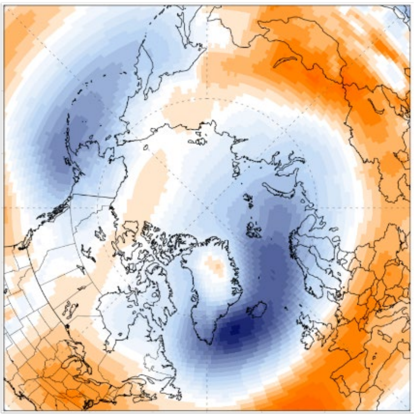

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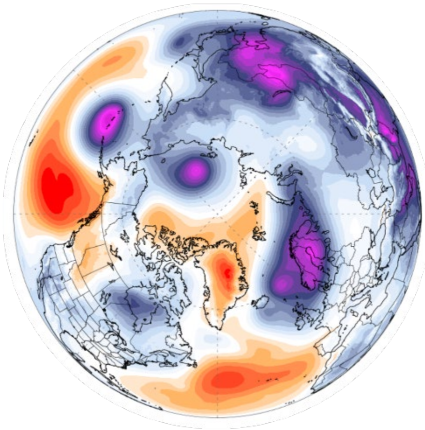

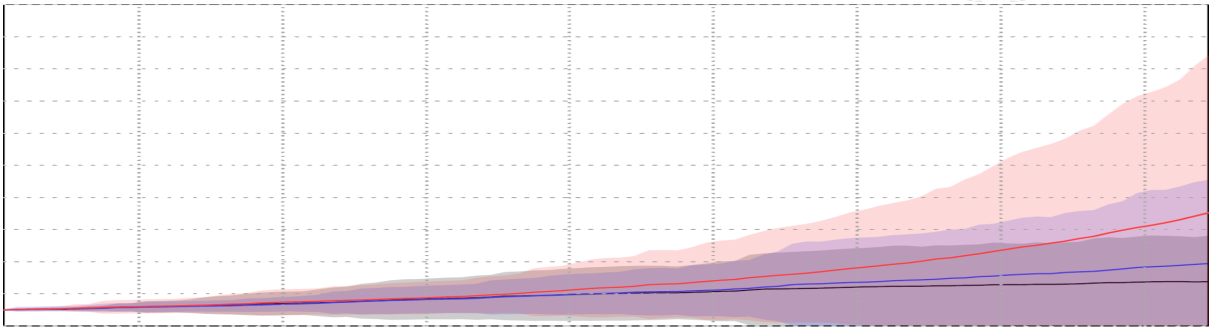

IMPLEMENTATION OF ‘BIOGEOENGINEERING’ SCENARIOS AND THE FACTORIAL SNOW MODEL

CHARTER Deliverable D5.3

Grant Agreement Number: 869471
Project Acronym: CHARTER
Project title: Drivers and Feedbacks of Changes in Arctic Terrestrial Biodiversity
Starting Date: 01/08/2020
Project Duration: 54 months
Project Officer: Alberto Zocchi
Project Coordinator: Bruce Forbes / LAY
Leading Author: Heidrun Matthes / AWI
Contributing partners: LAY, UEDIN

Co-financed by the Connecting Europe Facility of the European Union

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 869471

Implementation of 'biogeoengineering' scenarios and the Factorial Snow Model

CHARTER Deliverable 5.3
Version 2.0 (revised after the review)

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Project Officer: Alberto Zocchi
Project Coordinator: Bruce Forbes / LAY
Authors: Heidrun Matthes, Cécile Ménard, Chen Yangxin, Richard Essery, John Moore
Due Submission Date: 31/07/2023 (original due date was 31/07/2022; deadline extended after discussing with CHARTER PO)
Actual Submission Date: 30/08/2023
Revised version submitted: 29/11/2023

Status	
Draft	
Final	x

Type		
R	Document, report	x
DEM	Demonstrator, pilot, prototype	
DEC	Websites, patent fillings, videos, etc.	
OTHER		

Dissemination level		
PU	Public	
CO	Confidential, only for members of the consortium (incl. the Commission services)	x

Revision history

Date	Lead author(s)	Comments
20/07/2023	Heidrun Matthes	1st draft version
09/08/2023	Heidrun Matthes, Cécile Ménard, Chen Yangxin	2nd draft version
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29/11/2023	Heidrun Matthes, Chen Yangxin	Revised version 2.0; revised according to the comments given during the 36-month review, submitted

Short description of the deliverable

Within the framework of CHARTER, we developed 'biogeoengineering' scenarios with respect to reindeer herding as a 'nature-based solution' that could be used to mitigate climate change challenges. To explore these scenarios, model simulations with three different types of models were conducted. The Factorial Snow Model was run on a point scale, the regional Arctic climate model HIRHAM-CLM was run over a pan-Arctic domain, and the fully coupled global earth system model CESM2 was run globally, all of them with a focus on different herbivore management types.

This report describes the implementation of the different 'biogeoengineering' scenarios into the models, discussing the changes we made in physical parameters within the models to represent different herbivory densities, which forcing data was chosen for the modelling, and presents a very brief overview of some model results.

Purpose of the deliverable within the CHARTER research agenda

In task 5.2, we developed the 'biogeoengineering' scenarios for our modelling work. We decided to follow a "high reindeer number" and a "low reindeer number" scenario under different greenhouse gas futures. As there is no explicit representation of fauna in the models, the impact of herbivory on the environment has to be mimicked by modifying physical parameters in the models. WP1 and 2 provided extensive insight in perceiving herbivory as a driver of the environment, which were translated into physical parameters for the models to represent the different reindeer management scenarios.

Implementing these 'biogeoengineering' scenarios into the models enables us to analyze possible future impacts of different reindeer herding strategies on the environment, considering different future greenhouse gas developments. Specifically, we will be able to look at quality of life indicators for herders developed together with work packages 3 and 6 (climate indices for reindeer herding), as well as impacts on local climate change and cryosphere.

The resulting information will be shared with reindeer herders and their stake holders through work package 6, using the information on knowledge sharing that work package 6 has collected, especially concerning the way we present our results.

State of Work under D5.3

In the framework of task 5.3, models on 3 different scales are used. The Factorial Snow Model (FSM, Menard et al. 2014, Essery 2015), is a point model used for the analysis of grazing impacts on the process-level. HIRHAM-CLM (Matthes et al, 2017) is a state of the art regional climate model for the Artic that allows regional high resolution simulations to assess the impact of different grazing regimes on potential future Artic climate. CESM2 (Danabasoglu et al., 2020) is a global fully coupled earth system model that allows the analysis of global responses to regional changes in grazing.

Implementing the 'biogeoengineering' scenarios into these models required the translation of herbivory impacts onto the environment into physical parameters the models use in their descriptions of land surface processes. The different models used for task 5.3 chose different ways of doing that, using the results of task 5.2 and the review paper on the Ecosystem Effects of Reindeer published by WP2 (Stark et al, 2022).

The Factorial Snow Model considered changes in grazing pressure by changes on shrub abundance and snow compaction. To explore the impact of these changes, a series of sensitivity studies were conducted for two Arctic sites with adequate observational data, Trail Valley Creek and Saariselkä.

For the global earth system model CESM2 and the regional climate model HIRHAM-CLM, data from Stark et al. 2022 and other studies were used to characterize physical parameters in the models to reflect different grazing pressure. The review paper discusses the fact that most information regarding the impact of herbivory and reindeer in particular on the environment are based on exclosure studies. They also discuss that it is with the current data mostly not possible to find quantitative relationships between herbivory density and impact of herbivory on the environment. The existing quantitative information relates only to a removal of herbivores from the system.

In addition, because of the presence of herbivores in the Arctic, all existing large scale physical model parameters impacted by herbivory already contain the impacts of herbivory. For example, satellite derived vegetation distribution used in the models provides information on shrub abundance in the presence of herbivores, albedo data derived from satellite measurements reflects the abundance of ground lichens in the presence of herbivores. Our reference data sets therefore can be interpreted as a "biogeoengineering" scenario with high reindeer numbers. Based on the data from the exclosure studies summarized in Stark et al 2022, we constructed physical parameters for a scenario with low reindeer numbers. We refer to the high reindeer number scenario as the reference scenario, and to the low reindeer number scenario as the exclosure experiment.

This approach has been followed by the regional climate model used in CHARTER, leading to model simulations covering the time period 1990-2050 under three different greenhouse gas futures (SSP1-RCP2.6, SSP2-RCP4.5 and SSP5-RCP8.5) with boundary forcing from MRI-ESM-2-0 (Yukimoto et al, 2019).

The global model uses “high reindeer number” definitions following the suggestions of the Pleistocene Park scenario, representing a very high number of herbivores in the Arctic ecosystem, according to the approach presented in Beer et al 2020. Here, present day reindeer numbers are used to estimate biomass removal by reindeer, this is implemented into the model using the estimates in the existing capability of the model to simulate harvest. Snow compaction is modified according to Beer et al (2020). For the low reindeer number scenario, present day numbers of animals were estimated, for the high reindeer number scenario, the estimated numbers were tripled. Here, the present day parameters serve as values to describe the “low reindeer number” or reference scenario, while changes implemented for vegetation distribution, biomass removal and snow are characterizing the “high reindeer number”/”Pleistocene Park” scenario. Simulations cover the time period 2015-2045, using different greenhouse gas futures (SSP2-RCP4.5 and SSP5-RCP8.5).

Data Sources

Definitions of the SSPs come from the global climate change research community’s developments of ”Narratives for shared socioeconomic pathways describing world futures in the 21st century” (e. g. O’Neill et al, 2017). Associated Representative Concentration Pathways (RCPs) are taken from the Coupled Model Intercomparison Project Phase 6 Global emissions pathways under different socioeconomic scenarios (e.g. Gidden et al., 2019, Feng et al., 2020).

HIRHAM-CLM is a regional climate model and therefor requires lateral and lower boundary forcing from a global model. In order to represent Arctic processes well, we used the evaluation of the CMIP6 models provided by the GCMeval tool (Parding et al., 2020) as well as by Kolbe et al, 2023, to choose a suitable model, MRI-ESM-2-0 (Yukimoto et al., 2019). From this model, air temperature, wind, humidity on the original model levels are used as lateral boundaries, sea surface temperature and sea ice concentration are used as lower boundaries.

Physical parameter adjustments for the exclosure experiment were taken from a number of studies. Estimates of shrub abundance changes in exclosure sites come from den Herder et al

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(2008), Ravolainen et al (2011), Akujärvi et al (2014), Vowles et al (2017) and Sundqvist et al (2019). Estimates of differences in lichen abundance between exclosure sites and grazing sites were taken from den Herder et al (2003), Akujärvi et al (2014), Vowles et al (2017),Heggenes et al (2017) and Sundqvist et al (2019). Associations between lichen cover and albedo come from Cohen (2003), Aartsma et al (2020) and Finne et al (2023). Information about carbon storage was taken from Köster at al (2013), Köster et al (2015), Ylänne et al (2018) and Ylänne et al (2018).

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Results

Implementation of 'biogeoengineering' scenarios in the different models

This section presents a general schematic of how the environmental impacts of reindeer were implemented into the CHARTER modelling framework (Figure 1) as well as a detailed description of the implementation into each of the three models.

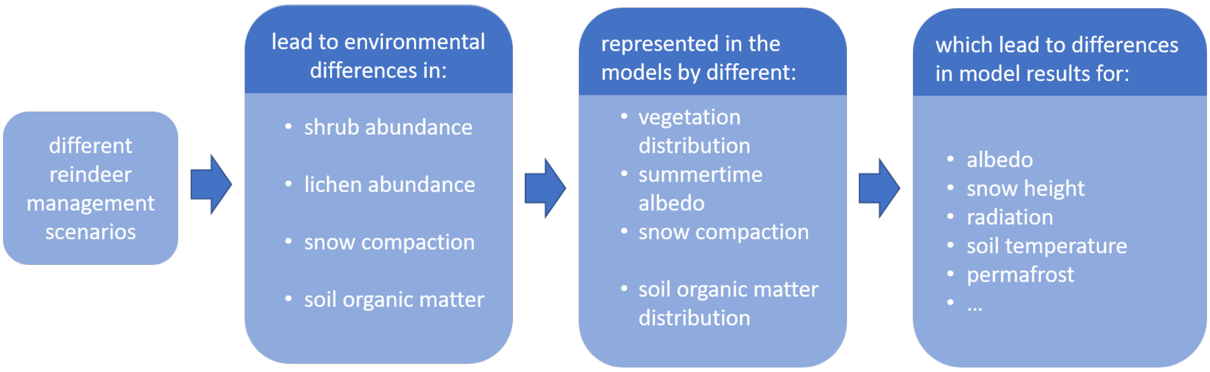

Figure 1 Schematic description of the implementation of reindeer impacts on the environment into the CHARTER modelling framework.

FSM

FSM has recently been extended to include a model for vertical interception of falling snow in trees. For CHARTER, this model is being further extended to represent horizontal trapping of windblown snow by shrubs and the influence of shrub branches exposed above the snow on surface energy balance (Menard et al. 2014). Because the shrub model is not ready yet, we instead present a sensitivity study here.

HIRHAM-CLM

We have implemented 4 different factors of reindeer impacts on the environment into our model, abundance differences in shrubs and ground lichen, snow density changes due to trampling and changes in the organic matter distribution throughout the soil due to trampling.

Vegetation distribution in the model is represented by plant functional types (pft), generalized descriptions of plant traits by functional groups. Changes in shrub abundance in exclosure sites are represented by changing the abundance of the pft associated with boreal deciduous shrubs on the expanse of Arctic grasses, as illustrated in Figure 2. From literature, we take an increase of shrubs of 15% as an average over the measurements presented in different studies.

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Since the model has no explicit representation of lichen as a plant functional type, we represent the changes in albedo caused by changes in abundance of ground lichen through reduced herbivory as changes in background albedo of the model. This works because tundra, where the shifts in the abundance of ground lichen influence albedo distinctively, is represented as a mixture of bare ground and Arctic grasses in the model, and the albedo of bare ground is consistent with the background albedo. Figure 3 illustrates this process, showing the abundance of bare ground in the model domain as well as the soil color class as representation of the background albedo. We assume an increase of ground lichen of 10% corresponds to a change of albedo from 0.01 to 0.02, which corresponds to a change of soil color class by 1.

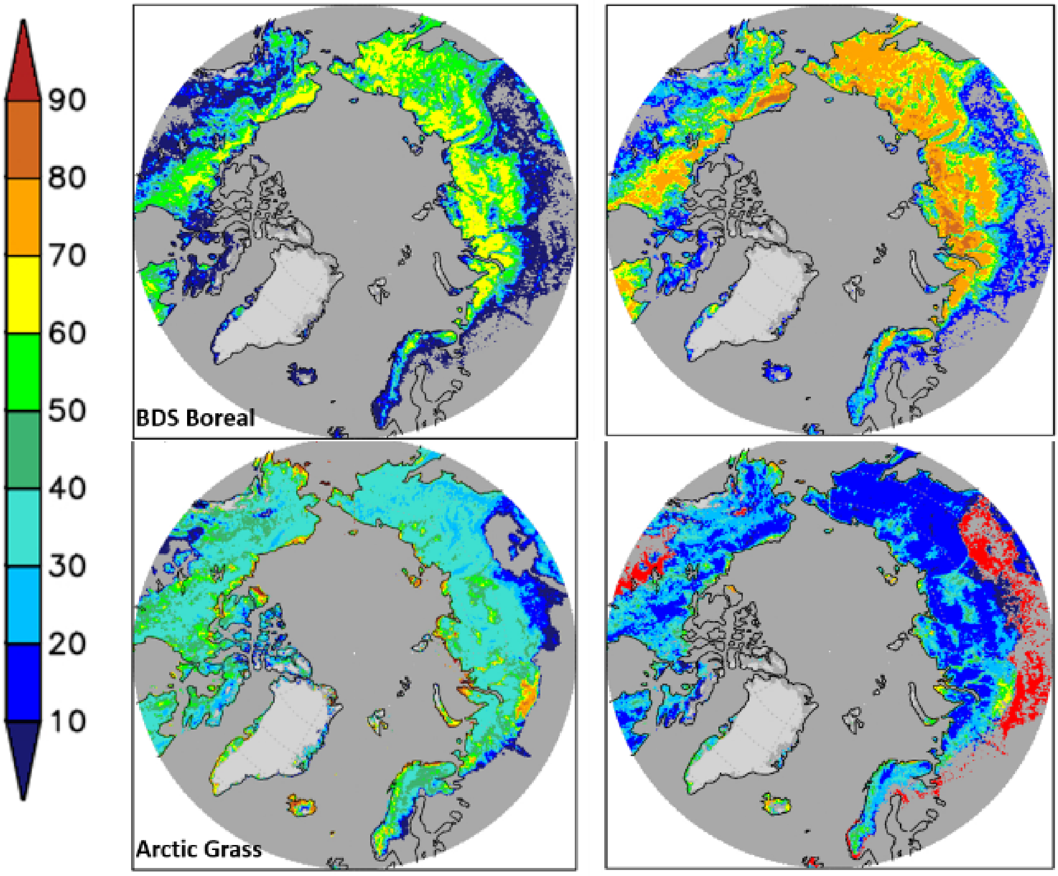

Figure 2: Abundance of the pft Boreal Deciduous Shrubs and Arctic Grasses in the standard model setup (top left, top right) and the exclosure experiment setup (bottom left for shrubs, bottom right for grasses).

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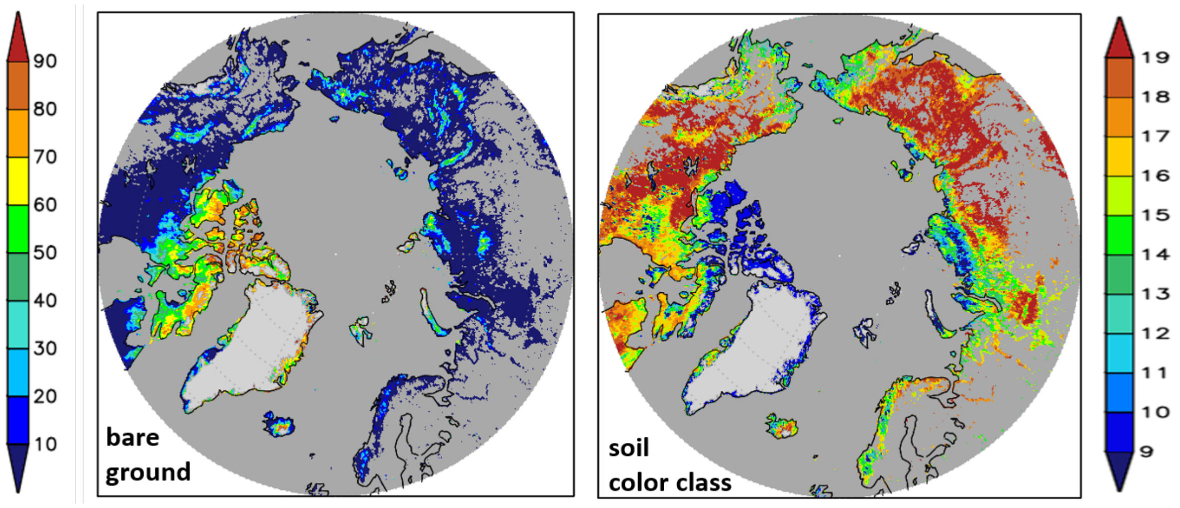

Figure 2: Bare ground distribution in the model (left) and soil color class (right).

Assessing the impact of excluding herbivores from the environment to snow density via trampling is difficult. Beer et al describe the impact of reindeer on measured snow depth for to sites where feeding craters are compared with undisturbed sites, and conclude that snow depth is significantly reduced in the feeding craters. In order to account for this effect, we modified the initial snow density in our model. This allows us to keep the processes within the snow model intact and identical in both model setups. Contrary to the vegetation distributions we use in our model that already reflect grazing in their standard setup, the snow model contained in the used land surface scheme was developed with observations from sites with no herbivory impact, so we cannot assume that the parameters in this model already reflect the impact of herbivores. Therefor, we modified initial snow densities in the reference run to mimic the impact of trampling on the snow. From the feeding experiment data shown in Beer et al (2020), snow density in the feeding crater is around 4.5 times higher than in the exclosure site (assuming similar snow water equivalents in both sites and using the median heights of the distributions). This data reflects extreme trampling that only occurs very locally, but gives a general guidance on an upper boundary of possible snow density modification by trampling. We chose to multiply the initial snow density with a factor of 1.5 in comparison with the standard setup, which leads to an initial snow density distribution of the standard setup for the exclosure experiment, while the reference setup has higher initial snow densities (Figure 4).

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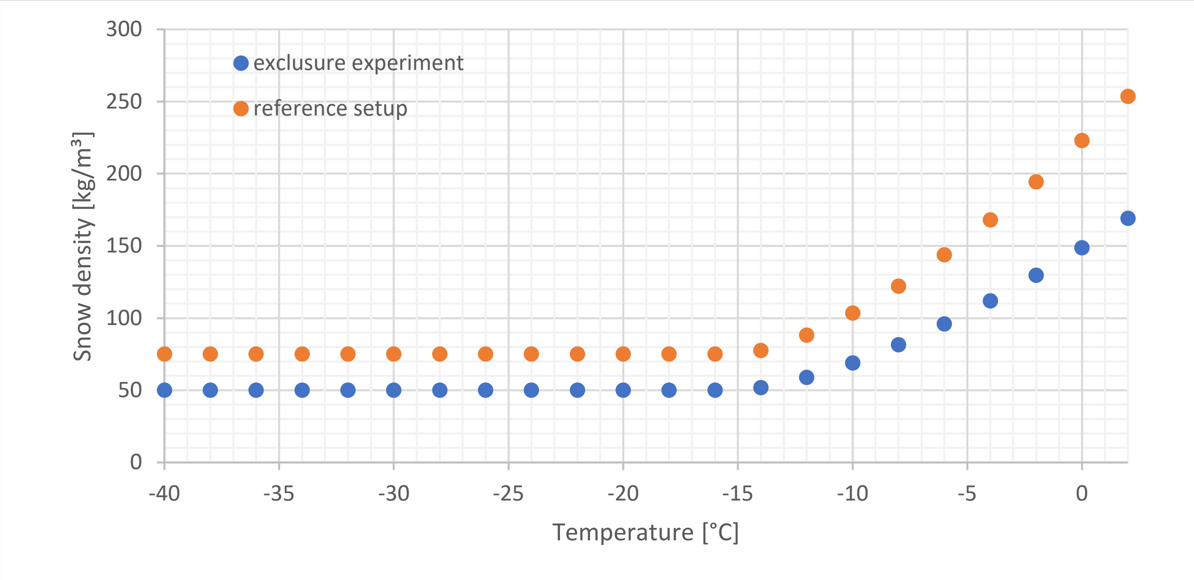

Figure 4: Initial snow density in the model, standard model setup for the exclosure experiment and modified dependency for the reference setup.

In exclosure sites, thicker organic soil layers were found in comparison to grazed areas, but with an overall similar carbon storage, associated with the erosion of the top soil layers by trampling. In the model, organic soils are represented using an assignment of organic matter content (OMC) to each soil layer in each grid cell up to a depth of 3.6m. In order to account for a higher OMC in the exclosure experiment, we increased the OMC by 10% in the upper four soil layers (up to a depth of 15.5cm) where that was possible. The model considers 130kg/m³ OMC as an upper boundary that may not be exceeded, so the changes in soils with very high OMC content was less pronounced. Figure 5 demonstrates the OMC of the upper for soil layers from the reference setup as well as the changes we imposed. In order to keep the total carbon storage of the soil column constant, we removed the appropriate amount of OMC in layers 5 and 6 of each column, overall affecting the soil column up to a depth of 46cm.

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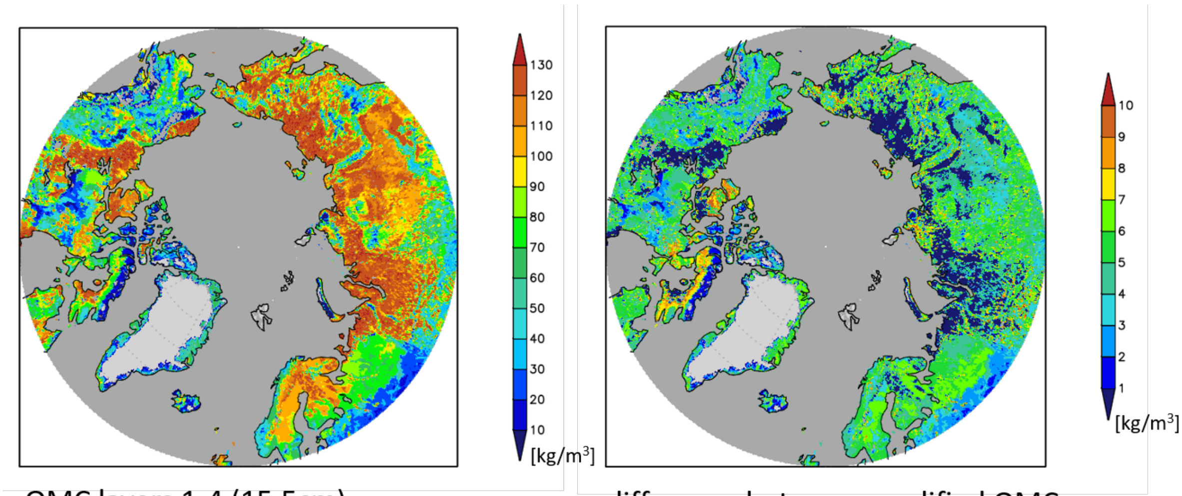

OMC layers 1-4 (15,5cm)

difference between modified OMC (layers 1-4) and original OMC

Figure 5: Organic matter content of the upper 4 soil layers of the reference setup (left panel) and changes imposed for the exclosure experiment (right panel).

CESM2

The global model CESM2-WACCM is used to implement the 'pleistocene park' simulation (Zimov 2012, Porada 2016, Beer 2020). This model is a fully coupled earth system model (with active simulations of ocean, ice, land and atmosphere) and active carbon cycling. To mimic the very high herbivore densities suggested by the Pleistocene Park experiment, the following impact are considered: Higher snow trampling is represented by an increase of snow compaction with the age of snow, increasing compaction by overburden pressure and melt metamorphism. The effects of trampling on vegetation are included in the model by changing the turnover times for grasses and mosses. The impacts of grazing are represented by changing the mortality rates of the plant functional types that reindeer feed on.

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Model outputs

FSM

To demonstrate the impact of changes in snow insulation as they can be associated with the presence of reindeer, simulations with FSM for two different locations with extensive measurements are shown (Figure 6): Trail Valley Creek and Saariseklä. Figure 7 shows the snow depth and 5 cm soil temperature under snow from the Trail Valley Creek simulation in Figure 8, labelled as the control experiment. To mimic removal of snow by wind in an exposed, shrub-free location, another simulation was performed with the input snowfall halved; this clearly reduces the snow depth and also reduces the soil temperature because of the decrease in snow insulation. In another simulation with the original snowfall but with snow on the ground compacted to match depths in the simulation with reduced snowfall, the soil temperature is further decreased because compaction increases the thermal conductivity of the snow.

Figure 6: Locations used for demonstrating model results for the snow model FSM (Saariselkä, Trail Valley Creek) and the regional climate model HIRHAM-CLM (Saariselkä, Taymir Peninsula, Eastern Siberia).

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The marginal influence of snow insulation decreases for snow depth greater than about 50cm (Slater et al. 2017). Snow sensitivity experiments for Saariselkä (Figure 8) still have noticeable differences in soil temperature, but the differences are reduced because of the wetter and milder climate than Trail Valley Creek.

Trapping of snow by shrubs and resulting insulation is generally thought to increase winter soil temperatures (Kropp et al. 2021). Domine et al. (2022), however, have suggested that shrubs can act as thermal bridges through the snow and decrease soil temperatures; this process is not currently represented in models.

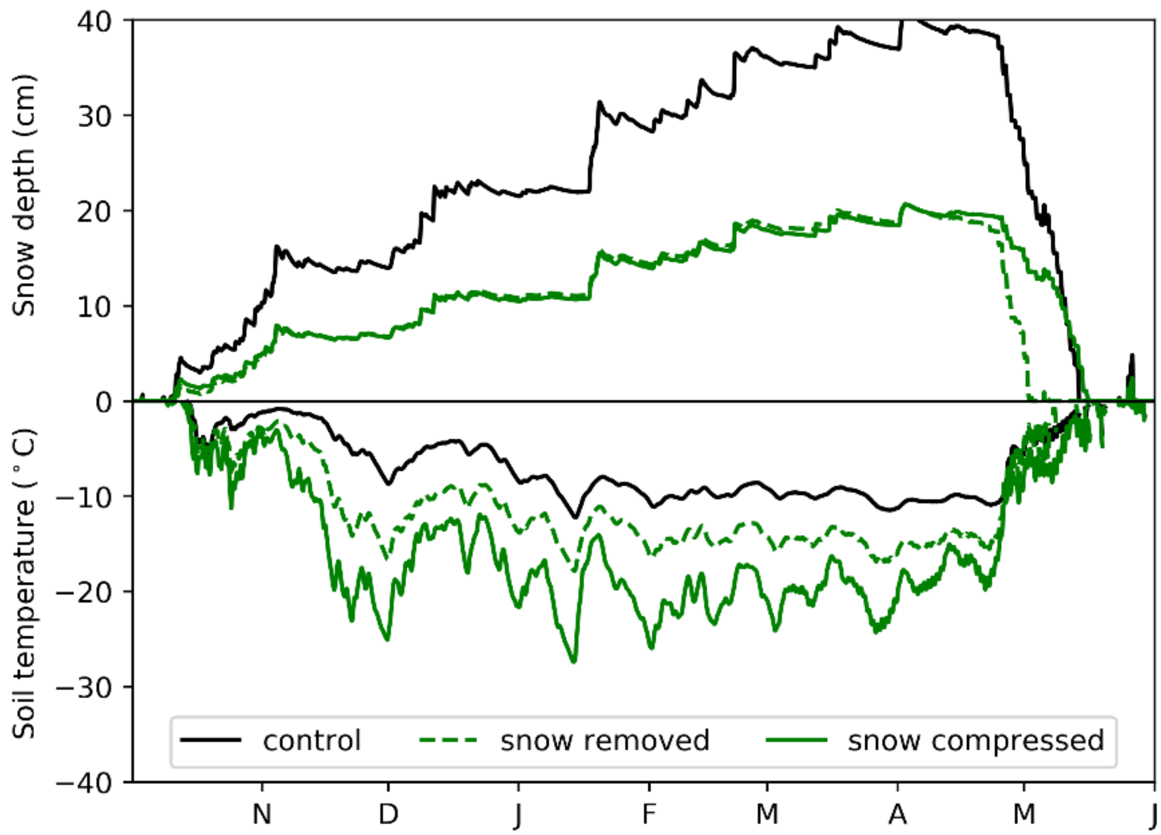

Figure 7: Snow depth and soil temperature in the 2017-2018 control simulation for Trail Valley Creek and experiments with snow either removed or compacted.

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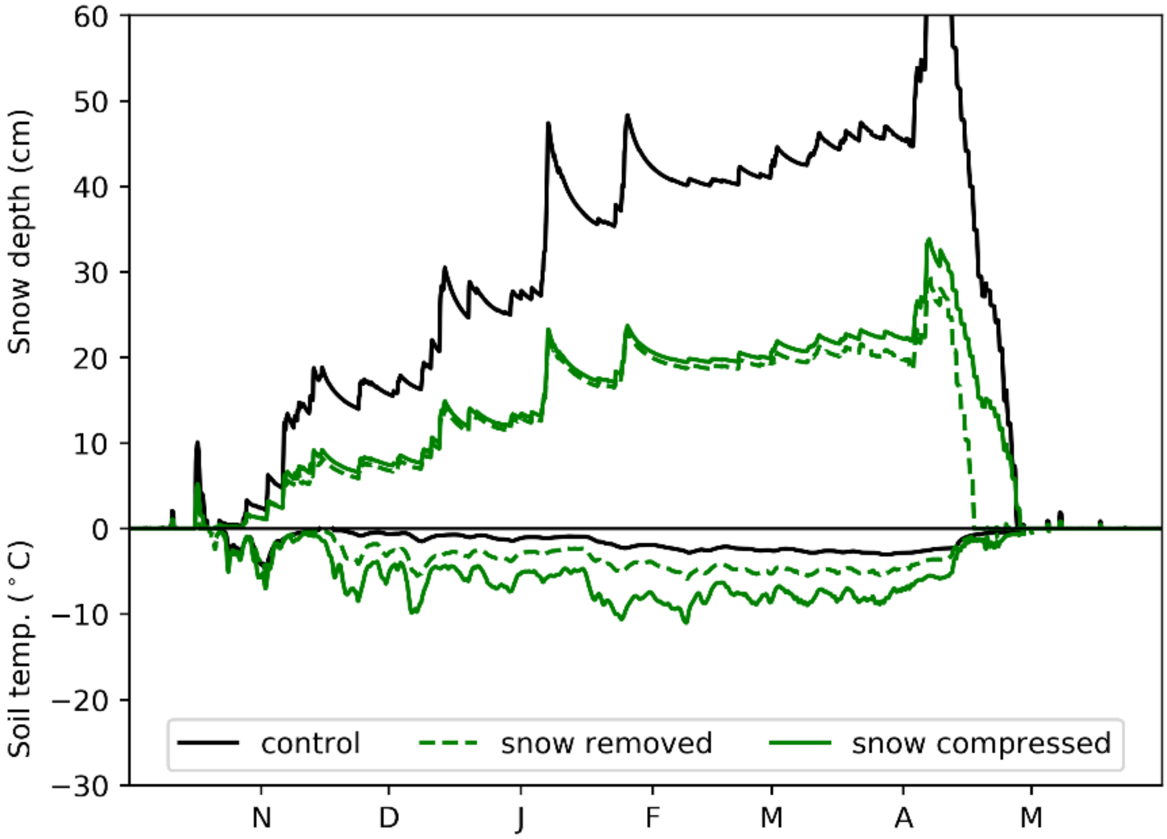

Figure 8: As Figure 5, but for Saariselkä in 2017-2018.

HIRHAM-CLM

The results of implementation of the exclosure experiment concerning soil temperatures was analyzed from the historical simulations. The combination of all changes leads to distinct differences in modelled soil temperatures, the amplitude of the differences depends on the location of the grid cell. Snow density modifications lead to differences in snow insulation, the impacts are larger the colder the forcing air temperatures are. Moving OMC from lower to higher soil layers in the other hand increases the thermal insulation of the lower soil layers, counteracting the snow insulation effect to some degree. The changes in background albedo only impact the summer surface energy balance, and are expected to have a cooling effect on soil temperatures. The changes in shrub abundance have a multitude of possible impacts, the most distinct ones are on surface albedo in the transition seasons (when there is snow on the ground and sunlight) and on roughness length, which changes the vertical fluxes in the atmosphere.

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Figure 9 shows soil temperature simulations from a location at Saariselkä, on Taymir peninsula and in Eastern Siberia (see locations of points in Figure 5) for the reference setup and the exclosure experiment. Soil temperatures are affected in all depths, and are generally are lower for the exclosure experiment. Impacts on winter time temperatures are more distinct than on summer time temperatures, indicating that overall impacts on active layer depth are small. Differences also increase with depth.

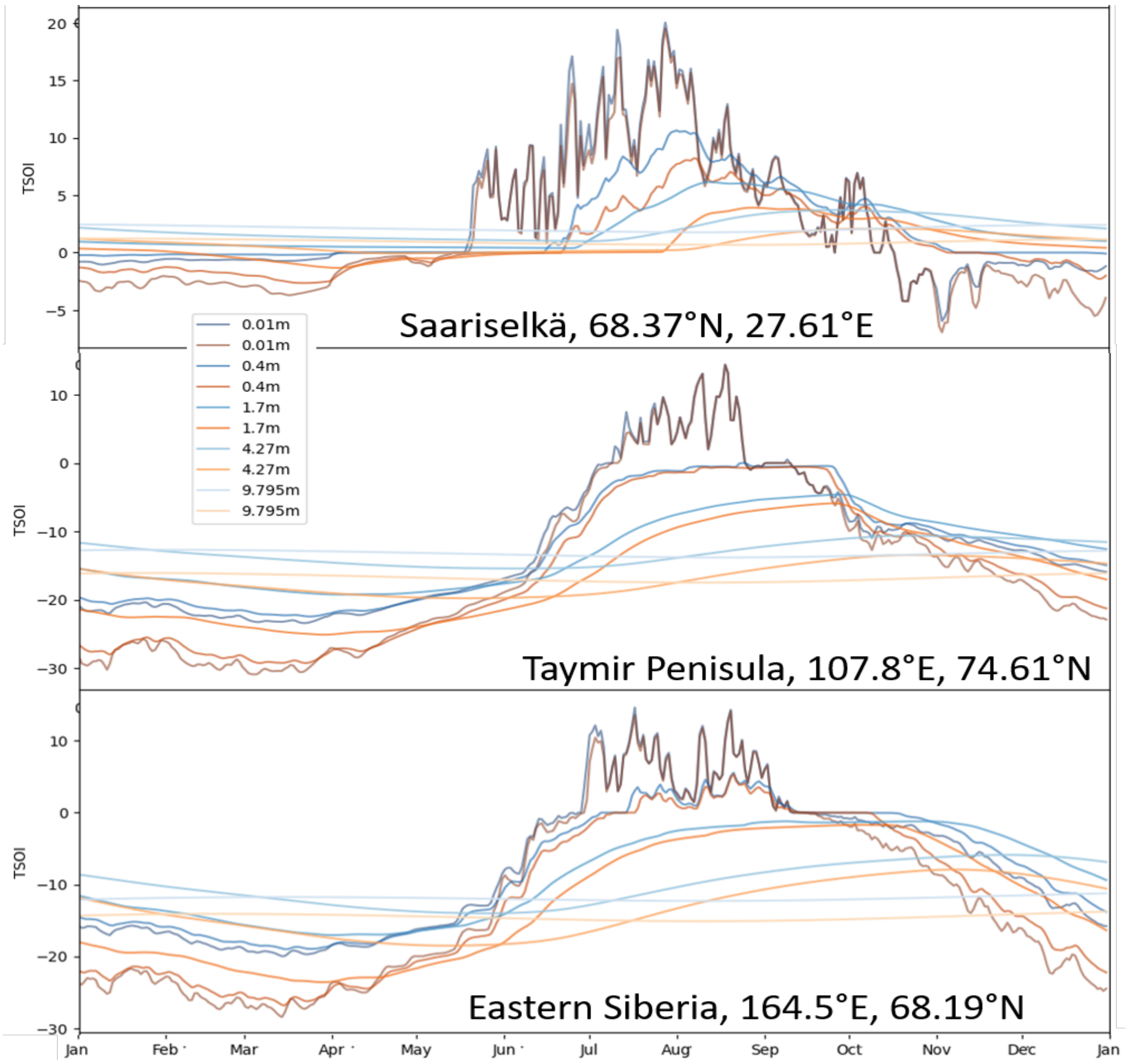

Figure 9: Soil temperature simulations at two different locations under historical forcing and for the two different scenarios. Blue lines show the reference simulation, orange lines the exclosure experiment.

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CESM2

To assess the impact of the modifications in snow through trampling and their effect on soil temperature, the effective snow depth (snd_{Eff}) in each year is calculated as the mean snow depth across the snow season (starts in October this year at the earliest, and ends in March next year at the latest). During 2035-2050, the snd_{Eff} is generally thinner north of 60°N under the "high reindeer number" scenarios (RHM) than for the reference/"low reindeer number" scenarios (SSP), leading to lower soil temperature across the year, with annual mean differences of 0.38 /0.81 ^{o}C, and the largest cooling in late winter or early spring of 0.69/1.22 ^{o}C, under ssp245 and ssp585, respectively (Figure 10).

The cooling effects of large herbivore trampling in the snow protect about 0.13 million km^2 of near-surface permafrost from thawing under SSP2-RCP4.5 and about 0.61 million km^2 under SSP5-RCP8.5. Permafrost area in the model is calculated from active layer thickness, each grid cell with an active layer thickness below 3m is considered permafrost. The shallower active thickness across the majority of the permafrost region apparent in the "high reindeer number" scenario would expose less soil carbon vulnerable to microbial decomposition under these scenarios (Figure 11).

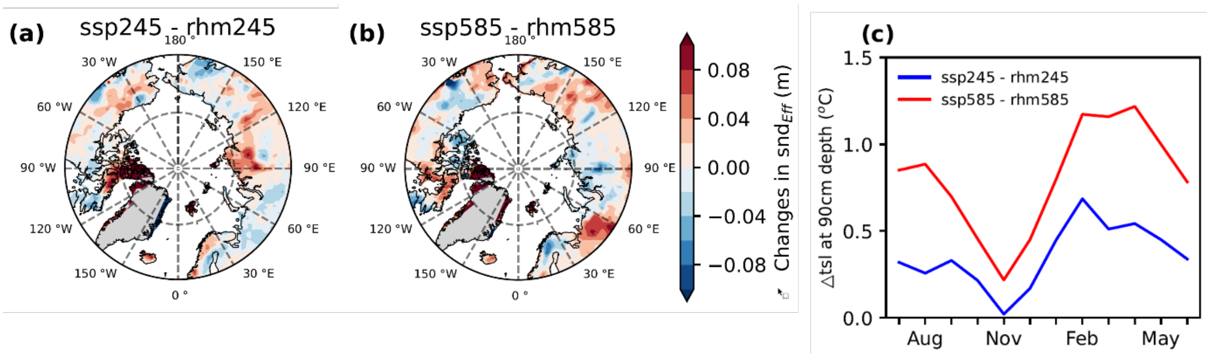

Figure 10: Simulated changes during 2035-2050. Changes in (a-b) effective snow depth in 60 degrees north and (c) soil temperature at 90 cm depth in reindeer herding region.

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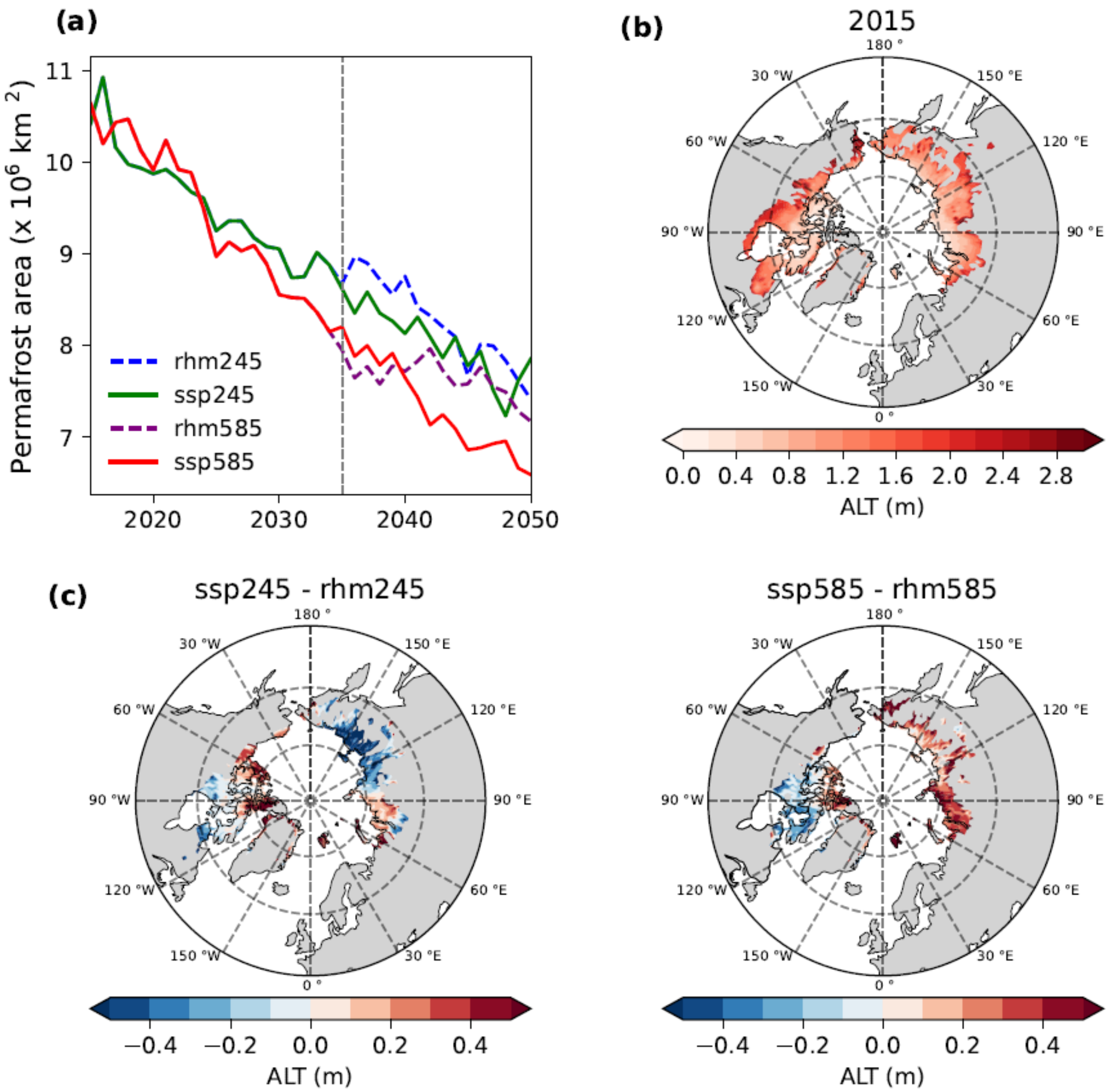

Figure 11: Comparisons of permafrost area and active layer thickness. (a) Timeseries of permafrost area changes, (b) active layer thicknesses in year 2015 and (c-d) changes in active layer thicknesses between SSPs and "high reindeer number" scenarios.

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Next Steps

Representation of the Arctic snowpack in ESMs and snow physics models

The way snow layers are built in FSM and in ESM snow models is historically linked to snow physics models having first been developed for avalanche forecasting, i.e. for mid-latitude snowpacks with fine lose grains of low density at the top and dense compacted grains at the bottom. In addition, most models do not or poorly simulate the strong thermal gradients between the soil/snow interface and the snow/air interface. As a consequence, the effect of these gradients on the structure of the snowpack is absent. This limits our confidence in the information provided by snow models for ecological applications and when investigating carbon-permafrost feedback as both need detailed information about snowpack structure and thermal properties. We have decided to address these long-standing issues in CHARTER. Our approach involves interviewing snow physics and ESM modelers, as well as stakeholders, to understand why snow models have yet to be developed to simulate Arctic snowpack properties. Additionally, we aim to identify new challenges that could be addressed if progress is made in this field. The results of these investigations will be presented in an upcoming report.

Analysis of regional and global model runs

In cooperation with WP3 and WP6, we have developed a number of climate indices that quantify the quality of a year with respect to successful reindeer herding. These indices were already calculated from CMIP6 models and from the CORDEX EURO-11 ensemble to provide a frame of reference for the future development of these indices under different greenhouse gas scenarios. From these multi-model simulations, we were also able to calculate uncertainties of these developments.

We will repeat this analysis for the 'biogeoengineering' scenarios, which will allow us to quantify the impact of different herbivore management options onto the climate indices relevant for herding work.

Making data available to a broad community

A subset of the data sets produced from the models will be made available through the respective HPC centers of the institutes that are responsible for the model runs, providing a doi for the data for easy citation and usage. We will focus on the variables identified for the climate indices for reindeer herding (see above).

References

Aartsma, P., Asplund, J., Odland, A., Reinhardt, S., & Renssen, H. (2020). Surface albedo of alpine lichen heaths and shrub vegetation. *Arctic, Antarctic, and Alpine Research*, *52*(1), 312-322. https://doi.org/10.1080/15230430.2020.1778890

Akujärvi, A., V. Hallikainen, M. Hyppönen, E. Mattila, K. Mikkola, Rautio, P. (2014): Effects of reindeer grazing and forestry on ground lichens in Finnish Lapland. *Silva Fennica, 48*, article id 1153. https://doi.org/10.14214/sf.1153

Beer, C., Zimov, N., Olofsson, J. et al. (2020): Protection of Permafrost Soils from Thawing by Increasing Herbivore Density. *Scientific Reports* *10***,** 4170 (2020). https://doi.org/10.1038/s41598-020-60938-y

Cohen, J., Pulliainen, J., Ménard, C. B., Johansen, B., Oksanen, L., Luojus, K., Ikonen, J. (2013): Effect of reindeer grazing on snowmelt, albedo and energy balance based on satellite data analyses. *Remote Sensing of Environment* *135*, 107–117. https://doi.org/10.1016/j.rse.2013.03.029

Danabasoglu, G., Lamarque, J. F., Bacmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., ... & Strand, W. G. (2020). The community earth system model version 2 (CESM2). *Journal of Advances in Modeling Earth Systems*, *12*(2), e2019MS001916.

den Herder, M., R. Virtanen, Roininen, H. (2008): Reindeer herbivory reduces willow growth and grouse forage in a forest-tundra ecotone. *Basic and Applied Ecology, 9*(3), 324-331. https://doi.org/10.1016/j.baae.2007.03.005

den Herder, M., M.-M. Kytöviita, Niemelä, P. (2003): Growth of reindeer lichens and effects of reindeer grazing on ground cover vegetation in a Scots pine forest and a subarctic heathland in Finnish Lapland. *Ecography, 26*, 3-12. http://www.jstor.org/stable/3683520

Domine, F., Fourteau, K., Picard, G. *et al.* Permafrost cooled in winter by thermal bridging through snow-covered shrub branches. *Nature Geosciences, 15*, 554–560 (2022). https://doi.org/10.1038/s41561-022-00979-2

Essery, R. (2015). A factorial snowpack model (FSM 1.0). *Geoscientific Model Development*, *8*(12), 3867-3876. https://doi.org/10.5194/gmd-8-3867-2015

Feng, L., Smith, S. J., Braun, C., Crippa, M., Gidden, M. J., Hoesly, R., Klimont, Z., van Marle, M., van den Berg, M., van der Werf, G. R. (2020): The generation of gridded emissions data for CMIP6, *Geoscientific Model Development, 13*, 461–482. https://doi.org/10.5194/gmd-13-461-2020

Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D. P., van den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J. C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., Horing, J., Popp, A., Stehfest, E., Takahashi, K. (2019): Global emissions pathways under different socioeconomic scenarios for use in CMIP6:

a dataset of harmonized emissions trajectories through the end of the century, *Geoscientific Model Development, 12*, 1443–1475. https://doi.org/10.5194/gmd-12-1443-2019

Heggenes, J., Odland, A., Chevalier, T., Ahlberg J., Berg, A., Larsson, H., Bjerketvedt, D.K. (2017): Herbivore grazing – or trampling? Trampling effects by a large ungulate in cold high-latitude ecosystems. *Ecology and Evolution, 7*, 6423-6431. https://doi.org/10.1002/ece3.3130

Köster, K., Berninger, F., Köster, E., & Pumpanen, J. (2015). Influences of reindeer grazing on above-and belowground biomass and soil carbon dynamics. *Arctic, Antarctic, and Alpine Research*, *47*(3), 495-503. https://doi.org/10.1657/AAAR0014-062

Köster, E., Köster, K., Aurela, M., Laurila, T., Berninger, F., Lohila, A., & Pumpanen, J. (2013). Impact of reindeer herding on vegetation biomass and soil carbon content: a case study from Sodankyla, Finland. *Boreal Environment Research*, *18*(6), 35-43.

Kolbe, M., Bintanja, R., & van der Linden, E. C. (2023). Seasonal and regional contrasts of future trends in interannual arctic climate variability. *Climate Dynamics*, 1-34. https://doi.org/10.1007/s00382-023-06766-y

Kropp, H., Loranty, M. M., Natali, S. M., Kholodov, A. L., Rocha, A. V., Myers-Smith, I., ... & Lund, M. (2020). Shallow soils are warmer under trees and tall shrubs across Arctic and Boreal ecosystems. *Environmental research letters*, *16*(1), 015001. https://doi.org /10.1088/1748-9326/abc994

Matthes, H., Rinke, A., Zhou, X., & Dethloff, K. (2017). Uncertainties in coupled regional Arctic climate simulations associated with the used land surface model. *Journal of Geophysical Research: Atmospheres*, *122*(15), 7755-7771. https://doi.org/10.1002/2016JD026213

Ménard, C. B., Essery, R., & Pomeroy, J. (2014). Modelled sensitivity of the snow regime to topography, shrub fraction and shrub height. *Hydrology and Earth System Sciences*, *18*(6), 2375-2392. https://doi.org/10.5194/hess-18-2375-2014

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., et al. (2017): The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global environmental change, 42*, 169-180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Parding, K. M., Dobler, A., McSweeney, C. F., Landgren, O. A., Benestad, R., Erlandsen, H. B., ... & Loukos, H. (2020). GCMeval–An interactive tool for evaluation and selection of climate model ensembles. *Climate Services*, *18*, 100167. https://doi.org/10.1016/j.cliser.2020.100167

Ravolainen, V. T., Bråthen, K. A., Ims, R. A., Yoccoz, N. G., Henden, J. A., & Killengreen, S. T. (2011). Rapid, landscape scale responses in riparian tundra vegetation to exclusion of small

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and large mammalian herbivores. *Basic and Applied Ecology*, *12*(8), 643-653. https://doi.org/10.1016/j.baae.2011.09.009

Stark, S., Horstkotte, T., Kumpula, J., Olofsson, J., Tømmervik, H., & Turunen, M. (2022). The ecosystem effects of reindeer (Rangifer tarandus) in northern Fennoscandia: Past, present and future. *Perspectives in Plant Ecology, Evolution and Systematics*, 125716. https://doi.org/10.1016/j.ppees.2022.125716

Slater, A. G., Lawrence, D. M., & Koven, C. D. (2017). Process-level model evaluation: a snow and heat transfer metric. *The Cryosphere*, *11*(2), 989-996. https://doi.org/10.5194/tc-11-989-2017

Sundqvist, M. K., Moen, J., Björk, R. G., Vowles, T., Kytöviita, M. M., Parsons, M. A., & Olofsson, J. (2019). Experimental evidence of the long-term effects of reindeer on Arctic vegetation greenness and species richness at a larger landscape scale. *Journal of Ecology*, *107*(6), 2724-2736. doi.org/10.1111/1365-2745.13201

Vowles, T., Gunnarsson, B., Molau, U., Hickler, T., Klemedtsson, L., & Björk, R. G. (2017). Expansion of deciduous tall shrubs but not evergreen dwarf shrubs inhibited by reindeer in Scandes mountain range. *Journal of Ecology*, *105*(6), 1547-1561. https://doi.org/10.1111/1365-2745.12753

Ylänne, H., Madsen, R. L., Castaño, C., Metcalfe, D. B., & Clemmensen, K. E. (2021). Reindeer control over subarctic treeline alters soil fungal communities with potential consequences for soil carbon storage. *Global Change Biology*, *27*(18), 4254-4268. https://doi.org/10.1111/gcb.15722

Ylänne, H., Olofsson, J., Oksanen, L., & Stark, S. (2018). Consequences of grazer-induced vegetation transitions on ecosystem carbon storage in the tundra. *Functional Ecology*, *32*(4), 1091-1102. https://doi.org/10.1111/1365-2435.13029

Yukimoto, S., Kawai, H., Koshiro, T., Oshima, N., Yoshida, K., Urakawa, S., ... & Ishii, M. (2019). The Meteorological Research Institute Earth System Model version 2.0, MRI-ESM2. 0: Description and basic evaluation of the physical component. *Journal of the Meteorological Society of Japan. Ser. II*, *97*(5), 931-965. https://doi.org/10.2151/jmsj.2019-051

Zimov, S. A., Zimov, N. S., Tikhonov, A. N., Chapin Iii, F. S. (2012): Mammoth steppe: a high-productivity phenomenon. *Quaternary Science Reviews, 57*, 26-45. https://doi.org/10.1016/j.quascirev.2012.10.005