SUPPLEMETARY MATERIAL: PLEISTOCENE ARCTIC MEGAFAUNAL ECOLOGICAL ENGINEERING AS A NATURAL CLIMATE SOLUTION?

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The following section discusses the assumptions/simplifications we have taken and suggests future research to address the uncertainties stemming from them.

Assumption 1. *Reference Megafaunal Density*: the effective animal density is 1 MEG/km^2 (5 bison and 7.5 horse km^{-2}) stems from estimated animal densities in Northern Russia in the late Pleistocene [1]. There is at present no experimental setup able to better constrain this number. Failing to achieve a density able to convert land would probably result in a net increase in greenhouse gas emissions.

Assumption 2. *Immediate conversion to grassland*: our quantitative exercise assumes immediate vegetation conversion and permafrost protection. As stated in *Section 4.5*, in reality a period of time –estimated to be >8 years– will be required to achieve this state change. The animal density estimate of 1 MEG km^{-2} occurred in the late Pleistocene, in a region where large megafauna/soil/vegetation feedbacks had operated for millennia and thus with soils that were much richer in nutrients than those in current forest-tundra and tundra. Experience in Pleistocene Park suggests that nutrient limitation and seed availability is key in the early years of Pleistocene Arctic *MEE*. Without an initial management phase –*ranching kickstart phase*– which includes at least allochthonous winter fodder while the local feedbacks start enriching soils, high herbivore densities might not be self-maintained in the early years. After such phase, self-sustainable herds –much cheaper to maintain– are anticipated.

Assumption 3. *Effectiveness of mammoth steppe on thermal, nutrient, and carbon budgets*: our MEG growth model assumes that in the short term grassland systems will effectively delay permafrost melt. However, in the coming decades the efficiency of this cooling effect (measured as ~2ºC in annual average temperature) will eventually depend on climate warming. Ultimately, this *NCS* can delay permafrost melt, but needs being implemented in conjunction with many other actions, most importantly reduction of greenhouse gas emissions. The net effect of Arctic *MEE* will also be determined by the following:

3.1 Initial greenhouse gas emissions from land vegetation removal: transitioning from wet moss/shrubby tundra and forest tundra to grasslands implies an initial loss of biomass. Epstein *et al.* [2] estimated a recent gain of aboveground biomass of 0.4Pg C in 3 decades due to tundra greening across the whole biome. Even if we account for twice this value by adding belowground biomass [3], the amount of carbon gained by increased shrub biomass is small at a global scale –see *Section 3*, and to this we need to take into account the fact that forbs and grasses aboveground/belowground ratio is smaller and their productivity higher. Berner *et al.* [4] estimated the overall aboveground standing biomass in the North Slope of Alaska to be 700 gm^{-2}, with 43% of such biomass attributed to tall shrubs (i.e. 300 gm^{-2}): compared with average 21st century emissions from permafrost of 100$gm^{-2}yr^{-1}$, this number could be offset in a short period with effective *MEE*, especially in Yedoma soils and if avoiding abrupt permafrost collapse. In here, initial emissions due to transport of animals and additional forage in the *ranching kickstart phase* should also be accounted for: these can be large, especially if animals need being air-freighted from other continents, although they are a one-off and should be rapidly recovered by an effective *MEE*. An in-depth study of the most carbon-efficient way to move the animals, as well as the overall carbon contained by the increasing biomass in the megafauna itself, would be able to quantify these effects in detail.

3.2 Greenhouse gas emissions and changes in hydrology: a central point in permafrost carbon emissions is the balance between emitted CH_4 and CO_2, in which hydrology plays a critical role. Thermokarst lakes and water-saturated areas with anoxic conditions are the main source of CH_4 [5, 6]. Establishment of drainage networks decreases lake and standing water and leads many lakes to eventually drain, exposing unfrozen ground – *talik*, which may refreeze again if mean annual temperatures are <0ºC, but after having lost much carbon [5]. Thus, drier soils on permafrost have lower global warming potential than wet ones due to lower CH_4/CO_2 emission ratios [6]. Whether permafrost regions become wetter or drier in a warmer Earth was not yet been determined and constitutes a major research question [7], although we know that thermokarst lake formation was a large CH_4 source in the *LP/EH* and is likely to occur in a warmer planet in the ice-rich Yedoma regions [5]. Conversion to grassland through effective Arctic *MEE* will increase transpiration and contribute to drier land, thus reducing greenhouse warming potential. Moreover, it can also favour permafrost aggradation in drained lakes in areas within continuous permafrost [8]. The overall effect of such action will depend on the difference between the effect of *MEE* on permafrost hydrology and the trajectory of these landscapes in the absence of any action.

3.3. Albedo effect: we did not account for the effects of albedo modification in the quantitative thought process presented in this study, however existing literature points to a significant reinforcement of the cooling effects of landcover change from wet moss/shrubby tundra to grass-dominated ecosystem when accounting for albedo [see Section 3; 9, 10]. An energy budget on the net effects of Arctic *MEE* requires measurement of changes in radiative forcing (Wm^{-2}) due to albedo.

Assumption 4. *Herbivore growth model:* a 10% $year^{-1}$ growth was used from experience on re-establishing bison in Romania, and a lack of literature on growth rates of translocated herbivores was noted. Such estimates can be refined in the experimental phase defined in *Section 4.4*.

Assumption 5. *Herbivore size of a MEE experimental unit*: 1,000 animals are considered sufficient for an experimental MEE area according to the experience of running Pleistocene Park. This number could be refined by modelling exercises as well as literature search on herd sizes able to enact ecosystem phase transitions.

Assumption 6. *The role of predators*: Pleistocene Park has excluded predators in an attempt to boost current herbivore numbers. Predators (wolf, possibly tiger) are expected to increase landscape heterogeneity by modifying herbivore behaviour and herd movement [11] –see *Section 2*. Inclusion of predators in experimental phases starting with ≥~1,000 large herbivores would be achieved early, as it is deemed crucial to avoid pockets of overgrazed terrain.

Assumption 7. *Price of carbon* is discussed in *Section 4.6*. Given the wide range of values for carbon in the market depending on whether these are obtained in compliance or voluntary market initiatives, we conservatively used carbon price estimates on the lower range of possible values.

References

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