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Faculty of Science
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Soil formation and biological soil crust development in glacier forelands of Svalbard (High Arctic)

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1 Introduction and objectives

- Rapid enlargement of ice-free areas in glacier forelands in Arctic, Antarctic and Alpine regions over the last decades by progressive glacier melting induced by climate change [1]
- Biological soil crusts (BSC) formed by cryptogamic species on the surface as major component of tundra plant communities of glacier forelands
- BSC development and soil formation in glacier forelands being fundamental to future development of mature tundra contributing to an increase in soil organic carbon and nitrogen [2]
- Heterogeneous terrain and distance to the glacier terminus affecting spatial variation in soil and vegetation characteristics [3]
- Objective: Extracting relationships between soil, vegetation and terrain considering the importance of different scales to map the spatial variation in soil and vegetation characteristics in glacier forelands

2 Data and Methods

- Soil and vegetation samples from 104 locations in glacier forelands of Svalbard (Tab.1, Fig.1) [4]
- Multi-scale terrain covariates from ArcticDEM (2x2m) [5] using contextual soil mapping (CSM): 1) stepwise reduction of the resolution of the DEM (scales) 2) derivation of terrain covariates at each scale (Fig.2) [6]
- Spatial covariates using Euclidean distance fields for machine learning (EDM) (Fig.3) [7]
- Digital soil mapping (DSM) [8] using random forests (RF) [9] with the caret package [10] in R [11]

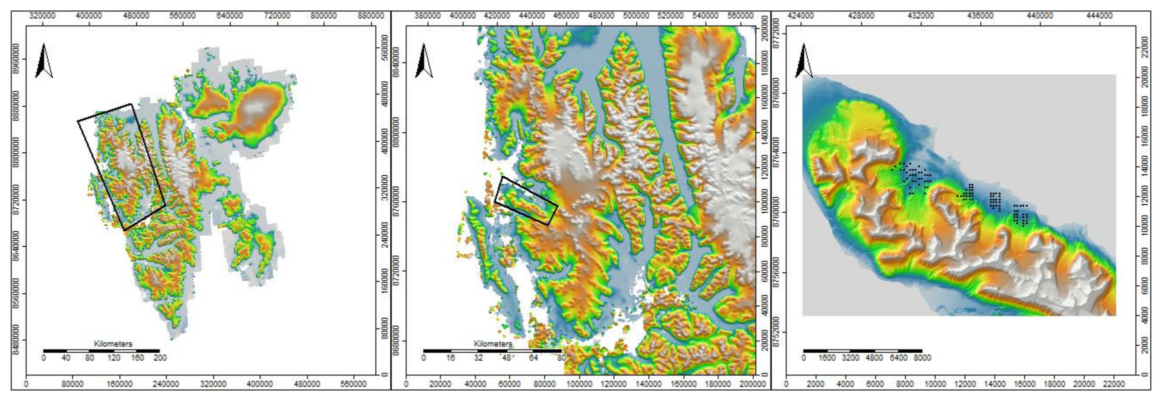


Fig.1: Sampling locations in forelands of Svalbard glaciers of Kongsfjorden area: Vestre Brøggerbreen, Austre Brøggerbreen, Vestre Lovénbreen, Midtre Lovénbreen and Austre Lovénbreen. (Map basis data from ArcticDEM [5])

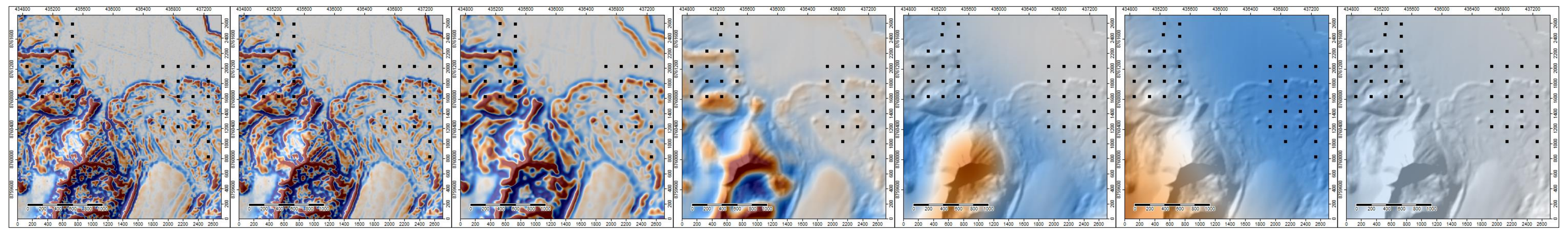


Fig. 2: Example of multi-scale terrain covariates: average curvature at seven different scales. Small-scale terrain characteristics (e.g. moraines) fade and general landscape elements (e.g. valley) emerge with larger scales (from left to right).

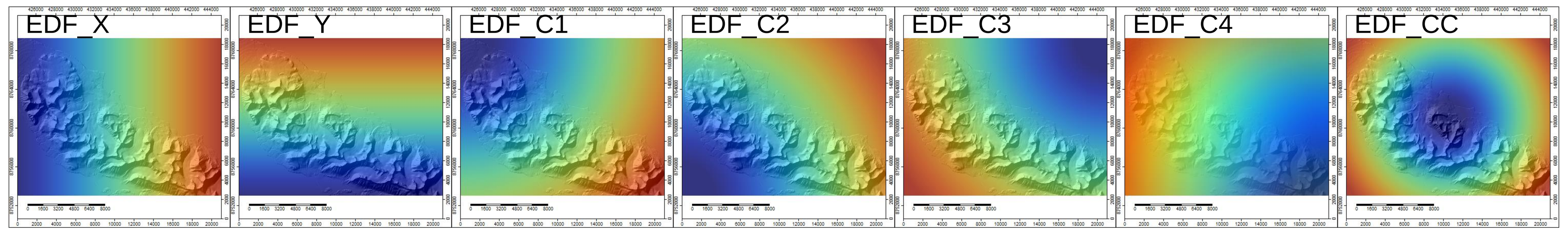


Fig. 3: Euclidean distance fields (EDF) representing the Euclidean distance to the left (EDF_X) and bottom boundary (EDF_Y), upper left (EDF_C1), lower left (EDF_C2), upper right (EDF_C3) and lower right corner (EDF_C4) and the center (EDF_CC) of the study area.

4 Results

	Observed				Model quality		Predicted			
	Min	Mean	Max	Sd	R^2	RMSE	Min	Mean	Max	Sd
BSC carbon (BSCC) [%]	2.50	12.58	33.16	7.68	0.44	6.38	4.95	12.66	24.93	5.14
BSC nitrogen (BSCN) [%]	0.12	0.54	1.27	0.29	0.33	0.24	0.25	0.54	0.96	0.18
Soil sand content (Sand) [%]	14.00	45.04	77.00	15.86	0.19	15.04	28.43	44.48	61.91	4.56
Soil silt content (Silt) [%]	22.00	49.54	77.00	13.13	0.14	12.76	36.36	49.86	63.80	3.49
Soil clay content (Clay) [%]	1.00	5.53	13.00	3.45	0.29	2.99	1.66	5.77	10.14	1.49
BSC cover (BSCcov) [%]	5.00	45.35	94.00	23.35	0.37	20.56	18.03	45.01	76.45	14.60
Vascular plant cover (Vplantcov) [%]	0.00	36.27	95.00	24.92	0.57	16.61	4.23	36.61	93.02	19.61

Table 1: Descriptive statistics of observed and predicted values of BSC carbon (BSCC), BSC nitrogen (BSCN), soil sand content (Sand), soil silt content (Silt), soil clay content (Clay), BSC cover (BSCcov) and vascular plant cover (Vplantcov) at 104 locations in glacier forelands on Svalbard.

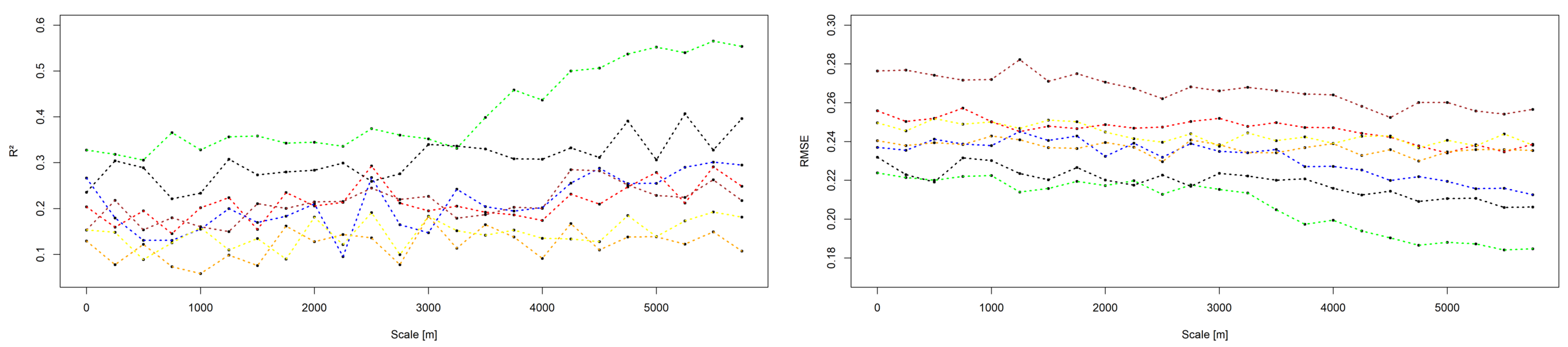


Fig. 4: Variation in RF model qualities (left: R^2; right: RMSE) for stepwise adding terrain covariates from next larger scale for BSCC (black), BSCN (blue), Sand (yellow), Silt (orange), Clay (brown), BSCcov (red) and Vplantcov (green).

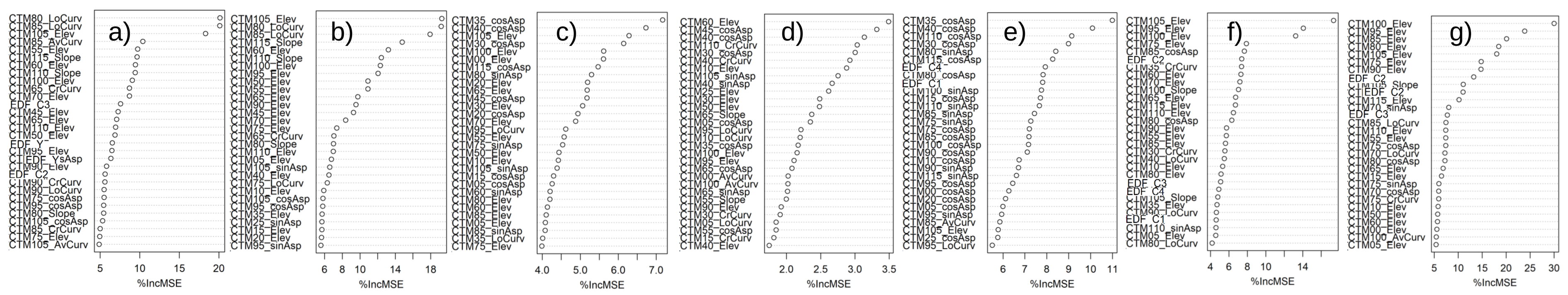
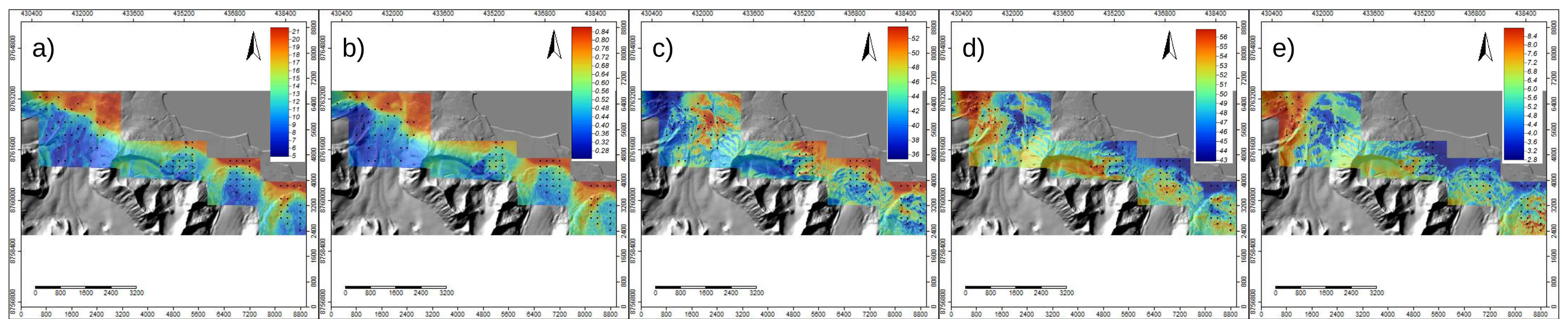


Fig. 5: Variable importance for BSCC (a), BSCN (b), Sand (c), Silt (d), Clay (e), BSCcov (f), Vplantcov (g). Elevation (Elev), average curvature (AvCurv), cross-sectional cur-vature (CrCurv), longitudinal curvature (LoCurv), northness (CosAsp), eastness (SinAsp), maximum slope (Slope).



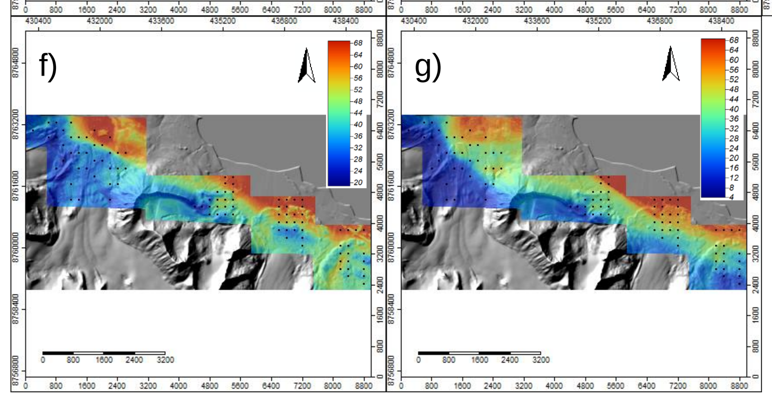


Fig. 6: Predicted spatial variation in BSCC (a), BSCN (b), Sand (c), Silt (d), Clay (e), BSCcov (f) and Vplantcov (g) using RF with multi-scale terrain and spatial covariates and soil and vegetation information from 104 sampling locations in forelands of Svalbard glaciers of Kongsfjorden area.

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4 Discussion

- RF model quality for vegetation characteristics (BSCC, BSCN, BSCcov, Vplantcov) improves with the additional usage of large-scale terrain covariates (Fig. 4). Large-scale longitudinal curvature (e.g. CTM80_ LoCurv) and elevation (e.g. CTM105_Elev) (Fig. 5) represent general landscape elements of the glacier forelands and EDF_C2 (Fig. 3; Fig.5) the distance to the glacier terminus both connected to the glacier retreat. BSCC, BSCN, BSCcov and Vplantcov increase with distance to the glacier terminus (Fig.6) due to longer time for vegetation evolution and soil formation [3].
- Small-scale variations in soil and vegetation in Arctic environments depend on geomorphological characteristics [3, 12, 13, 14] which are represented by small-scale terrain covariates (Fig. 5). By the usage of these covariates, the RF models can extract distinct differences in BSCC, BSCN and BSCcov between the glacier foreland and the mature tundra being shown in Fig. 6.
- For soil texture (Sand, Silt, Clay), there is no improve of the RF models with the usage of additional large-scale terrain covariates (Fig. 4). Due to relatively short time period since the glacier retreat, the modification in soil texture is low [15] and large-scale redistribution of fine material, e.g. through aeolian processes [16], plays a subordinate role. Therefore, the spatial variation in soil texture is linked to the geomorphology on a small scale (Fig. 6) represented by small-scale terrain covariates (Fig. 5).

5 Summary

- DSM in combination with ML is a suitable tool to extract complex relationships between terrain and both soil and vegetation.
- The multi-scale approach improves the understanding of the spatial variation in soil and vegetation by considering influencing factors acting on different scales.

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References: [1] Nuth et al., 2013, Cryosphere 7. [2] Rippin et al., 2018, DEMS Microbiol. Ecol. 94. [3] Wietrzyk et al., 2018, Plant Soil 428. [4] Wietrzyk et al., 2020, Sci. Total Environ. 717. [5] Porter et al., 2018. [6] Behrens et al., 2018, Geoderma 310. [7] Behrens et al., 2018, Eur J Soil Sci. 69. [8] McBratney et al., 2003, Geoderma 117. [9] Breiman, 2001, Mach. Learn 45. [10] Kuhn, 2017. [11] R Core Team 2017. [12] Wojcik et al., 2019, AAAR 51. [13] Gries et al., 2020, J Plant Nutr Soil Sci. [14] Henkner et al., 2016, Geoderma 282. [15] Matthews, 1992, CUP. [16] Müller et al., 2016, The Holocene 26.