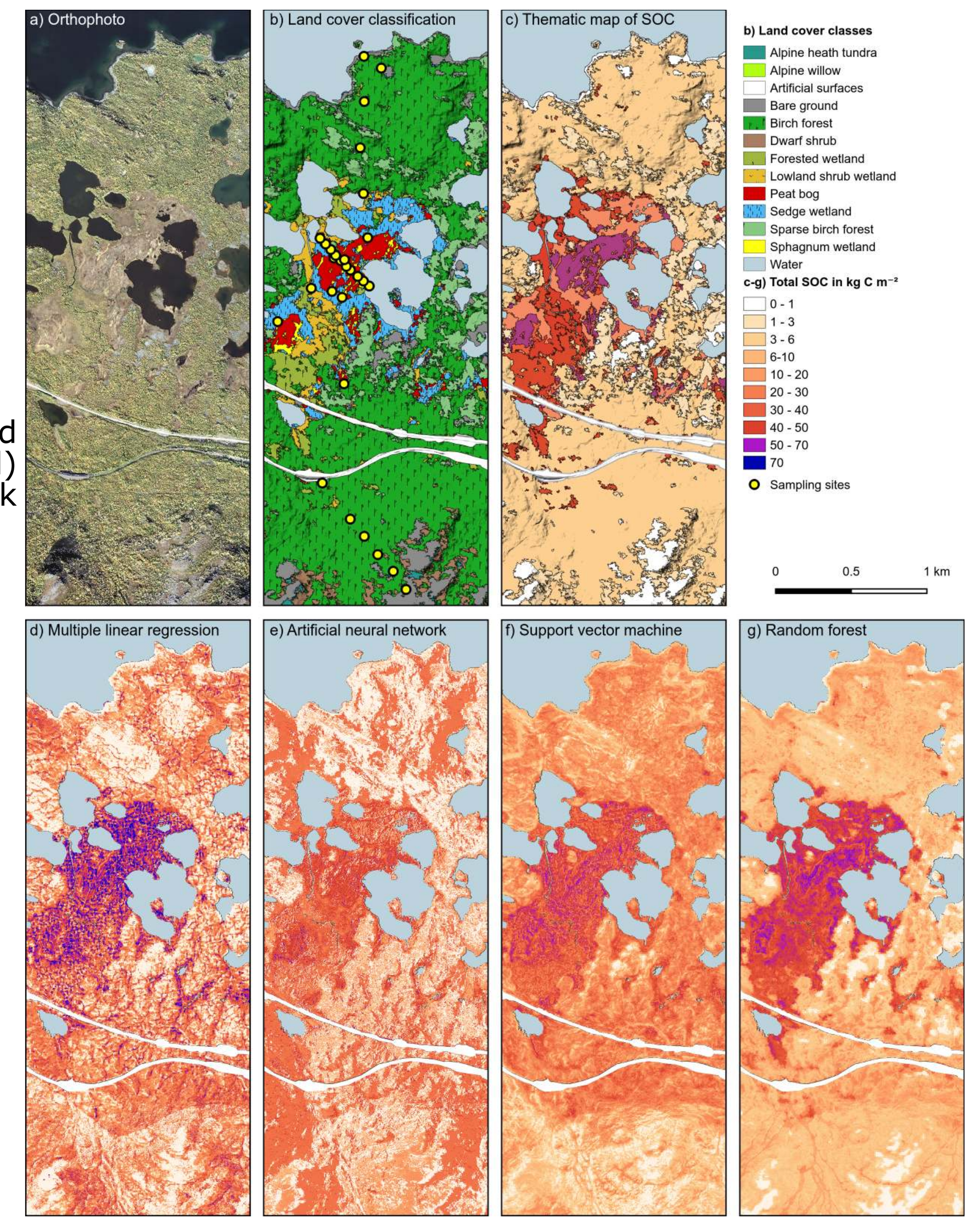
Digital soil mapping can significantly improve SOC estimates in permafrost environments.

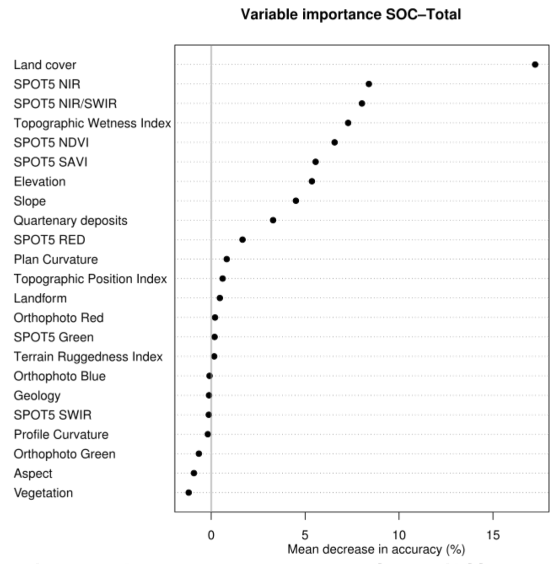
Random forest model performs best (R^2 = 0.936).

Most relevant predictive variables are:
- **Land cover**
- **Vegetation related satellite data**
- **Topographic variables**

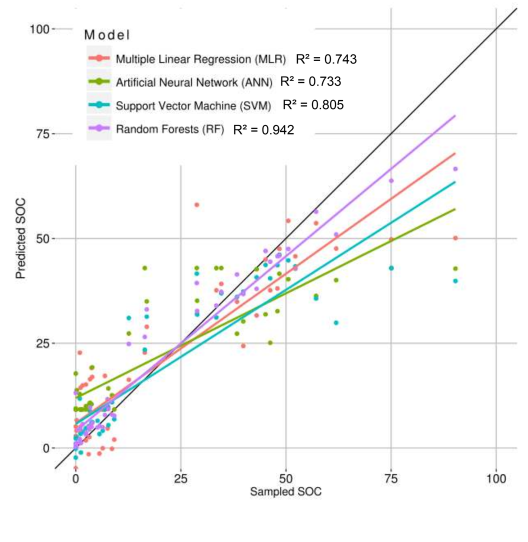
High-resolution approach (2x2 m) reveals many small wetlands and peatlands not yet addressed in the literature.

Digital soil mapping results from Abisko. a) Orthophoto. b) Land cover classification, c) SOC storage using thematic mapping. d) multiple linear regression model (MLR), e) artificial neural network (ANN), f) support vector machine (SVM), g) random forest (RF).





The importance of different predictor variables to estimate total SOC using a random forests model.



Performance of four different prediction models comparing sampled against predicted SOC values.