

Ancient DNA analyses exclude humans as the driving force behind late Pleistocene musk ox (*Ovibos moschatus*) population dynamics

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The causes of the late Pleistocene megafaunal extinctions are poorly understood. Different lines of evidence point to climate change, the arrival of humans, or a combination of these events as the trigger. Although many species went extinct, others, such as caribou and bison, survived to the present. The musk ox has an intermediate story: relatively abundant during the Pleistocene, it is now restricted to Greenland and the Arctic Archipelago. In this study, we use ancient DNA sequences, temporally unbiased summary statistics, and Bayesian analytical techniques to infer musk ox population dynamics throughout the late Pleistocene and Holocene. Our results reveal that musk ox genetic diversity was much higher during the Pleistocene than at present, and has undergone several expansions and contractions over the past 60,000 years. Northeast Siberia was of key importance, as it was the geographic origin of all samples studied and held a large diverse population until local extinction at $\approx 45,000$ radiocarbon years before present (^{14}C YBP). Subsequently, musk ox genetic diversity reincreased at ca. 30,000 ^{14}C YBP, recontracted at ca. 18,000 ^{14}C YBP, and finally recovered in the middle Holocene. The arrival of humans into relevant areas of the musk ox range did not affect their mitochondrial diversity, and both musk ox and humans expanded into Greenland concomitantly. Thus, their population dynamics are better explained by a nonanthropogenic cause (for example, environmental change), a hypothesis supported by historic observations on the sensitivity of the species to both climatic warming and fluctuations.

climate change | human impact | quaternary | megafauna extinctions

The late Pleistocene saw significant changes in the geographic distribution and composition of the Beringian megafauna. Although many iconic Beringian herbivores, such as mammoths (*Mammuthus primigenius*) and woolly rhinoceroses (*Coelodonta antiquitatis*) became extinct, others, such as horses (*Equus caballus*), saiga (*Saiga tatarica*), caribou (*Rangifer tarandus*), and bison (*Bison bison*) survived to the present. The reasons for these markedly different survival patterns have been widely debated, with the extinctions predominantly attributed to either human impact (1) or climate change associated with the last glacial cycle (2). The relative contribution of the two remains a key evolutionary debate (cf. 3, 4). For example, it is well known that global climate fluctuated significantly throughout the

Pleistocene (5–7); the Eurasian fossil record indicates that late Pleistocene climatic changes reduced the range of several species, and the last glacial-interglacial transition appears to correlate with major extinction events. However, none of the previous Pleistocene glacial cycles appear to have caused widespread extinction events (3, 8), and the demise of the Beringian megafauna also appears to coincide neatly with the arrival and spread of modern human populations (9, 10). Similar evidence of a human-driven effect can be seen in central North America, where the arrival of Clovis-style hunters, extinction of megafauna, and marked climate change all cluster closely together (11, 12).

Ancient DNA (aDNA) analyses of temporally and geographically distributed megafaunal remains offer a means to address the relative roles of humans versus the climate in the Beringian megafaunal extinctions. The capacity of this technique to detect changes in genetic diversity within populations over geologically significant time scales provides the means to examine past population variation and to explore directly how populations respond to climate and environmental changes (13). Geographic and temporal discontinuity in the genetic data can be compared to past climate reconstructions and specific ecological events, such as advancing ice sheets, a volcanic eruption, or human colonization. Previous large-scale aDNA studies of this kind have focused on herbivores, such as bison and horses that survived to the present in relatively large numbers and are thus relatively

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abundant today (13, 14), or others, such as the mammoth that are now extinct (15, 16). We focus on the musk ox, *Ovibos moschatus*, one of the few large mammals adapted to a high arctic environment, and which has a distinctly different pattern of survival than the previously studied species. Although the musk ox was holarctically distributed at the beginning of the Holocene, only small, relict natural populations isolated on Greenland and the North American Arctic Archipelago survive to the present day. The Pleistocene musk ox went extinct over most of its Eurasian range at the beginning of the Holocene. In Europe, the latest known occurrences are in late glacial deposits in Scandinavia, and in the Taimyr Peninsula and the Lena River mouth at the Bykovsky Peninsula (Northeast Siberia) they survived until around 2,500 years before present (YBP) (17, 18), extending the survival of this species in northern Russia well into the Holocene epoch.

Whether musk ox population decline can be attributed to human or other effects is unclear. In North America, the decline of related ovibovines appears to correlate closely with the arrival of humans, whereas longer human-ovibovine cohabitation is observed in northern Eurasia (3, 19). Given the conflicting evidence, a principal aim of this study was to further investigate the question, through reconstruction of past musk ox population dynamics using aDNA, and comparison of the findings against human and climatic records from the late Pleistocene and Holocene and known biological characteristics of the species.

Results and Discussion

To investigate changes in genetic diversity among musk ox since the late Pleistocene, we analyzed 682 bp of the mitochondrial control region, obtained from 149 radiocarbon dated specimens that range in age from 56,900 radiocarbon (^{14}C) YBP to the present (Fig. 1). Specimens were sampled from their previous geographic range, spanning from the Urals ($n = 26$) and the Taimyr Peninsula ($n = 54$) in the west, through Northeast Siberia ($n = 12$) and into North America ($n = 14$) and across to Greenland ($n = 43$) in the east. Our data demonstrate continuous

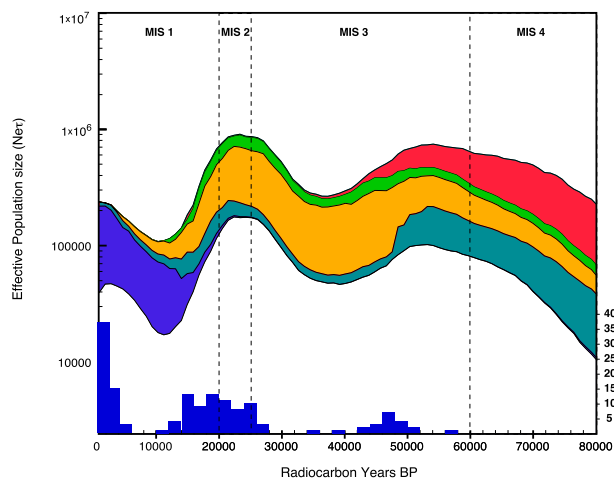


Fig. 1. Bayesian Skyride derived from the geospatial analysis of 135 ancient and 14 modern musk ox mtDNA control region sequences. The x axis is in units of radiocarbon years in the past, and the y axis is equal to $Ne^*\tau$ (the product of the effective population size and the generation length in radiocarbon years). The colors represent the relative contribution of each of the geolocations to the overall estimated effective population size. Colors indicate geographical origins of the samples: blue, Greenland; red, Northeast Siberia; orange, Taimyr; green, Urals; light blue, Canada. The bar graph shows the number of radiocarbon-dated samples in bins of 2,000 radiocarbon years. No relation is apparent between the absolute number of samples and the estimated effective population size or transition time.

presence of musk ox in Eurasia and North America throughout radiocarbon time until their extinction in Eurasia ($\sim 2,500$ YBP) and demographic retraction in North America ($\sim 10,000$ YBP).

Loss of Mitochondrial DNA Diversity. Modern musk ox harbor little genetic diversity at both the nuclear and mitochondrial levels (20–22). Our data indicate that total past genetic diversity (samples older than 100 ^{14}C YBP), as measured by temporally unbiased π (23), was significantly higher than present (Table 1 and Fig. S1), with Serial SimCoal (SSC) simulations indicating that this decrease in genetic diversity cannot be explained by genetic drift in a constant-sized population. This observation is consistent with the results of a smaller, previous aDNA study (24) and with paleontological evidence, which suggests a large decrease in musk ox geographic range and population size during the late Pleistocene. To investigate whether the arrival of humans into the musk ox range played any effect on the species' genetic diversity, a similar analysis was performed on the Taimyr and Canada datasets (the only two with a meaningful number of musk ox on either side of the entry). In neither case was human arrival associated with any statistically significant change in genetic diversity (Table 1 and Fig. S1).

Three Geographically Structured Clades. Phylogenetic analyses of the data subdivides musk ox into three, well-supported and temporally structured clades (clades 1–3) (Fig. 2). The phylogeny is consistent with that recovered when (i) 13 radiocarbon-infinite sequences are added to the alignment, or (ii) the analysis is restricted to a subset of 60 samples for which the complete control region sequence was obtained (Figs. S2 and S3). Clade 1 comprises samples that range in age from beyond the ^{14}C limit to 42,550 ^{14}C YBP, originating predominantly in Northeast Siberia but also in the Taimyr Peninsula. By $\approx 45,000$ ^{14}C YBP, most of the diversity present before this time had been lost.

Clade 2 consists of specimens almost exclusively originating from the Urals and Taimyr region, ranging in age from beyond the ^{14}C limit to ca. 13,000 ^{14}C YBP (although a single outlier in this study is associated with a much more recent date of 3374 ^{14}C YBP). The geographic distribution of samples belonging to clade 2 suggests: (i) that these regions were either independently populated from a mixed source population, (ii) that no significant physical barriers to gene flow were present across this wide geographic expanse, or (iii) a combination of these. During the Quaternary, ice sheets over the Barents and Kara seas expanded several times onto mainland Russia, blocking north-flowing rivers such as the Yenisei, Ob, Pechora, and Mezen. Large ice-dammed lakes formed a barrier

Table 1. Observed nucleotide diversity and polymorphic sites of data subsets

Data subset	π^*	Significance [†]	M	PM
All modern samples (<100 ^{14}C YBP)	0.008	6,417	26	9
All ancient samples (>100 ^{14}C YBP)	0.021	9,993 [‡]	575	549
Canada, prehuman contact [§]	0.026	4,801	70	Na
Canada posthuman contact [§]	0.019	6,689	45	Na
Taimyr prehuman contact [§]	0.025	4,006	136	Na
Taimyr posthuman contact [§]	0.017	6,815	39	Na

M, number of polymorphic sites; Na, Not applicable; PM, number of private mutations.

*Temporally unbiased π calculated following Depaulis et al. (23).

[†]Rank (of 10,000, of uncorrected π) among data generated through Serial SimCoal simulations of a constant population in which gene frequencies are changing only through genetic drift. Placement of the observed value outside of the 95th percentile (i.e., outside of rank 250–9,750) can be considered as significant at <5% level.

[‡]Significant at $P = 0.0007$.

[§]Contact time as shown in Fig. 3.

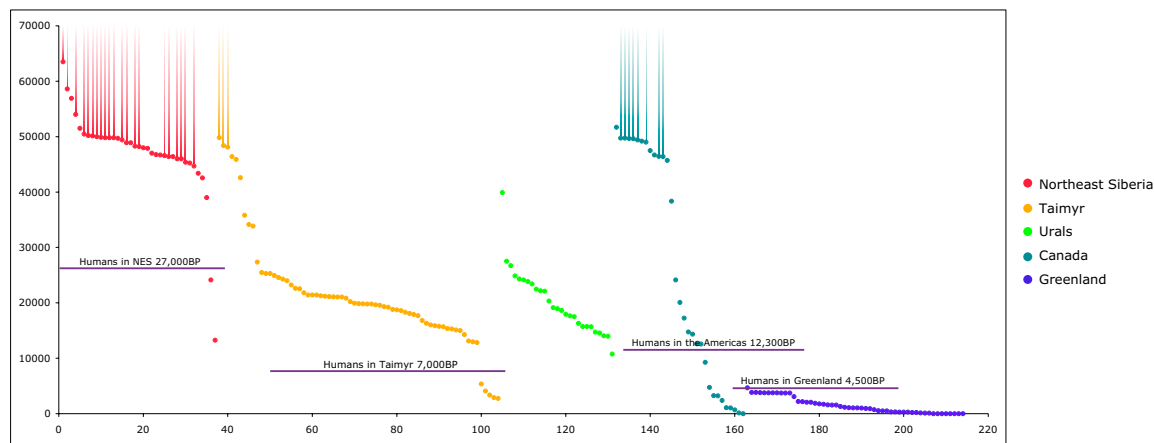


Fig. 3. Temporal distribution of the 210 ^{14}C dated fossil musk ox used in the present study. For a number of individuals, indicated by the extended timelines, finite dates could not be calculated. Samples are grouped in five major regions: Northeast Siberia, Taimyr, Urals, Canada, and Greenland. The approximate earliest presence of anatomically modern humans in the regions is added for comparison. Radiocarbon accession numbers associated with specific specimens are given in Table S1.

The periods during which musk ox populations are seen to increase are, in general, those of global climatic cooling (in particular as peak diversity coincides with the LGM). Furthermore, the musk ox populations decline during the warmer and climatically unstable interstadials (Fig. S6), such as MIS 3, and in the postglacial warming following the LGM (Fig. 1 and Fig. S7). Although this is by no means conclusive evidence, a role of the environment as opposed to humans as the driving force is also supported by several other observations drawn from both our, and previously published data, as discussed below.

The results of the geospatial analyses point to a significant role of Northeast Siberia in the species' population history. This region not only harbored the greatest mitochondrial genetic diversity, but also the most recent common ancestor of all sampled musk ox [$\approx 96,009$ years ago (95% highest posterior density [HPD] 103,249–82,780 years ago)] and was the geographic source of all three clades. Despite its key role in musk ox history, both the time of extinction of clade 1 and the temporal distribution of the ^{14}C dated specimens (Figs. 2 and 3) indicate that a major reduction in musk ox diversity occurred in this region at ca. 45,000 ^{14}C YBP. There is no archaeological evidence of human presence this far north at this time; the first well-supported evidence of human settlements in Northeast Siberia are at a Paleolithic site in the Yana River basin at 27,000 ^{14}C YBP (37). Thus, an alternate explanation for the loss is required. Intriguingly, the loss of a distinct mtDNA clade for mammoths has also been observed in this region at this time (15, 16, 38), suggesting the cause was not species-specific. Given that during MIS 3 both polar ice-core records and pollen, plant macrofossils, mammal, and insect remains indicate that the climate started to both fluctuate significantly and become increasingly warmer and wetter (39–41) (Fig. S7), and that, as discussed above, musk ox are sensitive to both climate warming and fluctuations (32, 42), climatic-driven environmental change is a plausible hypothesis.

The distribution of the ^{14}C dated samples in both the Taimyr and Urals indicates a widespread loss of musk ox in these regions following the LGM, culminating by around 13,000 ^{14}C YBP (Fig. 3). There is no evidence for the presence of modern humans in the area until the very end of the Pleistocene or early Holocene (43–45), and as mentioned above, the human arrival in the Taimyr is associated with no statistically significant change in genetic diversity (Table 1). However, this time does coincide with the Bølling/Allerød period, during which the climate became more humid and a general degradation of permafrost started, accompanied by a dramatic change in vegetation from tundra-steppe to wet tundra and forest tundra

(7). Thus, once again, the data directly suggest that these fluctuations were driven by nonanthropogenic factors.

Further evidence of the competing roles of humans versus environment is provided by the Greenlandic data. Although musk ox were present in the Americas throughout the Pleistocene, they did not colonize Greenland until very recently. Although other species, such as caribou, are known to have been present in Greenland during the last interglacial (46), the fossil record shows that musk ox first arrived in Greenland during the mid-Holocene, with the oldest samples dated to 4,500 ^{14}C YBP, from Paleoeskimo Independence I archeological sites in Northeast and Northwest Greenland (47). The fossil record and the modern geographical range of the musk ox suggest that dispersal into Greenland took place from Ellesmere Island in Canada by way of the Robeson Channel to Northwest Greenland, followed by dispersal along the east coast into central East Greenland (48, 49). Our results are consistent with this pattern, and support a single colonization event followed by population expansion.

Bayesian skyline analysis of the restricted Greenlandic dataset suggests rapid population growth following this initial dispersal into Greenland (Fig. S8). This theory is consistent with the expected dynamics of a species entering virgin terrain in the absence of competition and the fact that musk ox thrive during climatically stable periods (42), such as those reconstructed for the last ca. 10,000 years in Greenland using GISP2 records (Fig. S7) (50, 51). This finding, plus the contemporaneous arrival and colonization of Greenland by humans and musk ox, and the fact that musk ox genetic diversity in Canada did not change significantly following human arrival in the Americas (Table 1), provides further evidence of a negligible effect of humans on musk ox. Arguments that musk ox were not of interest to the first humans as prey can also be discounted, as the Independence I culture are known to have been expert musk ox hunters, as demonstrated by the large number of musk ox bones recovered from archeological sites across the high Arctic of Canada and Greenland that have been associated with this culture (52).

In summary, although humans may have played a significant role in the history of other large Beringian mammalian herbivores, to our knowledge this example is unique in showing there is no evidence that humans drove musk ox demographic fluctuations over the last 60,000 years. We argue that an alternate cause, possibly environmental change driven by the climate (53), was the major force behind musk ox population dynamics over this period, and expect that with the arrival of future aDNA and climatic reconstructions, this hypothesis can be more explicitly tested.

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