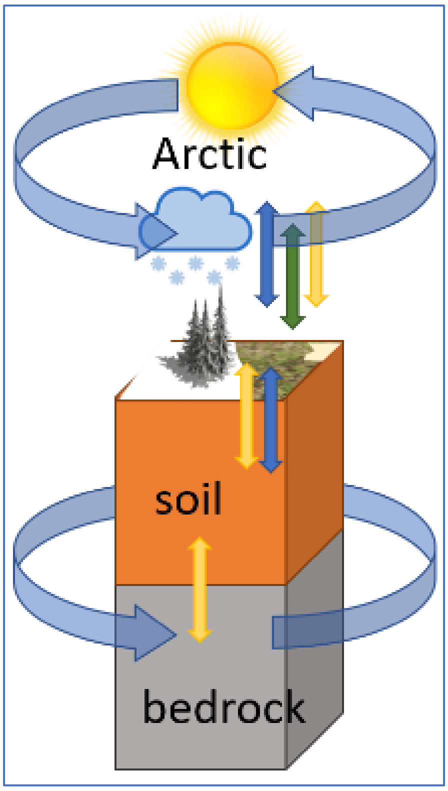

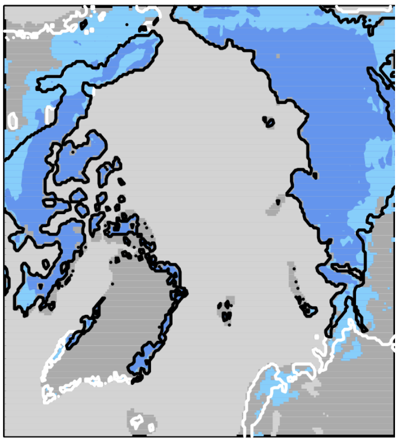

DEFINITION OF ‘BIOGEOENGINEERING’ SCENARIO EXPERIMENTS

CHARTER Deliverable 5.2

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: 48 months
Project Officer: Alberto Zocchi
Project Coordinator: Bruce Forbes / LAY
Author: AWI
Contributing partners: UHAM, LAY, UH, NINA, NMBU, UmU, UZH, BGEOS, UEDIN

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

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Due Submission Date: 31/01/2022 (original due date was 31/07/2021; deadline extended until the end of January 2022 after discussing with CHARTER PO)
Actual Submission Date: 31/01/2022

Status	
Draft	
Final	x

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

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

Revision history

Date	Lead author(s)	Comments
24/01/2022	Heidrun Matthes	1st draft version
28/01/2022	Heidrun Matthes, John Moore, Jussi Eronen, Gabriela Schaepman-Strub	2nd draft version
31/01/2022	Heidrun Matthes	Final version 1.0, submitted

Short description of the deliverable

The climate modelling work in CHARTER is based on the idea that we can incorporate findings from all other work packages (WPs) on biodiversity changes, ongoing climate change, changes in land use, and possible and desirable futures of reindeer herding in different communities into specific 'biogeoengineering' scenarios. This term is meant to refer to 'nature-based solutions' that could be used to mitigate climate change challenges. Results of model runs exploring these scenarios are then analyzed and compared, looking at quality of life indicators for herders as well as impacts on local climate change and cryosphere.

This report describes the "construction" of these 'biogeoengineering' scenarios, considering different socio-economic pathways, impacts of reindeer on the environment and the local agenda of the peoples in the region. In addition, to further examine impacts of large herbivores on permafrost landscape and the climate, a mammoth tundra-steppe rangeland (typified by the Pleistocene Park in Siberia), as an end-member of potential alternative large herbivore management scenarios is implemented in a global earth system model.

Purpose of the deliverable within the CHARTER research agenda

The 'biogeoengineering' scenarios defined here lay out the framework for regional climate modelling within CHARTER, integrating data from other work packages and producing information for other work packages. The modelling will provide a projection of possible impacts of different reindeer herding strategies on the environment, considering different future climate change developments.

WP1 and 2 provide extensive insight in perceiving herbivory as a driver of the environment as well as into climate change impacts on biodiversity, local climate and herding as a livelihood ('biogeoengineering'). The results from these work packages define the physical parameters that form the basis of implementing different reindeer management scenarios into the CHARTER models.

The resulting model runs will allow an assessment of

1. the differing effectivity that different strategies in herding might have in terms of adaptability to effects of climate change
2. the possibilities of regulating global climate feedbacks through different methods of herbivory management (both for wild ungulates as well as livestock)

This analysis will provide input for WP6, producing quantitative data for the "co-development of land use and biodiversity narratives and policy options that support Arctic adaptation and mitigation strategies and increase resilience of Arctic local communities and livelihoods."

State of Work under D5.2

For the definition of the ‘biogeoengineering’ scenarios, various tasks had to be considered:

1) the shared socio-economic pathways (SSPs) and associated Representative Concentration Pathways (RCPs) developed for the IPCC framework as a basis of driving climate change
2) the association of physical parameter sets to specific impacts of reindeer/ungulates on the environment
3) Consideration of the local agenda of the peoples in the region.

In close cooperation with WP6, we decided on the combination of SSPs and associated RCPs we will use. We settled on the following set: SSP1 + RCP2.6 (sustainable green road + low emissions), SSP2+RCP4.5 (middle of the road socio-economic pathway + close to current emission trajectory), and SSP5+RCP8.5 (fossil fuel driven development + high emissions). We assessed which impacts of ungulates on the environment can be translated into physical parameters used in the setup of our climate models. In addition, we collected results from literature as well as from other work packages that indicate relationships between these physical parameters and ungulate density. We also collected information on current managed and wild ungulate density in the Arctic from literature and WP2 and 3.

Due to the Covid-19 situation, field work and stakeholder interaction as planned in the project were largely postponed. Considering the agenda of local people in the Arctic in our construction of future ‘biogeoengineering’ scenarios is therefore at the moment limited to information on policy and land use strategies analysed by WP6. As a first approximation, we will consider extreme ends “possible futures” (high ungulate density versus low ungulate density) to create an envelope of possible future developments. The results of those simulations will then be taken to the local people/stakeholders in year 3 of the project as a basis for discussion, so that we can adjust our narratives based on that.

For the mammoth-tundra-steppe rangeland, model adjustments were defined to mimic mammoth impacts on the environment. In addition, improvements in the albedo parameterization of the snowpack have been realized to allow better representation of dirt in snow, density, and thin snow packs (Wang et al 2022).

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).

Data for different parameters describing functional relationships between ungulate density and environmental parameters are provided by WPs 1 and 2 as well as literature (e.g. the literature review worked on by WP 2). Data on ungulate density (managed and wild) as well as migratory systems for managed reindeer are provided by WPs 2 and 3 as well as from the CARMA network (https://carma.caff.is/index.php)

Results

Shared Socio-economic Pathways and associated Representative Concentration Pathways for 'biogeoengineering' scenarios

From the framework of the shared socio-economic pathways and associated representative concentration pathways, we decided to implement SSP126, SSP245 and SSP585.

SSP126 represents the pathway for the 2°C global warming target of the Paris agreement and will be explored as an optimal possible future. SSP245 represents the current global warming curve and will be used as an estimate of a likely future development. Since there are possible economical benefits to overshoot scenarios (a scenario where the projected rise in global temperature exceeds 2°C temporarily, but drops below this goal at the end of the century), we will emulate an overshoot scenario using emissions and land use from SSP585 as a proxy, although the abundant fossil fuel resources use in SSP5 is not desirable. Since our modelling will cover a time period until the mid of this century, the temperature decline of an overshoot scenario will be outside the modelling range.

Reindeer management options and association of physical model parameters to the impacts of ungulates/herbivores on the environment

A. Impact of ungulates on the environment and parameter association for modelling

Large herbivores impact the environment through a number of processes related to animal behaviour, most prominently grazing, trampling, defecating and browsing (e.g. Bernes et al. (2015), Heggenes et al. (2017), Sundqvist et al. (2019), Barthelemy et al. (2015), Moen et al. (2003)). Impacts can be seasonally varying (e. g. Manseau et al. (1996), Kumpula et al. (2011)) and may strongly depend on management (wild herds, largely free herds that follow similar migratory patterns as wild herds, strongly managed herds, e. g. Kumpula et al. (2014)), herbivory density and vegetation zone (e.g. dry boreal forests versus herbaceous tundra, Sundqvist et al. (2019)). Figure 1 presents an overview of the relations between animal behaviour and environmental impact in a qualitative way without specific consideration of the functional structure of those relationships.

Land surface models typically do not contain explicit representation of fauna. The influence of animals on land surface processes have therefore to be mimicked through parameter changes that can be associated with animal impacts. WP 2 is working on a review paper on this topic, focussing on two aspects: (1) summarizing field study results on the impacts of large herbivores on specific environmental parameters (e. g. species abundance, soil nutrient cycles, vegetation structure) and (2) the dependencies of these impacts on external factors like land use history, migratory patterns or vegetation zones. In addition, a number of studies have discussed the implications of those impacts, for example extensive modification of albedo due to trampling and grazing and its impacts on the surface energy balance (e. g. Zimov et al. (2012), Cohen et al. (2013)). Literature taken from the WP2 review has been extensively used to assess which parameter modifications in our land surface model can be used to emulate the impact of herbivores on the environment.

Land surface models use a column structure to represent area dependent differences in physical parameters characterizing the environment in the model. Figure 2 gives a schematic overview of one such column (often also referred to as grid cell) with various types of vegetation, depth dependent soil characteristics and partial snow cover, listing some of the parameters that can be changed to emulate herbivory impact (Figure 2c). "On top" of the land surface column, there is the atmospheric column, which provides meteorological input for the land surface model and is in turn influenced by the land processes via an exchange in heat, moisture and momentum fluxes (Figure 2a). The impact of herbivores on plant species abundance could for example be emulated by changing the vegetation distribution (plant functional types, pft) in the model. The effect of trampling on the density of the snow pack could be implemented by changing the intensity of snow compaction. Soil characteristics of the top soil layer could be changed to again account for trampling.

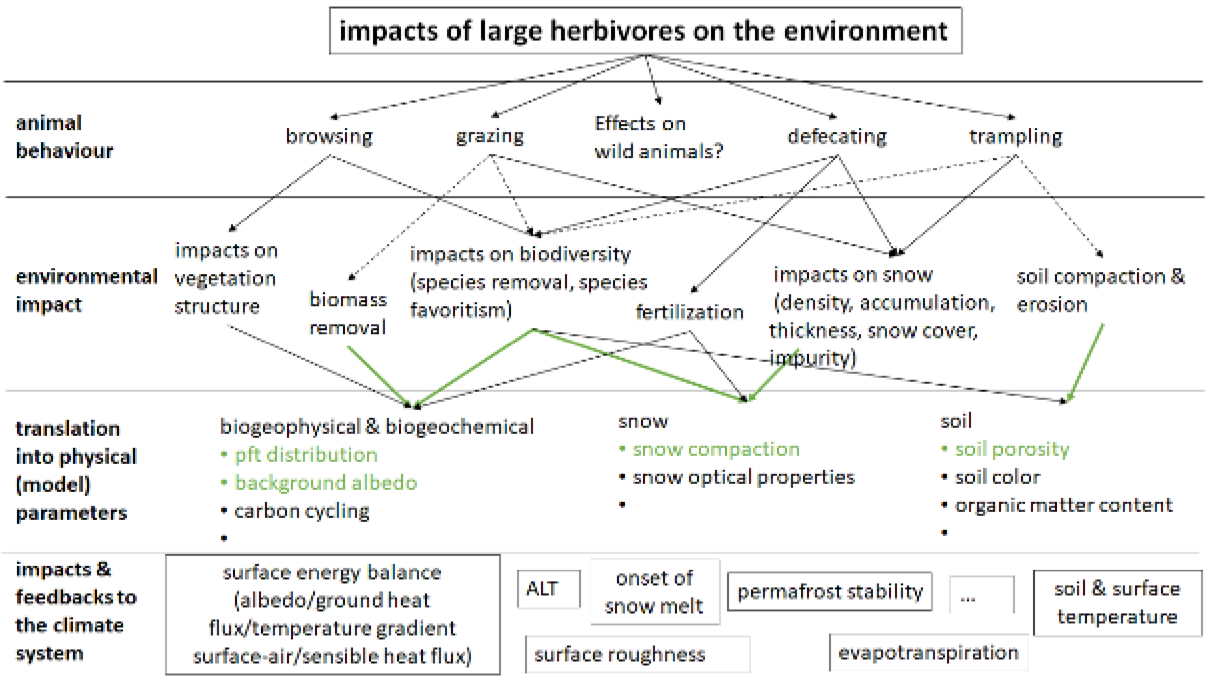

Figure 1: Overview of (systematic) impacts of large herbivores on the environment. Strong seasonal impacts are marked with dashed lines (e.g. where the impact on summertime pastures is different from the impact on wintertime pastures). Processes and associated parameter changes that will be considered in the 'biogeoengineering' scenarios are marked in green.

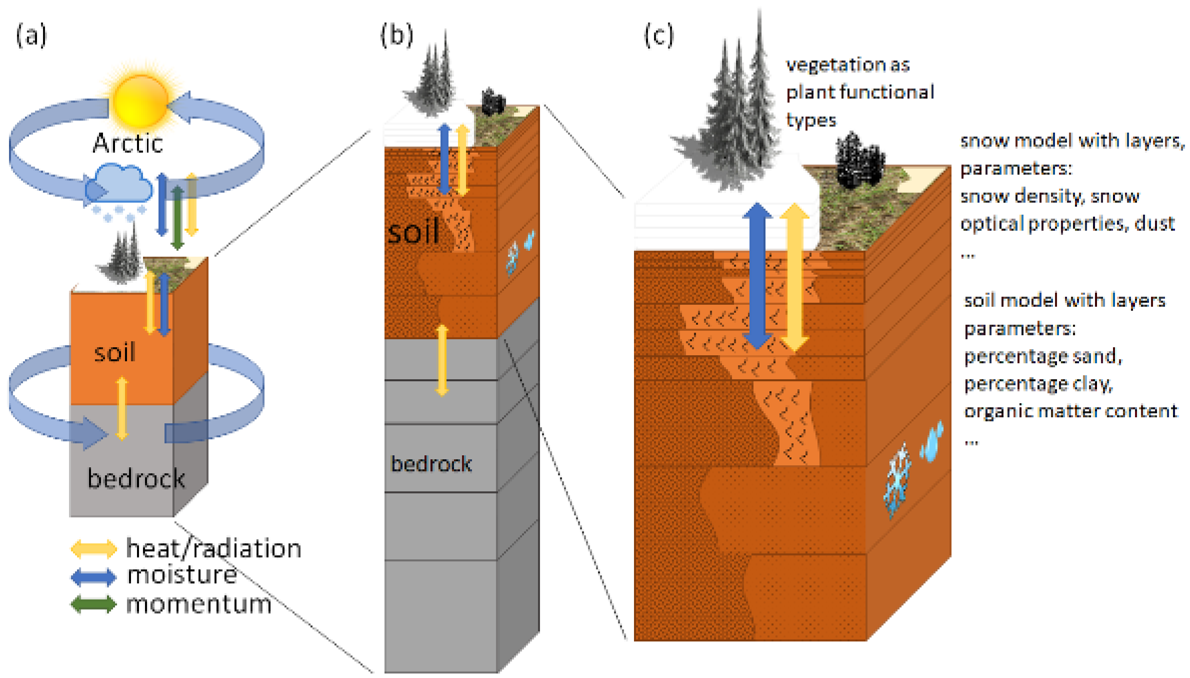

Figure 2: Conceptual sketch of the atmospheric and land columns in an Earth System Model. Atmospheric processes are only shown as input to the land model. 2a demonstrates the interaction between atmosphere and land, 2b shows the complete land model column, 2c shows the upper layers of the land model column that are treated as soil layers.

B. High/low ungulate density scenarios and parameter ranges

Most information on parameter ranges that are available from field studies come from exclosure analysis and therefore compare a state of no grazing by herbivores to a state of "normal" grazing for the specific field site. We will therefore explore possible futures on the basis of "extreme ends" scenarios, where we consider on the one hand a very low ungulate density, which reflects to some extent the state of parameters in the exclosures, and on the other hand a very high ungulate density, whose parameters are estimated from the control data outside the exclosures. In combination with the emission pathways we will follow, six different 'biogeoengineering' scenarios are constructed as listed in Table 1.

Table 1: 'biogeoengineering' scenarios as cross table of socio-economic pathways/RCPs defining climate change forcing and ungulate density scenarios defining strength of ungulate's impact on the environment.

	socio-economic pathway/ RCP		
ungulate density	SSP126	SSP245	SSP585
high	SSP126+	SSP245+	SSP585+
low	SSP126-	SSP245-	SSP585-

Also, from a circum-arctic perspective, the impacts of ungulates on the environment are very heterogeneous. For example, impacts on plant community composition are found to be dependent on nutrient availability (e. g. Gough et al. (2007), Sundqvist et al. (2019)), vegetation zone (e. g. Sundqvist et al. (2019)) or soil characteristics (Francini et al. (2014)). We identified a number of modelling parameters that were found to have similar changes between high and low ungulate densities throughout vegetation zones, so that they can be applied pan-Arctic with reasonable simplification.

However, most studies do not relate their results and data to specific herbivore density. Tuomi et al. (2020) for example suggest a conceptual functional relationship between trampling and soil density that is highly nonlinear (Figure 3). While the functional relationship is similar for different plant community compositions, no quantitative relation is given.

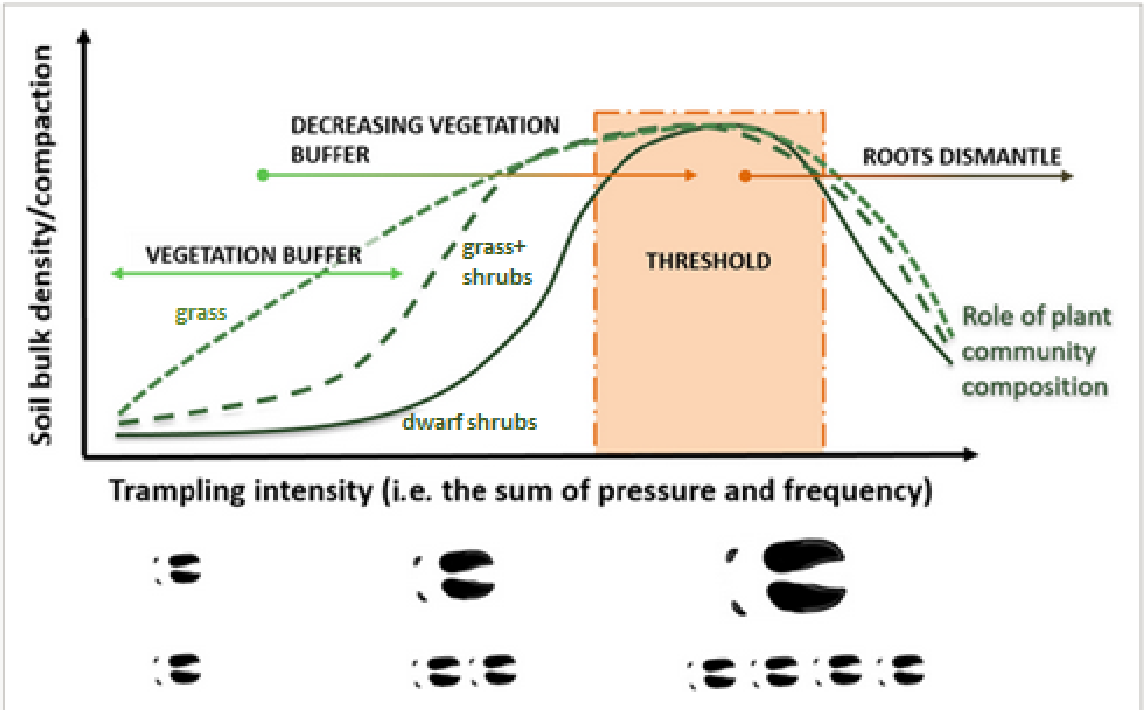

Figure 3: Non-linear relationship between trampling intensity and soil density in tundra, based on different species abundance. Altered from Tuomi et al. (2020), Figure 2.

Lindén et al. (2021) suggest from their study on the impact of herbivores on tundra vegetation for different vegetation types in Alaska and Scandinavia that large herbivores had a negative impact on vegetation height and abundance of deciduous shrubs, regardless of the study site. Lower abundance of deciduous shrubs was also found by den Herder et al. (2008) for a tundra habitat. Ravolainen et al. (2014) found that in three Arctic Norwegian river catchments, the exclusion of large herbivores promoted enhanced recruit survival of *salix* shrubs.

Beer et al. (2020) derived estimates of large herbivore impacts on snow compaction by analysing two exclosure sites in Sweden. At one of the sites (Vassijaure), the exclosure site (no trampling) was compared to a feeding site (very high trampling), the resulting histogram of snow depths is shown in Figure 4. Here, the impact of the reindeer on snow height is so strong that the two distributions do not overlap.

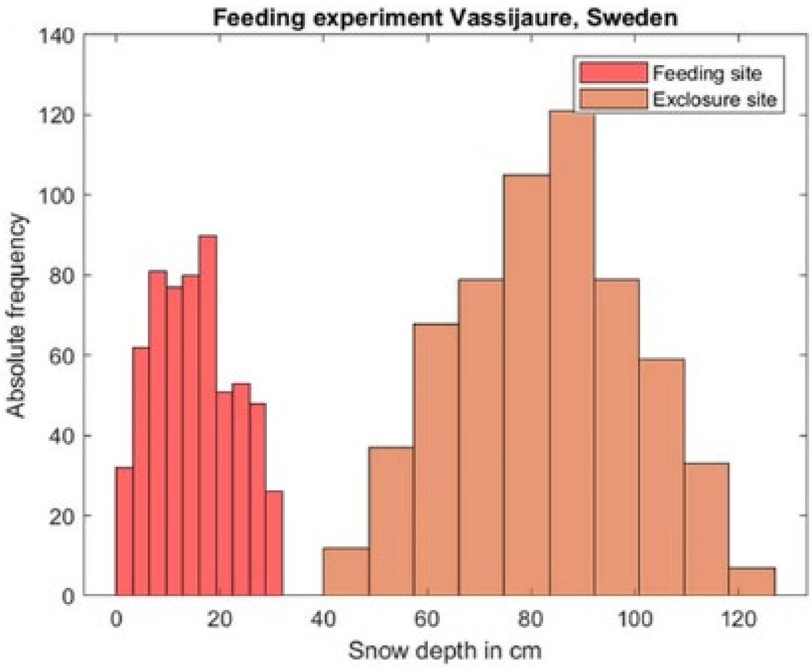

Figure 4: Impact of reindeer on histograms of snow depths from Vassijaure, Sweden. Adapted from Beer et al. (2020).

The impact of reindeer on lichen cover has been discussed in literature for quite some time (e. g. Pegau (1970), den Herder et al. (2003), Akujärvi et al. (2014), Bernes et al. (2015)). Since lichen are an integral part of reindeer diet, a higher abundance of lichen at exclosure sites is a reasonable expectation (e. g. Sundqvist et al. (2018), Lindén et al. (2021)). However, Lindén et al. also show that the impact of large herbivores on lichen thickness depends significantly on the study site. We will use data provided by WP1 to estimate the impact of herbivores on lichen cover using surface albedo, since background albedo will be used as a proxy for differences in lichen abundance in the model.

The resulting relative parameter assumptions for high and low large herbivore densities are summarized in Table 2.

Table 2: Qualitative description of modelling parameters to emulate high and low ungulate density scenarios.

parameter	high ungulate density	low ungulate density
background albedo (as proxy for lichen cover)	low (low lichen cover)	high (high lichen cover)
shrub abundance	low	high
shrub height	low	high
snow compaction	high	low
soil density	high were trampling is moderate low were trampling is so intense that it causes soil erosion	low

C. Analysis of current Arctic ungulate density and parameter distribution

In order to apply the parameter changes for the 'biogeoengineering' scenarios defined in table 1, we need to consider current ungulate density throughout the Arctic. This density estimate as a proxy for grazing pressure has to consider both wild ungulates and managed reindeer herds. Figure 5 shows estimates of grazing areas for wild reindeer and caribou throughout the Arctic from the databases of the CircumArctic Rangifer Monitoring and Assessment Network (CARMA), where also herd sizes are available (Russel, 2018). These data will be combined with assessments on managed reindeer numbers for Fennoscandia from WP 2 and Russia from WP 3 to create a circum-arctic map of estimated grazing pressure. The application of changed vegetation abundance or soil density needs to be done according to current ungulate density, since the maps that are the basis for modelling reflect the current state of vegetation and soil characteristics that are already influenced by ungulates (e. g. there already is low lichen cover/ low shrub abundance/ high grass abundance/lower soil porosity in areas with high density of ungulates).

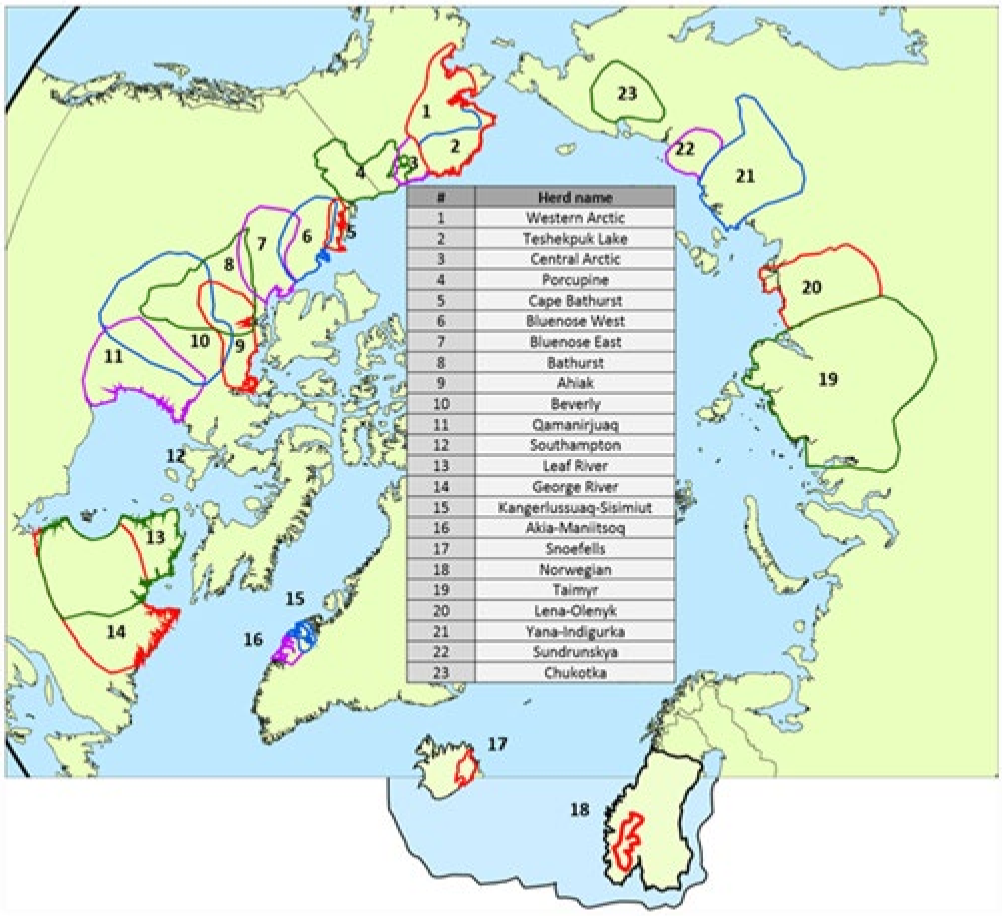

Figure 5: migratory herds of caribou (North America and Greenland) and wild reindeer (Russia and Norway) in the Arctic. Herd sizes are available from the CARMA network (https://carma.caff.is) and varies between a few thousand (e.g. Cape Bathurst) to more than 300,000 animals (Taymir, Bluenose East).

Mammoth tundra steppe rangeland definition

To examine impacts of large herbivores on permafrost landscape and the climate in a global Earth System Model, we chose the following model adjustments:

1) snow pack, such as snow cover, snow depth, snow albedo (dirtying).

2) vegetation cover. We can specify over what region – a) the present reindeer herding region and b) the whole permafrost region.

3) thermal insulation effects of soil organic matter (SOM), without the insulation effects of SOM, permafrost might thaw faster. Mammoth might destroy or enhance it?

4) surface SOM vertical movement, currently models simulate the impacts of cryoturbation on SOM as vertical diffusion, with a constant diffusion coefficient.

5) microbial environment, it determines the soil carbon decomposition.

We will use the land surface models first without feedback to the atmosphere, to assess the strength of the impacts of the suggested model adjustments. Based on that analysis, we decide which adjustments to use in a global Earth System Model. Various methods have been used previously in land models, for example Beer et al (2020) made changes in snow density – but it probably relies on too high density of animals. Also modified the biochemistry, but snow density was the dominant factor in changing soil temperatures. A recent article in PNAS (Monteath et al, 2021) suggests that vegetation change at the end of the last glacial period was climate driven rather than due to animal extinctions. These results suggest that very large region land surface type modification is needed to affect climate.

Next Steps

Both the 'biogeoengineering' scenarios defined in table 1 as well as the modifications for the tundra steppe rangeland will be implemented into the CHARTER models, cooperating with WPs 1, 2 and 3 on the specific parameter ranges. In a fist step, the implementation will be used in the land surface models to assess the impacts of the modifications.

For the tundra steppe rangeland, the following experiments the land surface model are envisioned:

1. Mimic mammoth's impacts on snow density (as Beer et al., 2020) and snow albedo dirtying (not sure if any field observations available), use CoLM to study their impacts on soil temperature and permafrost active layer thickness.

2. Mimic mammoth's perturbation on regional vegetation dynamics, such as in winter animals eating the grasses that grow the previous summer, this should have some impacts on vegetation competition during the following year. It seems it's not considered in Beer's study, possible due to no field observations to support and it might take one or two decades to find out impacts.

3. Estimate CH_4 emission due to large density of mammoth/herbivore. As mammoth/herbivore eat grass, less carbon into soil, and possibly less permafrost thaw, but mammoth/herbivore might produce more CH_4 and it might have more profound warming impacts than CO_2.

For the 'biogeoengineering' scenarios, parameter changes according to table 2 will be used in pan-Arctic simulations covering at least the time period 2015-2050. Fully coupled simulations will follow according to the scenario definitions in table 1. As a basis for an adaptive process, specific scenario definitions can be refined based on participatory work (what are feasible/desirable reindeer management options for the future; how would they impact possible future conditions for herding/cryosphere/biodiversity/extreme events).

References

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

Barthelemy, H., Stark, S., Olofsson, J. (2015): Increased plant productivity by long-term faeces addition in tundra ecosystems. Ecosystems 18, 740-751. https://doi.org/10.1007/s10021-015-9856-y

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

Bernes, C., K. A. Bråthen, B. C. Forbes, J. D. M. Speed, Moen, J.. (2015): What are the impacts of reindeer/caribou (Rangifer tarandus L.) on arctic and alpine vegetation? A systematic review. Environmental Evidence 4(4). https://doi.org/10.1186/s13750-014-0030-3

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

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

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

Francini, G., Liiri, M., Männistö, M. K. , Stark, S., Kytöviita, M.-M. (2014): Response to reindeer grazing removal depends on soil characteristics in low Arctic meadows. Applied Soil Ecology 76, 14-25. https://doi.org/10.1016/j.apsoil.2013.12.003

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

Kumpula, J., S. Stark, Holand, O. (2011): Seasonal grazing effects by semi-domesticated reindeer on subarctic mountain birch forests. Polar Biology: 441-453. https://doi.org/10.1007/s00300-010-0899-4

Kumpula, J., Kurkilahti, M., Helle, T., Colpaert, A. (2014): Both reindeer management and several other land use factors explain the reduction in ground lichens (Cladonia spp.) in pastures grazed by semi-domesticated reindeer in Finland. – Regional Environmental Change 14, 541–559. https://doi.org/10.1007/s10113-013-0508-5

Lindén, E., Gough, L., Olofsson, J. (2021): Large and small herbivores have strong effects on tundra vegetation in Scandinavia and Alaska. Ecology and Evolution 11, 12141– 12152. https://doi.org/10.1002/ece3.7977

Manseau, M., J. Huot, Crete, M. (1996): Effects of summer grazing by caribou on composition and productivity of vegetation: community and landscape level. Journal of Ecology 84, 503-513.

Moen, J. and Danell, Ö., (2003): Reindeer in the Swedish mountains: An assessment of grazing impacts. AMBIO: A Journal of the Human Environment, 32(6), 397-402. https://doi.org/10.1579/0044-7447-32.6.397

Monteath, A. J. , Gaglioti, B. V., Edwards, M. E., Froese, D. (2021): Late Pleistocene shrub expansion preceded megafauna turnover and extinctions in eastern Beringia, Proceedings of the National Academy of Sciences Dec 2021, 118 (52) e2107977118; https://doi.org/10.1073/pnas.2107977118

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

Pegau, R.E. (1970). Effect of reindeer trampling and grazing on lichens. Journal of Range Management 23, 95-97.

Ravolainen, V.T., Bråthen, K.A., Yoccoz, N.G., Nguyen, J.K., Ims, R.A. (2014): Complementary impacts of small rodents and semi-domesticated ungulates limit tall shrub expansion in the tundra. Journal of Applied Ecology 51, 234-241. https://doi.org/10.1111/1365-2664.12180

Russell, D. E., A. Gunn, S. Kutz (2018): Migratory Tundra Caribou and Wild Reindeer, Arctic Report Card 2018, https://arctic.noaa.gov/Report-Card/Report-Card-2018/ArtMID/7878/ArticleID/784/Migratory-Tundra-Caribou-and-Wild-Reindeer

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. doi.org/10.1111/1365-2745.13201

Tuomi, M, Väisänen, M, Ylänne, H, et al. (2021): Stomping in silence: Conceptualizing trampling effects on soils in polar tundra. Functional Ecology 35, 306– 317. https://doi.org/10.1111/1365-2435.13719

Wang, W., He, C., Moore, J., Wang, G., Niu, G. Y. Wang, W., He, C., Moore, J., Wang, G., Niu, G. Y. (2022): Physics-Based Narrowband Optical Parameters for Snow Albedo Simulation in Climate Models. Journal of Advances in Modeling Earth Systems 14(1), e2020MS002431. https://doi.org/10.1029/2020MS002431

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