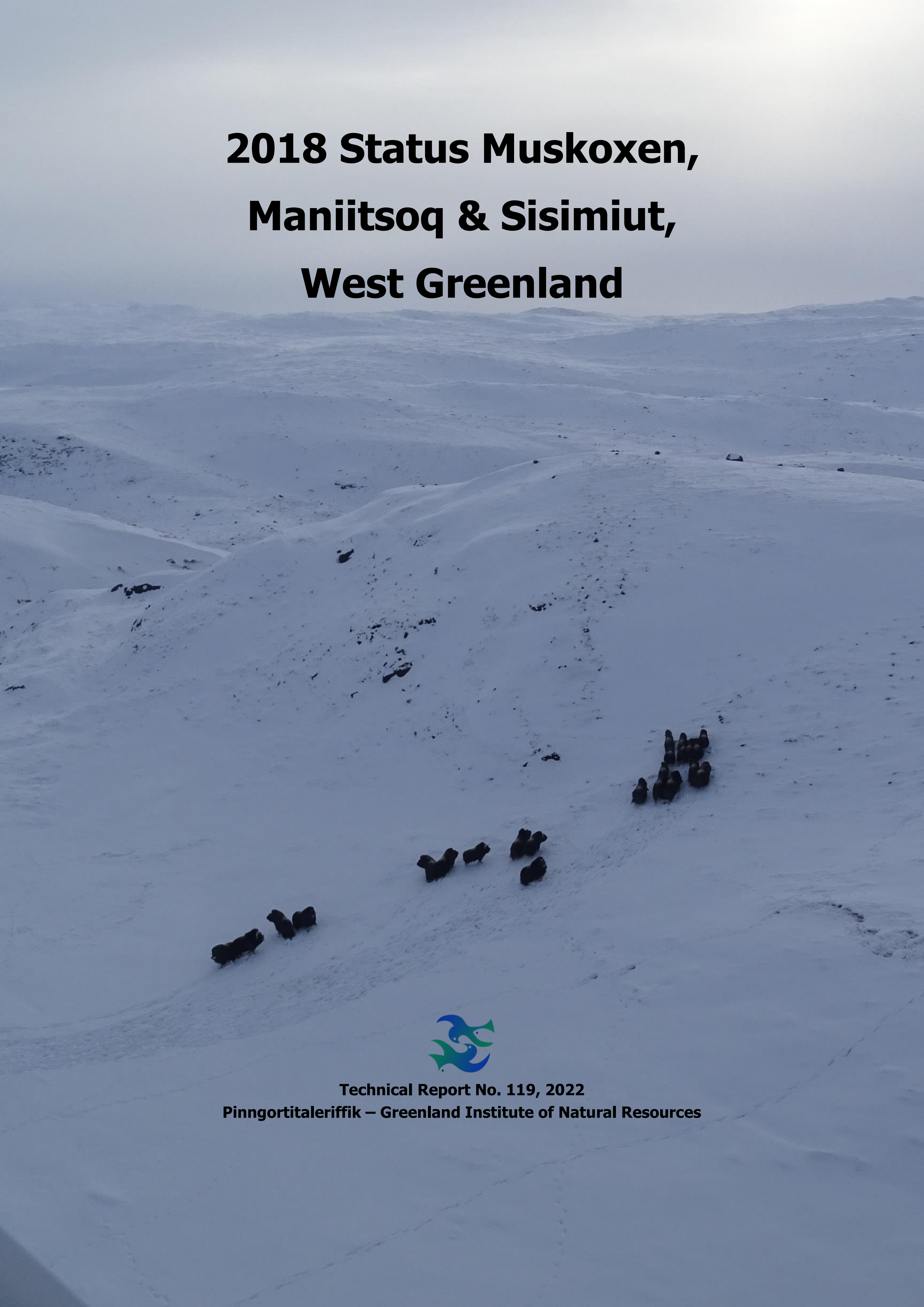

2018 Status Muskoxen, Maniitsoq & Sisimiut, West Greenland

Technical Report No. 119, 2022
Pinngortitaleriffik – Greenland Institute of Natural Resources

Title: 2018 status muskoxen, Maniitsoq & Sisimiut, West Greenland

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Cover photo: Christine Cuyler: Group of 23 muskoxen in the Sisimiut sub-area, between town of Kangerlussuaq and the Isortoq river.

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2018 status muskoxen, Maniitsoq & Sisimiut, West Greenland

By

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Raw data may be accessed by contacting the Pinngortitaleriffik – Greenland Institute of Natural Resources, Department of Mammals and Birds, Nuuk, Greenland.

Summary

This report presents results from the first systematic aerial survey of muskoxen in southwest Greenland. The survey involved the North region (66°-68°N), which was divided into three sub-areas (Angujaartorfiup, Sisimiut, Sisimiut South). The survey occurred early March 2018 and provides the first estimate for muskox abundance in two muskox harvest management areas, Maniitsoq (66°-67°N) and Sisimiut (67°-68°N).

The behavior of most muskox groups was unaffected by the helicopter fly-by at 40 m altitude. Regardless of group size, 77% of groups simply stood still. Detecting stationary groups is clearly essential for accurate population estimates.

Sisimiut muskoxen were most often observed at elevations of ca. 200 m, which is typical for this species as they prefer to forage in lowland elevations even in winter. In sharp contrast, Maniitsoq muskoxen used 700-800 m elevations, despite their documented year-round preference for lowlands <400 m. Further, at the time of the survey, Maniitsoq muskoxen were clumped into two 'hotspots' almost inaccessible by motor vehicle and relatively far from human habitation. Since 84% of all muskox harvest (commercial and recreational), as well as most trophy hunting and qiviut (muskox inner wool) production in Greenland are taken from the Maniitsoq muskox population, these activities may have a role in the disruption of normal lowland distribution of the Maniitsoq muskoxen in winter.

From a subset of the Maniitsoq data, the calf (age <1-year) percentage was ascertained ca. 18% for Maniitsoq muskoxen. Considering the absence of large predators, the current value is considered low. Factors involved may include density-dependent issues associated with the Maniitsoq muskoxen now foraging on high elevation suboptimal habitat in winter. Since this coincides with late gestation for muskoxen, calf production could be negatively affected. Whether current calf percentage is sufficient to support population size stability or growth is debatable.

Population size & density estimates

Conventional Distance Sampling (DS) design-based methods and analyses, as well as Generalized Additive Models/Density Surface Modelling (GAM/DSM) based analyses were applied to the dataset to obtain estimates of muskox population size and density. Most muskoxen occurred in the Maniitsoq muskox harvest management area (surveyed Angujaartorfiup sub-area). Far fewer muskoxen inhabited the Sisimiut muskox harvest management area (surveyed Sisimiut sub-area), and zero muskoxen were observed in the surveyed Sisimiut South sub-area. Densities from the GAM/DSM model-based analysis supported that in early March, muskoxen strongly preferred

Southwest facing slopes and specifically for Maniitsoq muskoxen the highest densities coincided with high elevations.

For the entire North region, the DS design-based March 2018 muskox population abundance was estimated at 21,746 muskoxen (95% CI: 11,061–42,751; CV = 28.5%; SE: 6,194), with a density of 1.1 muskoxen/km² (95% CI: 0.559–2.160; CV = 28.5%; SE = 0.313). Alternately for the entire North region, the GAM/DSM model-based March 2018 muskox population abundance was estimated 23,256 muskoxen (95% CI: 18,102–29,877; CV = 11.36%), with mean density of 3.69 muskoxen/km² (95% CI: 2.87-4.74).

DS estimates as per specific sub-area:

Maniitsoq muskoxen (Angujaartorfiup sub-area): The DS design-based estimate was ca. 18,906 muskoxen (95% CI: 8,726–40,960; CV = 0.315; SE = 5,948), with a density of ca. 2.6 muskoxen/km2 (95% CI: 1.223–5.742; CV = 0.315; SE = 0.834).

Sisimiut muskoxen (Sisimiut sub-area): The DS design-based estimate was ca. 2,840 muskoxen (95% CI: 662–12,178; CV = 0.568; SE = 1,613), with a density of ca. 0.22 muskoxen/km² (95% CI: 0.052–0.962; CV = 0.568; SE = 0.127).

The population size estimates from the two approaches were similar since the 95%CIs overlap. Despite the good survey coverage (10.6%), the high variability within the dataset was responsible for substantial uncertainty in the DS estimates and less so in the GAM/DSM. Regardless, calculating the CV for probability of detection of muskoxen permitted comparison of the two approaches. The DS probability of muskox detection had a CV of 5.98%, which was better than the CV of 11.36% for the GAM/DSM. Thus, for the 2018 survey for muskoxen, we recommend using the DS design-based abundance and density estimates when making management decisions.

Alone, the 2018 estimate cannot indicate population trend. That requires at least two additional aerial survey estimate points using similar methods. Meanwhile, past counts, densities, harvests, and calf percentages do not suggest recent population growth but possibly a decline prior to the 2018 survey. Regardless, specifically the 2018 population size estimate for Maniitsoq muskoxen is larger than previous estimates for populations anywhere in Greenland. Also, Maniitsoq muskox density is much higher than elsewhere in the Arctic. This could increase exposure of individuals to infectious pathogens. Given possible density-dependent influences acting at current population size, population growth may not be advisable. Whether the 2018 population size and density for the Maniitsoq muskox harvest management area are within the current herbivore carrying-capacity of the pasture/range remains to be seen.

Eqikkaaneq (kalaallisut)

Nalunaarusiami uani Kalaallit Nunaata kitaata kujataani timmisartoq qulimiguulik atorlugu umimmannik siullerpaamik aaqqisuussanik kisitsinernik ingerlataqarnernit inernerit saqqummiunneqassapput. Kisitsinerni Avannaata aqutsiveqarfia ilanngullugu kisitsivigineqarpoq (66°-68°N), Aqutsiveqarfillu nunap immikkoortuinut mikinernut pingasunut immikkoortinneqarsimavoq (Angujaartorfiup, Sisimiut, Sisimiut Kujataa). Kisitsinerit Aqutsiveqarfinni marlunni Maniitsumi (66°-67°N) Sisimiunilu (67°-68°N) martsip aallartisimalernerani 2018 ingerlanneqarput. Taamaalilluni Aqutsiveqarfinni Maniitsumi Sisimiunilu umimmaqassutsinik missiliuussinernit kisitsisit pigineqalerlutik.

Kisitsinermi timmisartoq qulimiguulik umimmannik qulangiuaarivoq, nunamiit qutsissutsimi 40 meteriniit, umimmaalli kisitsinernit sunnerneqarpasigatik eqqissisimaaginnarput nikigatillu. Ataatsimoortut iluminni katigigaanerat apeqqutaanani qulangiuaakkat 77 %-iisa missaat nipiliortitsisumit qulaanneqaraangamik nikinnerluunniit ajorput. Taamatut umimmaat immikkoortukkuutaartut nassaaralugit takusarnissaat kisitsinermut pingaaruteqarpoq, amerlassutsinik missiliuussineq tutsuiginaateqassappat.

Sisimiut Aqutsiveqarfiani umimmaat amerlanerpaat immamiit qatsissutsini 200 meterit missaanniinniarnerusarput, tassa umimmannut taakkununnga tamanna ilisarnaataavoq, tassami umimmaat taavaniittut pukkitsukujooqarfinni ukiuugaluartumiluunniit uumaniarnerusuugamik. Umimmaalli Maniitsup Aqutsiveqarfianiittartut allarluinnarmik pissusilersortarput, tassami immamiit qatsissutsini 700-800 meterit missaanni uninngaarniarnerusarmata, naak siusinnerusukkut appasissuniikkusunnerusarnikuugaluartut, <400 m. Aamma kisitsinerup nalaani umimmaat Aqutsiveqarfimmi Maniitsumi eqimattanut marlunnut immikkoorsimapput, motoorilinnik angallatinut inoqarfinniillu ungasissupilussuarnut tikikkuminaallisarsimapput. Kalaallit Nunaanni ukiumut umimmattarineqartartut tamavimmik 84 %-ii (piniartunit saniatigooralugulu umimmanniartartunit), taamatullu tammajuitsussarsiniartartut qiviunillu katersisartut umimmannit pissarsiarisartagaat Aqutsiveqarfimmit Maniitsumit pissarsiarineqartarput. Tamakku iliuusaasartut peqqutaaqataallutik nalinginnaasumik ukiuunerani umimmaat appasinnerusuni neriniartaraluartut qularnanngitsumik qummut nojaqqatsipaajaarsimavaat.

Aqutsiveqarfimmi Maniitsumit paasissutissat ilaasa takutippaat piaqqat (ukioq ataatseq inorlugu utoqqaassusillit) amerlassusiat umimmaat tamakkerlutik amerlassusiisa 18 %-erigaa. Sumiiffimmi pineqartumi kiisortoqannginnera eqqarsaatigigaanni, piaqqat amerlassusiattut missiliussaq appasigikulunnarpoq.

Peqqutaasinnaasut ilagaat imaassinnaasoq eqimavallaarnerinut tunngassutillit aammalu Aqutsiveqarfimmi Maniitsumi umimmaat ukiuunerani qatsissorujussuarni neriniarfissarsiortalersimammata. Ukulu ilimagisat kingulliit taasavut umimmaat Aqutsiveqarfimmiittut malunnartumik kingusinnerusumi piaqqisalernerinut nalaatsornerinnakkut piffissani pineqartuni pisalersimapput, immaqa tamakku taasavut peqqutaallutik piaqqiortarnerit pitsaanngitsumik sunnerneqartalersimapput. Tassa piaqqiarineqartartut sumiiffimmi pineqartumi amerlassusiat siunissami umimmaqassutsip naammattumik pilersorneqarneranik tunngaviliisuussanersut oqallisissaqqippoq.

Umimmaqassuseq eqimassusiannillu missiliuussisarnerit

Umimmaqassuseq eqimassusiallu naatsorsuutit atorneqartartut taaneqartartut Conventional Distance Sampling (DS) aamma Generalized Additive Models/Density Surface Modelling (GAM/DSM) atorlugit suliaapput, taamaalillunilu peqassutsimik aamma eqimassusiannik missiliuussinernik pissarsisoqarluni. Aqutsiveqarfimmi Maniitsumi umimmaat amerlanerpaat takuneqarpput (Angujartorfiup ilaa kisitsivigineqarluni). Aqutsiveqarfimmi Sisimiuni umimmaat ikinnerungaartut takuneqarput, tamatumalu kujataani Aqutsiveqarfik Sisimiut kujataani qulangiuaarigaluarnerni ataaserluunniit takuneqanngilaq. Natsorsuut GAM/DSM malillugu paasinarpoq martsi qaammat umimmaat Maniitsup Aqutsivianiittut assorujussuaq ammukkajaani kujammut sammisuniinniarnerusartut, Aqutsiveqarfimmullu tassunga tunngatillugu qatsinnerusumiittartut nalaatsortumik eqimanerusut takuneqarsinnaavoq.

Aqutsiveqarfik Avannaata tamakkerlugu umimmaqassusia naatsorsueriaaseq DS malillugu marts 2018-imi kisitsinerniit missiliuunneqarpoq **21,746-it** missaanni umimmaat amerlassuseqartut (95% CI: 11,061–42,751; CV = 28.5%; SE: 6,194), eqimassusiallu **1.1** umimmaat km^2 amerlassuseqarsimassasut missiliuunneqarluni (95% CI: 0.559–2.160; CV = 28.5%; SE = 0.313). Naatsorsueriaaseq DS naapertorlugu marts 2018 Aqutsiveqarfik Avannaa tamakkerlugu umimmaqassuseq missiliorneqarpoq umimmaat amerlas suseqarnissaat: **23,256** (95% CI: 18,102–29,877; CV = 11.36%), km^2-imut eqimassusiat **3.69** umimmaat amerlassuseqarnissaat missiliorneqarpoq (95% CI: 2.87-4.74).

Ataani sumiiffinni assigiinngitsuni umimmaqassutsimik missiliuussinerit imaapput:

***Aqutsiveqarfik Maniitsumi (Angujaartorfiup ilaa) umimmaat*:**
Naatsorsueriaaseq DS naapertorlugu umimmaat amerlassusiat missiliorneqarpoq: 18,906 (95% CI: 8,726–40,960; CV = 0.315; SE = 5,948) km^2-imut eqimassusiat 2.6 umimmaat amerlassuseqarnissaat missiliorneqarpoq (95% CI: 1.223–5.742; CV = 0.315; SE = 0.834).

Aqutsiveqarfik Sisimiuni (Aqutsiveqarfiup ilaani) umimmaat:
Naatsorsueriaaseq DS naapertorlugu marts 2018 umimmaqassuseq missiliorneqarpoq umimmaat amerlassuseqarnissaat: 2,840 (95% CI: 662–12,178; CV = 0.568; SE = 1,613), km^2-imut eqimassusiat 0,22 umimmaat amerlassuseqarnissaat missiliorneqarpoq (95% CI: 0.052–0.962; CV = 0.568; SE = 0.127).

Naatsorsueriutsit marluk assigiinngitsut atorneqartut inerneri assigiipajaarput, tassami naatsorsuutit nangaassutitaasa %-ii qaleriiffeqarmata. Naak nuna kisitsiviusoq annertoorujussuugaluartoq (kisitsiviusup tamakkerluni isorartussusiata 10.6 %-ia), paasissutissat pissarsiarineqartut nikerarpallaarnerisa kingunerinik DS missiliuussinerit nalornissutitaat annertungaatsiarput, kisiannili GAM/DSM natsorsuinerit taamarsuaq nangaassutitaqaratik. Taamaakkaluartoq, naatsorsueriaatsit marluk assigiinngitsut atornerisigut inernerusut sanilliuttaqattaarsinnaasimavagut. Naatsorsuinerit tunngavigalugit umimmannik takusaqarsinnaanissarput CV 5.98 %-inut naatsorsueriaatsip DS-ip takutippaa, ajunnginnervorli GAM/DSM-ip naatsorsusiornerinit, taassuma inernerimmagu CV 11,36 %. Taamaalilluta 2018-imi kisitsinernit misilittagarilikkagut aallaavigalugit umimmannik kisisisarnissani naatsorsueriaatsip DS-ip atorneragut siunissami siunnersuisarnissani atorneqartarnissaat innersuussutigaarput.

Kisitsinerit 2018-imi ingerlanneqartut kisiisa aallaavigalugit umimmaqassutsip ingerlarnga oqaatigineqarsinnaanngilaq. Taamaaliussaguttami periuseq taannaqqinnaaq atorlugu kisitsinernik ikinnerpaarpaanik marlunnik ingerlatsereersimasussaavugut. Utaqqiisaasumik, kisitsisarnerit siuliinit inernerusut, pisaasartut amerlassusiat, paasissutissat eqimassusiannut tunngassuteqartut piaqqallu amerlassusiinik misissuisarnernit paasissutissaatit - maannakkut pigineqartut - tamarmik takutippaat, umimmaat pineqartut amerliartunngitsut, immaqalu allaat 2018-imi kisitsinissat sioqqullugillu ikiliartulereersimassasut.

Aqutsiveqarfilli Maniitsoq Kalaallit Nunaanni umimmaqarfinnit tamanit amerlanerpaanik umimmaqartoq, pingaartumik 2018-imeersut kisitsisit qiviarlugit tamanna erseqqippoq. Kiisalu, Aqutsiveqarfik Maniitsumik umimmaat eqimassussiat

Issittumi tamarmi qaffasinnerpaamik inissisimavoq. Taamaattoqarnerata kingunerisinnaavaa umimmaat akornanni, imminnut qanippallaarneq peqqutaalluni, nappaatinik tuniluutikulanerulerneq. Maannarpiaq eqimavallaarnerinut tunngassuteqartut aporfiusinnaasut, sorlu umimmaqatigiiaat ataasiakkaat qassinik umimmattaqarnerat, eqqarsaatigalugit amerliartortinneqarnissaannik siunersuinissaq innersuussutigissallugu iluarpallaarunanngilaq. Naak 2018-imi kisitsisit pissarsiarisatta pasinarsisikkaluaraat nuna umimmaat neriniarfigisartagaasa umimmaqarpallaarneranut malinnaasinnaajunnaaleraluartoq immaqa, taamaattoq neriniartarfiit suli ersippput.

Resumé (dansk)

Denne rapport præsenterer resultaterne fra den første systematiske helikoptertælling af moskusokser i det sydvestlige Grønland. Tællingen dækker Region Nord (66-68° N), som blev opdelt i tre delområder: Angujaartorfiup, Sisimiut, og Sisimiut Syd. Tællingen blev udført i starten af marts 2018 og giver det første bestandsestimat af moskusokser i de to forvaltningsområder Maniitsoq (66-67° N) og Sisimiut (67-68° N).

De fleste grupper af moskusokser var upåvirkede af helikopteren, der fløj over dem i 40 meters højde. Uanset gruppens størrelse forblev 77 % af moskusokserne på det sted de først blev observeret. Det er derfor vigtigt at opdage stationære grupper for at kunne estimere bestandsstørrelser.

I Sisimiut blev moskusokserne oftest observeret i områder, der ligger ca. 200 m over havet (moh). Det er typisk for moskusokser, da de foretrækker at fouragere i lavtliggende områder, selv i vintermånederne. Moskusokserne i Maniitsoq blev derimod observeret i områder, der ligger 700-800 moh, selvom de året rundt normalt foretrækker lavtliggende områder under 400 moh. Desuden var moskusokserne i Maniitsoq på tællingstidspunktet klumpet sammen i to 'hot spots', som er meget vanskelige at nå med motorkøretøjer og som ligger relativt langt væk fra beboede områder. Da 84 % af al moskusoksefangst (både erhvervs- og fritidsfangst) samt næsten al trofæjagt og qiviut-produktion (qiviut = inderuld fra moskusoksen) i Grønland er rettet mod moskusoksebestanden i Maniitsoq, kan disse aktiviteter spille en rolle i den atypiske fordeling af moskusokserne i Maniitsoq i vinterhalvåret 2018.

Andelen af kalve (yngre end 1 år) blev bestemt til at være ca. 18 % for moskusokserne i forvaltningsområde Maniitsoq. Der ikke findes store rovdyr i området, og dette tal må derfor anses for at være lavt. Det lave tal kan bl.a. skyldes tæthedsafhængige faktorer i forbindelse med, at moskusokserne i forvaltningsområde Maniitsoq nu fouragerer i et

højtliggende og suboptimalt område i vinterhalvåret. Denne periode falder sammen med moskuskøernes drægtighedsperiode, og kan derfor have en negativ indvirkning på kalveproduktionen. Det vides ikke med sikkerhed, om den nuværende andel af kalve er tilstrækkelig til at sikre en stabil eller voksende bestand.

Estimering af bestandsstørrelse og bestandstæthed

Bestandsstørrelse og bestandstæthed blev estimeret ved at anvende metoder og analyser baseret på 'Distance Sampling' (DS) og på 'Generalised Additive Models'/'Density Surface Modelling' (GAM/DSM). De fleste moskusokser blev observeret i forvaltningsområde Maniitsoq (Angujaartorfiup-delområdet). Der var langt færre moskusokser i forvaltningsområde Sisimiut (Sisimiut-delområdet) og slet ingen i Sisimiut Syd-delområdet. Den GAM/DSM-baserede analyse pegede på, at moskusokserne i begyndelsen af marts i stor udstrækning foretrak de sydvestvendte skråninger, og at der især for Maniitsoq-moskusoksernes vedkommende var et sammenfald mellem de højeste bestandstætheder og højtliggende områder.

Bestandsstørrelsen i marts 2018 i hele Region Nord blev på baggrund af DS estimeret til 21.746 moskusokser med en tæthed på 1,1 moskusokser/km^2. Den alternative GAM/DSM-model estimerede bestandsstørrelsen i marts 2018 i hele Region Nord til 23.256 moskusokser med en gennemsnitlig tæthed på 3,69 moskusokser/km^2.

DS-estimater for de specifikke delområder var som følger:

- **Forvaltningsområde Maniitsoq** (Angujaartorfiup-delområdet): Bestanden af moskusokser blev på baggrund af DS estimeret til 18.906 moskusokser med en tæthed på ca. 2,6 moskusokser/km^2.
- **Forvaltningsområde Sisimiut** (Sisimiut-delområdet): Bestanden af moskusokser blev på baggrund af DS estimeret til 2.840 moskusokser med en tæthed på ca. 0,22 moskusokser/km^2.

De to beregningsmetoder giver sammenlignelige estimater af bestandsstørrelserne, da 95 %-konfidensintervallerne overlapper. Til trods for tællingens gode arealmæssige dækning (10,6 % af det samlede areal af Region Nord), var en stor variation i datasættet årsag til en betydelig usikkerhed i estimaterne i DS, men i mindre grad i GAM/DSM-estimaterne. Ikke desto mindre var det muligt at sammenligne de to fremgangsmåder ved at beregne variationskoefficienten for sandsynligheden for at opdage moskusokserne: Variationskoefficienten for DS var 5,98 %, hvilket var bedre end for GAM/DSM, hvor variationskoefficienten var 11,36 %. Derfor anbefaler vi, at man i forhold til 2018-tællingen baserer eventuelle forvaltningsbeslutninger på DS-baserede bestandsstørrelser og -tætheder.

2018-tallene kan i sig selv ikke bruges til at sige noget om bestandens udvikling. Dertil er der brug for yderligere mindst to punktestimater baseret på helikoptertælling og lignende beregningsmetoder. Tidligere optællinger, estimater af bestandstætheder, fangsttal og kalveandele tyder ikke på en nylig tilvækst i bestanden, men snarere et fald forud for 2018-tællingen. Dog er bestandsestimatet for moskusokser i forvaltningsområde Maniitsoq i 2018 højere end alle tidligere estimater for moskusoksebestande i Grønland. Tætheden af moskusokser i forvaltningsområde Maniitsoq er endvidere langt højere end andre steder i Arktis. Dette vil kunne medføre en forøget risiko for, at det enkelte dyr udsættes for smitsomme sygdomme. I lyset af de mulige negative, tæthedsafhængige effekter af den nuværende bestandsstørrelse anbefales det umiddelbart, at bestanden ikke vokser yderligere. Det er endnu ikke muligt at sige noget om, hvorvidt 2018-bestandsstørrelsen og -tætheden i Maniitsoq-området overskrider grænserne for, hvor mange planteædende dyr græsningsområdet kan bære.

Introduction

Muskoxen (*Ovibos moschatus* Zimmermann) are native only to the north and northeast part of Greenland. Nevertheless, there are currently several muskox populations in west and northwest Greenland. These resulted from translocations, excepting one (Inglefield Land), which is a combination of native and translocated muskoxen. Translocations began in the 1960s when 27 muskoxen live-captured in East Greenland were transported and introduced to Kangerlussuaq (Søndre Strømfjord) in West Greenland (Fig. 1). These animals became firmly established and until 2015 Pinngortitaleriffik – Greenland Institute of Natural Resources (GINR) publications referred to these as the Kangerlussuaq muskox population. Today, the Government of Greenland designates these as the Maniitsoq population. So named because they inhabit what was once the Maniitsoq municipality. From 1986 to 1991, the new Maniitsoq population became the source for several further muskox translocations along the west and northwest coast. Further, by the early 2000's some Maniitsoq animals expanded northward into what was then the Sisimiut municipality. Although not truly another population, harvest was managed separately in accordance with the then two separate municipal jurisdictions, and it became common to regard them as two populations, Maniitsoq and Sisimiut. In 2009, those two municipalities merged into one, Qeqqata Kommunia, however, harvest continues to be managed separately.

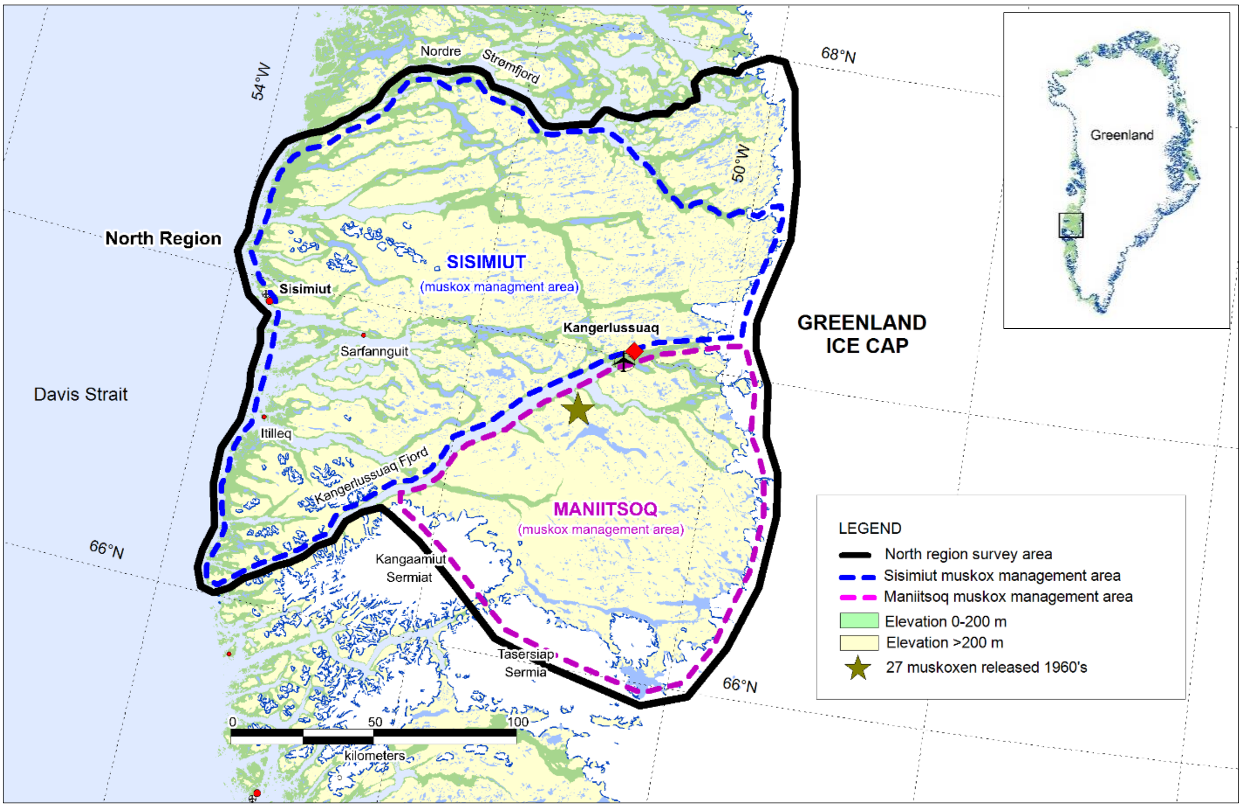

Figure 1. North region surveyed by helicopter in 2018, illustrating Maniitsoq and Sisimiut muskox management areas and the 1960's release location for the 27 translocated muskoxen originating from East Greenland.

Government regulated harvesting of the Maniitsoq muskox population began in 1988 with commercial harvest, and since 1993 has supported both recreational and commercial harvesting. Until 1998, annual harvests were typically under 500 muskoxen (Fig. 2). Starting in 2002, annual harvests increased sharply to more than 2,500 muskoxen by 2008 and generally declined thereafter with the 2017-2018 harvests almost half the peak value. Decreasing harvests contrast with steadily increasing hunter effort. For example, prior to the winter harvest season 2000 only hunters from Sisimiut and Maniitsoq participated. The Sisimiut hunters used primarily dogsleds, while the Maniitsoq hunters used ca. ten snowmobiles and in total there were ca. < 25 hunters. Since 2000, the number of motorized vehicles used for transportation to and from the hunting-areas has increased steadily (Hans S. Mølgaard & Nuka M. Lund pers. comm.). Recently, in the 2020 winter-hunt there were 60 hunters with motorized vehicles and in 2021 there were 70 hunters with motorized vehicles (Nuka M. Lund pers. comm.). The decrease in muskoxen harvested despite increased hunter effort suggests fewer muskoxen available. Causes would include decline in muskox population size or that muskoxen are increasingly adept at avoiding hunters.

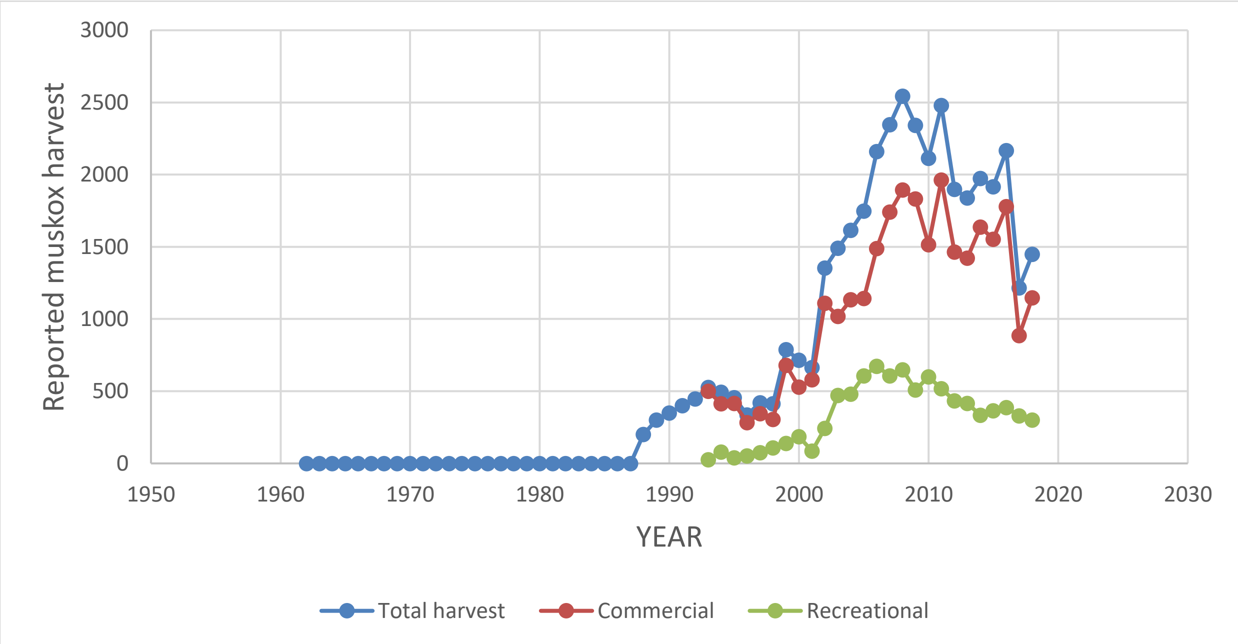

Figure 2. Reported harvest, commercial, recreational, and combined, for the Maniitsoq muskox population from 1962 to 2018. The 1988-1992 period was solely commercial harvest. Trophy harvest not included. Data from Piniarneq records.

Further to commercial and recreational hunting (Fig. 2), in the early 2000s trophy hunting began for Maniitsoq muskoxen. By the 2011/2012 season 108 muskoxen were killed as trophies. In 2012/2013 there were 120 trophy muskoxen killed (Cuyler & Raundrup 2014). Trophy hunting is now well established with specific hunting seasons and area concessions (i.e., area allocated for use by one trophy agent). As an industry, trophy hunting continues to grow (Naalakkersuisut 2018). Foreign trophy hunters pay up to Danish kroner 50.000,00 (ca. 7,900.00 US Dollars / 6,700 EUR) per trophy. In 2016, 236 muskoxen were killed as trophies and provided the Greenland government with revenues totally Danish kroner 312.000,00 (ca. 49,200.00 US Dollars / 42,000 EUR). In 2017, trophy hunting rose by 46% with 354 trophy muskoxen killed, which provided Danish kroner 548.000,00 (ca. 86,500.00 US Dollars / 73,700 EUR). Additionally, the Greenland qiviut (muskox wool) industry is founded primarily on the winter harvest of Maniitsoq muskoxen, and owing to increasing demand worldwide, over the past decade the qiviut industry expanded.

All the above attests to a substantial economic contribution to local communities from their use of today's Maniitsoq muskox population, and to a lesser extent also the Sisimiut muskoxen. Given declining annual harvests since 2008, ascertaining population abundance and trend are essential for appropriate management decisions for sustainable harvesting in the future.

In the past, infrequent winter ground surveys by snowmobile, over limited areas, provided minimum counts of the number of muskoxen observed (Appendix 1). Within the Maniitsoq management area (Fig. 1, Table 1), minimum counts in the period 2000-2006 ranged from 4186 to 5092 observed muskoxen. Applying Bayesian analysis to the 2000-2004 minimum counts resulted in a 2004 population estimate of ca. 7,312 (90%CI: 5538-10202) muskoxen in the Maniitsoq management area that was covered by the winter ground surveys (Cuyler & Witting 2004). Ground surveys of the Sisimiut management area were rarely completed. When these occurred, few muskoxen were observed, and ground effort was tiny relative to the management area.

This report focuses on the muskox population size estimates for Maniitsoq and Sisimiut attained in conjunction with the 2018 aerial helicopter survey of the Kangerlussuaq-Sisimiut (KS) caribou population in the North region. The name, North region, indicates a relatively northern geographical position within the context of West Greenland and delineates KS caribou distribution. The Government of Greenland's muskox harvest management areas, Maniitsoq and Sisimiut, are contained within the North region's boundaries (Fig. 1).

Present survey

This is the first Conventional Distance Sampling (DS) aerial survey of muskoxen in the Maniitsoq and Sisimiut management areas. This report investigates the DS data set for muskox observations obtained for those areas during GINR's March 2018 caribou survey, which is described in Cuyler et al. (2021). Initially, we use DS analyses to present the first ever pre-calving population estimates of muskox density and abundance for the Maniitsoq and Sisimiut muskox harvest management areas. Then, we create a Density Surface Model (DSM) for the muskoxen, where density can be spatially represented as a function of additional covariates collected during surveying. The DSM produces alternative estimates of density and abundance for Maniitsoq and Sisimiut muskox harvest management areas.

The report provides the first ever population size estimates for muskoxen in the North region and then presents separate estimates for the Maniitsoq and Sisimiut muskox management areas. It also presents information on immediate muskox reaction (movement or lack thereof) to the helicopter fly-by of muskox groups detected, and an approximate calf percentage for the Maniitsoq muskox management area.

Note that an earlier analysis for 2018 muskox abundance and density in the Maniitsoq and Sisimiut management areas was run on the same data (Marques 2018), however, the then known areas (km²) were incorrect. Marques' paper from 2018 is an internal CREEM (Centre for Research into Ecological and Environmental Modelling (St. Andrews, Scotland)) report, which is available upon request.

Table 1. Current naming of region, municipality, muskox population, harvest management- and surveyed areas for 2018 in West Greenland that are specific to this report.

Region	Municipality	Greenland Government Muskox harvest management area	Muskox Population	Surveyed sub-area 2018
North	Qeqqata kommunia	Sisimiut management area	Sisimiut	Sisimiut
North	Qeqqata kommunia	Maniitsoq management area	Maniitsoq[1]	Angujaartorfiup

[1] Previously referred to as the Kangerlussuaq muskox population, in GINR documents.

Methods

Study area

The North region is within Qeqqata Kommunia in West Greenland. Although Qeqqata Kommunia has ca. 9,400 inhabitants (in 2020), not all live within the boundaries of the North region. The only large settlement within the region is the coastal city of Sisimiut, with ca. 5,600 inhabitants, followed by the ca. 500 residing in the town of Kangerlussuaq. The latter is located on the eastern inland side of region near the Greenland Ice Cap and is also the site of Greenland's primary international airport. Together, the tiny coastal villages of Itilleq and Sarfannguit contain a further 200-300 people.

The North region is seasonally ice-free and covers an area of 23,303 km², (excluding lakes, rivers, sand, glaciers, and islands). Previous surveys reported a less precise land area of ca. 26,000 km² (Cuyler et al. 2002, 2005, 2011). Located between 66-68° N Lat, the

Arctic Circle (66.5° N Lat) passes through the North region. The northern border is provided by the Nassuttooq Fjord (Nordre Strømfjord). The southern border is formed by two ice caps (i.e., Kangaamiut Sermiat (Sukkertoppen Ice Cap) and Tasersiap Sermia) and the western portion of the Kangerlussuaq Fjord. Elevations reach ca. 1700 on the Kangaamiut Sermiat and ca. 1800 m on the Tasersiap Sermia. The outer half of the Kangerlussuaq Fjord is ice-free year-round and dominated by cliffs of ca. 1000 m. The western border of the region is the permanently ice-free seacoast of the Davis Strait, and eastern border is the Greenland Ice Cap.

The North region's coastal topography is mountainous with peaks whose elevation can be 1000-1800 m and glaciers are common. The Kangerlussuaq Fjord penetrates the region, from SW to NE, ending just before the town of Kangerlussuaq, i.e., close to the Greenland Ice Cap. The Kangerlussuaq Fjord is the primary boundary separating the Maniitsoq and Sisimiut muskox management areas. In the Sisimiut area, moving eastward, the coastal mountains gradually give way to rugged terrain generally ranging 10-900 m elevation. In the Maniitsoq area, immediately north of the two ice caps, Kangaamiut Sermiat and Tasersiap Sermia, the terrain is generally barren highlands with elevations > 1000 m. Continuing northward towards the town of Kangerlussuaq, elevations decrease, and the terrain includes lowland valleys < 400 m elevation and highlands of generally < 1000 m elevation.

Common to West Greenland, the North region exhibits a climate gradient on a west-east axis. The western seacoast is wet maritime; however, the climate becomes dry continental as one moves east towards the Greenland Ice Cap. Climate and weather in the west are under the maritime influences of the ice-free Davis Strait and the low-pressure oceanic storm systems that sweep in from the southwest. The climate in the inland of the North region, specifically the Maniitsoq area, is influenced by two ice caps at its southern boundary, the Kangaamiut Sermiat and Tasersiap Sermia. These have elevations of 1,700-1800 m respectively, and act as a barrier to the oceanic storm systems mentioned above, creating a precipitation shadow on the northern side, which in combination with the dominating high pressure over the Greenland Ice Cap creates the inland's xeric continental climate. Loess/sandstorms are common near the town of Kangerlussuaq (Cuyler et al. 2005). These are caused by katabatic winds, föhn winds descending off the Greenland Ice Cap, which are dry and can have speeds of 30-60 m/s (Putnins 1970, Rasmussen 1989, Tamstorf 2004). Between Kangerlussuaq, and the Greenland Ice Cap, there are two heavily braided rivers, the Akuliarusiarsuup Kuua and Qinnguata Kuussua. The associated valleys exemplify the above conditions, and their Danish names, Sandflugtdalen and Ørkendalen, translate loosely into 'Blown Sand Valley' and 'Desert Valley', respectively. Further, föhn winds can cause sharp increases in ambient temperature, which in winter or spring can result in extensive snowmelt (Hansen 1999). At Kangerlussuaq winter föhn winds produce large snow-free expanses (Fredskild 1996).

In general, the vegetation of the North region may be described as open or alpine tundra. Vegetation is dominated by low arctic species of mainly dwarf shrub heath, which changes to predominantly steppe and grassland when moving east towards the Greenland Ice Cap, where lichen heaths are rare (Tamstorf et al. 2005). Specifically, the Angujaartorfiup sub-area is a grass steppe landscape (Nellemann 1997). Higher elevations are often fell field, abrasion plateaus and bare ground (Tamstorf et al. 2005).

Aside from the now firmly established translocated population of muskoxen, native wild mammals present in the North region are caribou (*Rangifer tarandus groenlandicus*), arctic hare (*Lepus arcticus* Rhoads) and arctic fox (*Vulpes lagopus* Linnaeus). Large mammalian predators are absent.

Field methods

This study was possible owing to the 2018 aerial survey for caribou. The aerial survey occurred 01-15 March 2018 using a helicopter AS350 as the platform for observation. Period and platform were chosen as per criteria for caribou (details in Cuyler et al. 2021). A constant altitude above ground level was maintained while flying low (40 m) and slow (ca. 65 km/hour).

Participants included three observers, all with previous survey experience: GINR's senior scientist Christine Cuyler, GINR's project coordinator Peter Hegelund, and professional hunter Aslak Jensen (Greenland Association of Professional Hunters (KNAPK)) from Nuuk. Jensen and Hegelund were seated in the rear of the helicopter and observed animals for all distances from the side they were sitting, which alternated each time the helicopter was refueled, which was usually once daily and sometimes twice. Cuyler always sat in front, observed the track line, including distances to either side up to 100 m, and was the data recorder. Verbal contact among the observers permitted the digital audio recording of all observations. Two audio devices (SONY IC recorder, ICD-SX712) were used to record separately the observations specific to the left and right side of the line transect. Audio recording devices were on continual recording for each line transect. At the end of each survey day, audio data was downloaded to computer for storage and back-up. Observations were later paired with Global Positioning System (GPS) coordinates of the helicopter at the time of observation. The audio recording included distance to (see below), and size of, each muskox group observed and name of the observer. Often, behavioral reaction/flight by muskox groups and environmental conditions were recorded.

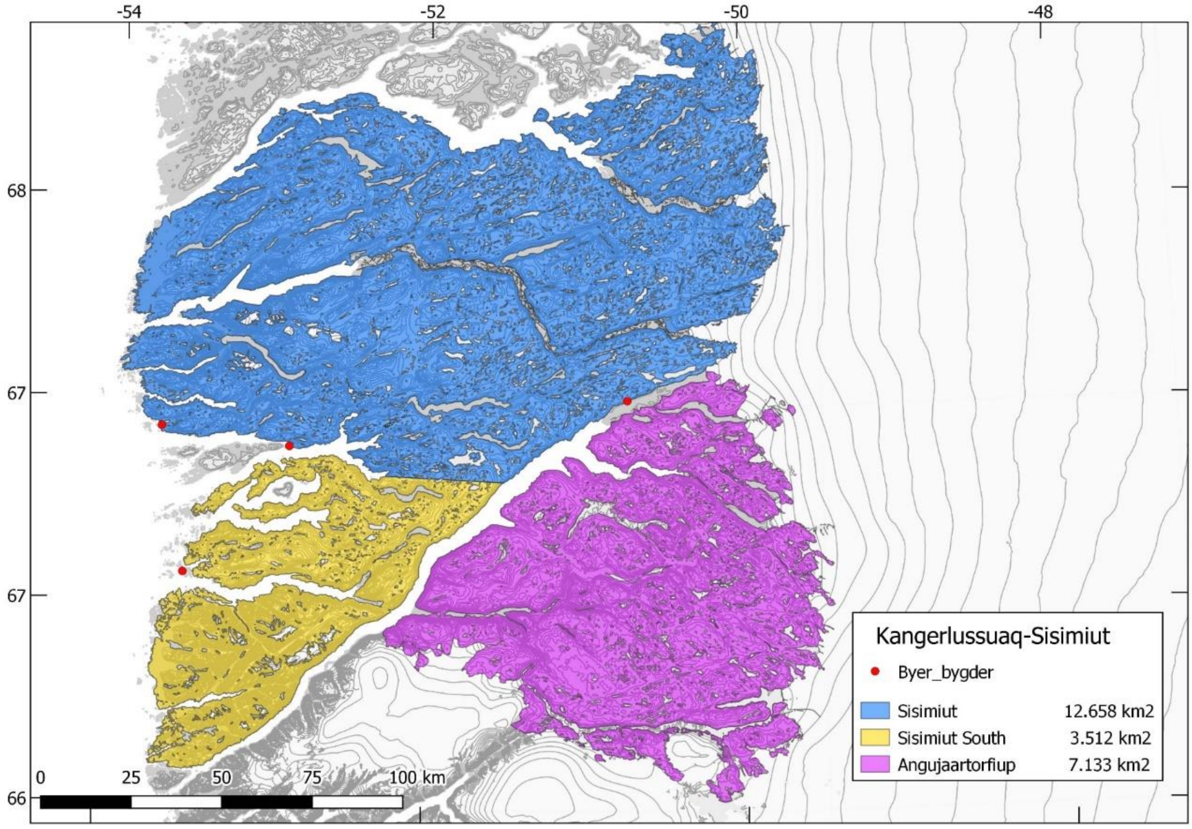

Figure 3. Area covered by the 2018 caribou survey of the North region (23,303 km²). Three different colours illustrate the three sub-areas, designated as Sisimiut (blue), Sisimiut South (orange) and Angujaartorfiup (purple). The term 'Byer bygder' refers to city/town/village identified in Fig. 1.

Survey design

The surveyed North region area, 23,303 km², was divided into three sub-areas (strata), arbitrarily named Sisimiut (12,658 km²), Sisimiut-South (3,512 km²) and Angujaartorfiup (7,133 km²) (Fig. 3). The sampling design for the 2018 survey considered 19 systematic parallel line transects of variable length separated by 15 km and placed over the three sub-areas (Fig. 4). Those transects provide the maximum area coverage possible given the financial resources available. An initial line transect was computer generated at random, and the others followed 15 km apart. Aligning line transects perpendicular to known gradients within the surveyed area can maximize precision of the resulting estimate by lowering the encounter rate variance (Buckland et al. 2001). Thus, the transect axis direction was chosen as perpendicular to previously known animal distribution gradients in March. Lines 1 to 13 followed a west-east axis, which also reflects the climate gradient from wet maritime to dry continental. Line transects 14 to 19 followed a north-south axis, reflecting animal, climate, and topological gradients that exist between the combined ice caps (Kangaamiut Sermiat and Tasersiap Sermia) and the town of Kangerlussuaq.

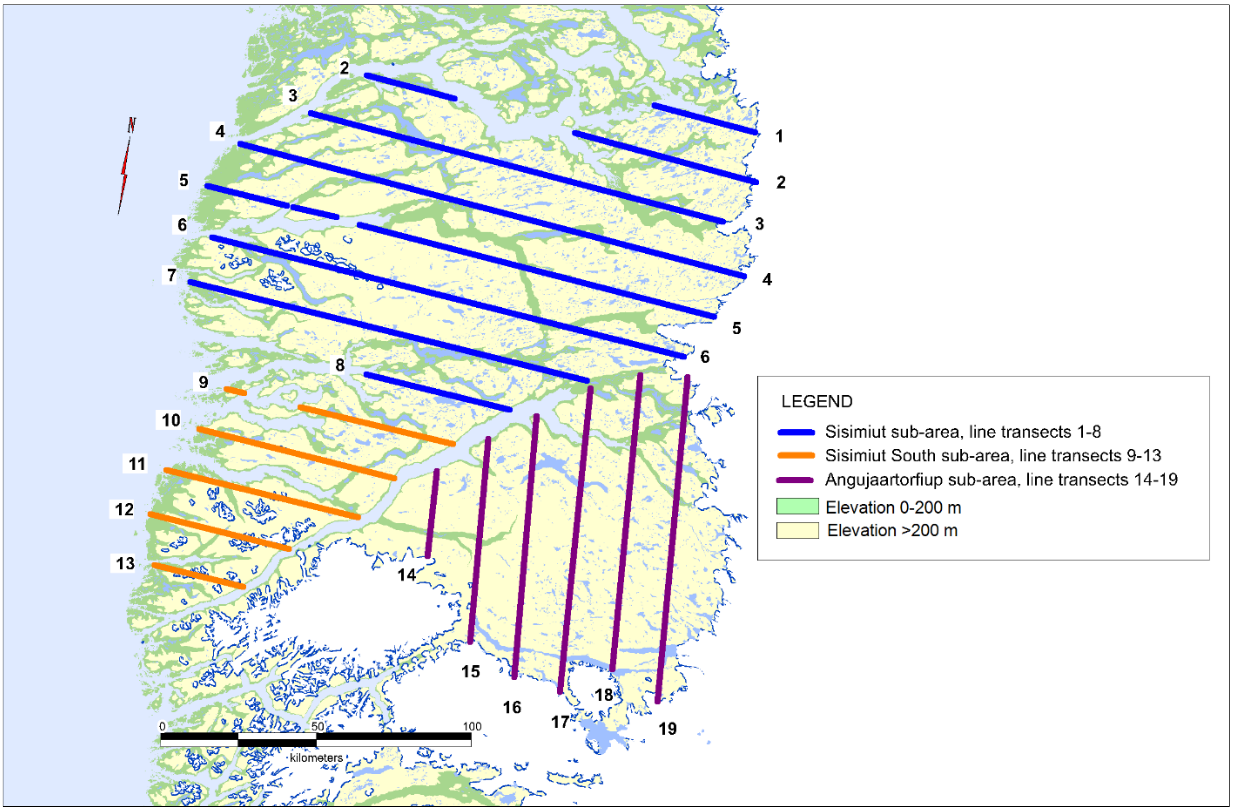

Figure 4. The 19 line transects used in the 2018 survey of the North region, employing the same three colours as applied to the three sub-areas in above figure 3: Sisimiut (blue), Sisimiut South (orange) and Angujaartorfiup (purple).

Distance collected was the perpendicular distance from the helicopter's flown track line to a muskox group (object-of-interest), i.e., one or more animals. Tightly cohesive behavior identified groups of multiple individuals. Distance recorded was the observer's instantaneous and subjective distance to the approximate center of the muskox group from the track line before any movement by the group occurred. Exact distance measurements were not possible primarily because of practical considerations for this survey (details in Cuyler et al. 2021). Instead, distance measurement used the following distance bins: 0, 50-, 100-, 200-, 300-, 400-, 500-, 750- and 1500-meters perpendicular to the line transect. These values correspond to the upper limit for a specific bin that the muskox observation was included in. For analysis, these were recoded to the mid distance for a specific bin. Note, binning accuracy relies heavily on observer ability to correctly estimate distance to the observed animals. Thus, before starting the survey the helicopter hovered at the 40m altitude used during line transects, while each observer used a Leica laser range finder 1600 to gauge distances across the terrain. Then they marked their window with masking tape delineating the approximate distances for each bin. When possible while flying line transects, the laser range finders were used to double-check reported bin distances to detected groups. The recorded distances are used to estimate a detection function, then estimate the detection probability and finally to estimate the density of the muskoxen within the surveyed area (Buckland et al. 2001). The detection function, $g(y)$, describes the probability of detecting an object-of-interest given that is at a distance y, from the centerline (0-line), thus being a non-increasing function of y (Buckland et al. 2015). For line transects, y is the perpendicular distance from the 0-line to the detected object. Within DS methods, the probability of detection is explained recurring to these observed distances (Buckland et al. 2001).

Distance Sampling

The muskox group was the selected sample unit for the DS analysis of the 2018 survey. Neither the individual muskoxen within a group, nor individual line transects were considered as the sample unit.

The recorded distances to the observed muskox groups were used to estimate a detection function. With this, both the muskox detection probability and density within the surveyed area could be estimated (Buckland et al. 2001). The detection function describes the probability of detecting an object-of-interest (muskox group) that is at a distance y, from the centerline (track line), thus being a non-increasing function of y (Buckland et al. 2015). For line transects, y is the perpendicular distance from the track line to the detected object. Within DS methods, the probability of detection is explained recurring to these observed distances (Buckland et al. 2001).

Prior to DS analysis, the raw data was first processed for inconsistencies, e.g., species or observer names written slightly differently had to be standardized before analyses to avoid being assigned a different category, and one observation lacked distance (replaced by the average observed distance). Then extensive exploratory data analysis was completed, including evaluation of observed distances, before proceeding to determining the detection function through model fitting and selection (Buckland et al. 2001; Marques et al. 2011; Thomas et al. 2010). To determine the detection function, several models were considered (Thomas et al. 2010). The model presenting the lowest AIC value was chosen. The subsequent analysis was based on Marques (2018). Details regarding DS theory, methods and analysis are available in Buckland et al. (1993, 2001, 2015), and a briefer summary provided in Appendix 2. For analysis, we used R Statistical Software (https://www.r-project.org/).

Generalized Additive Model (GAM)

Generalized Additive Models (GAM) are an extension to Linear Models (LM) and Generalized Linear Models (GLM) where non-linear responses with smoothing functions can be fitted to the data. Details regarding Generalized Additive Models, methods and analysis are available in Wood (2017), and a briefer summary is provided in Appendix 3.

Density Surface Model (DSM)

Conventional DS methods provide average estimates of abundance over a region but no information about the distribution of the objects of interest within the survey region. An efficient option is to build a spatial model that incorporates spatially referenced environmental covariates. Density surface modelling uses the GAM framework (Wood, 2017) to build models of abundance/density as a function of environmental covariates, typically as part of a two-stage method (Fig. 5). In the first stage, the detectability via DS is modelled and in the second stage the counts, corrected for detectability, are modelled over space. Details regarding DSM, methods and analysis are available in Katsanevakis (2007) and Miller et al. (2013). Briefer summary is in Appendix 4.

Figure 5. Flow diagram of the modelling process during the analysis, from the Distance Sampling analysis through to the Density Surface Modelling.

Results

Table 2. Summary of unprocessed results: Survey of the North region, 03-15 March 2018, Maniitsoq and Sisimiut populations by helicopter in the.

Parameter	North region sub-area			Total
	Sisimiut	Sisimiut South	Angujaartorfiup	
Flight altitude (m)	40	40	40	**40**
Flight speed (km/hr)	60-70	60-70	60-70	**60-70**
Sub-area size (km^2)	12,658	3,512	7,133	**23,303**
Number of lines	8	5	6	**19**
Distance flown (km)	916.5	258.1	470.5	**1,645**
Strip width[1] (m)	1000-1500	1000-1500	1000-1500	**1000-1500**
Coverage[2]	14.5-21.7 %	14.7-22 %	13.2-19.8 %	**14.1-21.2 %**
Coverage after truncation[3]	10.9 %	11.0 %	9.9 %	**10.6 %**
Total muskox observed	183	0	1,467	**1,650**
# Muskox groups observed	24	0	232	**256**
GROUP SIZE				
Mean	7.6	0	6.3	**6.4**
Standard Error	1.95	0	0.37	**0.38**
Median	3	0	4	**4**
Mode	3	0	2	**2**
Std Deviation	± 9,5	0	± 5.7	**± 6.1**
Sample variance	91.03	0	32.50	**37.79**
Maximum	35	0	30	**35**
Minimum	1	0	1	**1**

[1] Strip width provided is to one side of helicopter only. Must double for total strip width.
[2] Coverage prior to truncation of strip width to 750 m.
[3] Coverage after truncation of strip width to 750 m each side helicopter, for Distance Sampling analyses (see page 24).

Survey logistics & unprocessed data

In the period 01-15 March, we flew 11 of those days. Poor weather made three days non-flyable, as did airport closure one Sunday. Flight time totaled ca. 54 hours and 08 minutes, of which ca. 24½ hours were survey effort flying the 19 line transects. A further ca. 10 hours was effort to obtain caribou demographics, as this was primarily a survey for caribou. The remaining 19-20 hours were used for ferry and refueling flights. Typical of AS350 helicopters carrying three passengers and pilot, refueling was necessary after about 3 hours of flight time, an additional 15-20 minutes of flying were possible when wind conditions and distance to nearest airport permitted. The 2018 survey used 19 line transects for a total distance flown of 1645 km, i.e., Sisimiut 916.5 km, Sisimiut South 258.1 km and Angujaartorfiup 470.5 km. It was necessary to ferry the helicopter from Nuuk to Kangerlussuaq airport for the survey and return it to Nuuk once the survey was completed. Each of those ferry flights typically requires 1 hour and 45 minutes at an air speed of 110 knots (ca. 204 km/hour), however, added maneuvers to avoid fog and low cloud increased flight time on both trips.

Although tape on the windows marked the approximate distances for each bin, a relatively correct bin required level terrain. The rugged topography of the study area meant terrain sloped down or up from the helicopter's position, often sharply, which made marked windows of limited use. Observers then resorted to subjectively estimating bin distances to animals.

Given the 1645 km of line transects flown, an optimistic calculation of survey coverage of the North region's total area (23,303 km²) would be 14.1-21.2%, i.e., topography permitting and assuming maximum strip width of 1000-1500 m to either side of the helicopter. However, for analyses (see Distance Sampling analysis, page 25), the strip width was truncated to 750 m. Thus, coverage was 10.6% for final abundance estimate. The raw total of observed muskox groups was 256, for a raw count of 1,650 muskoxen (Table 2). Mean group size was 6.4 muskoxen, and median group size was 4 muskoxen.

Table 3. Behavioral reaction of muskoxen to helicopter fly-by, as per group size and distance from the centreline, North region survey, March 2018. Non-truncated dataset containing all three variables, muskox group size, behavior, and distance (n= 176 groups; 1,086 individuals).

Parameter	Muskox group reaction to helicopter fly-by			
	Running Away	Walking	Mixed[1]	Standing[2]
Sample size (no. groups)	30	2	9	135
% Group observations	17%	1%	5%	77%
GROUP SIZE				
Mean	6.1	1	8.8	6.1
Confidence Level (95%)	2.0129	0	3.6618	1.0821
Standard Error	0.9842	0	1.5880	0.5471
Median	4	1	8	4
Mode	2	1	NA	1
Standard deviation	5.4	0	4.7639	6.3569
Sample Variance	29.0586	0	22.6944	40.4100
Range	21	0	14	34
Minimum	1	1	2	1
Maximum	22	1	16	35
Number muskoxen involved	183	2	79	822
DISTANCE				
Mean	245	850	172	627
Confidence Level (95%)	111.0553	8259.0331	77.1332	88.9430
Standard Error	54	650	33.4489	44.9701
Median	100	850	200	400
Mode	50	NA	200	1500
Standard deviation	291.96	919.24	100.35	522.50
Sample Variance	85240.1478	845000	10069.4444	273011.8850
Range	1450	1300	250	1450
Minimum	50	200	50	50
Maximum	1500	1500	300	1500

[1] Mixed was combination of running away and standing.
[2] Includes defensive clumps of animals huddling together.

Muskox behavior: group reaction to helicopter fly-by

The survey of 2018 was the first to use digital audio recorders to collect behavioral observation data from West Greenland muskoxen. The digital recorders permitted including in the dataset what, if any, was the behavioral reaction of the muskox group to the helicopter flying a line transect past or over them. Behavior could then be put in relation to group size and distance from the line transect.

Although a total of 256 muskox groups were observed, behavioral reactions were recorded for only 176 of these groups, and not recorded for the remaining 80. Reactions of groups included running away from the helicopter (n = 32), standing (n = 135), mixed running and standing still (n = 9), and walking (n = 2) (Table 3). We were able to record calf presence for 36 out of the 176 groups with behavior recorded. Calves were present in 88% of eight groups with mixed running and standing behavior, in 78% of nine groups running away and in 58% of nineteen groups standing still. Thus, calves were typical among groups exhibiting running away behavior. However, calves were also present in well over half of the standing groups, and one standing group contained seven calves. Whether running away, standing, or mixed, calf presence did not predict behavioral reaction by muskox group ($P > 0.05$).

Muskox groups typically did not flee from the helicopter fly-by. Standing was the reaction for 77% of muskox groups, while running away was the reaction in 17% of the groups. Mixed reactions (included some running and standing) were exhibited by 5% of groups and walking by 1%. The latter involved two solitary bulls. Otherwise, group size did not vary significantly ($P > 0.05$) with the behavioral reaction (i.e., running away, standing, mixed) of the group to the helicopter fly-by. Notably, the behavioral opposites, running away or standing, had the same mean group size, 6.1 muskoxen. In contrast to group size, distance from the line transect flown by the helicopter affected the behavioral reaction. Muskox groups that ran away were substantially closer to the helicopter fly-by than standing muskoxen. For example, there was a significant difference between the mean distance at which groups ran away, 245 m, or were standing still, 627 m (t Stat = -5.54183; two-tailed testing $P < 0.0001$, $t = 1.99084$, $df = 78$).

Elevations where muskoxen observed

Elevation use by the muskoxen in early March was approximated from the GPS dataset for helicopter elevation and position and matching those timestamps with those of the digital audio recording of muskox observations. GPS and digital recorder timestamps were synchronized before the survey began. Before analysis, the helicopter's flight altitude of 40 m was subtracted from all elevations. Thereafter, and lacking a reliable constant correction factor, negative values were deleted.

All elevation results for muskoxen are approximate values (Table 4). There were several sources of error. The Greenland topography is mountainous and elevation changes can be abrupt, which could place the helicopter at a radically different elevation than the muskoxen observed. Matching the timestamps could create errors on muskox elevation when the digital recording was made before or after the helicopter passed the muskoxen's location. Even muskox on the track line flown did not necessarily receive correct GPS positions. Owing to flight behavior, these muskoxen were often digitally recorded while still some distance in front of the helicopter's position. Additionally, muskoxen not on the track line flown could be in terrain at a higher or lower elevation than the helicopter. From the author's experience, most muskoxen observed would have been at elevations below that recorded for the helicopter, even after subtracting the flight altitude of 40 m. Further error arose from the GPS device itself. Starting each day, the GPS device was manually synchronized to the Kangerlussuaq airport elevation, but commonly by the end of the day the GPS devise's value had changed.

Table 4. Approximate elevations for muskox groups observed in the Sisimiut and Angujaartorfiup sub-areas during the helicopter survey of the North region, 03-15 March 2018.

Parameter	North region sub-area		Total North region
	Sisimiut	Angujaartorfiup	
Sample size (no. groups)	22	222	**244**
ELEVATION			
Mean	310	521	**502**
Standard Error (SE)	41.4	16.8	**16.2**
Median	241	509	**476**
Mode	198	772	**772**
Standard Deviation	± 194	± 250	**± 252**
Variance	37789	62470	**63763**
Range	715	1099	**1099**
Min	97	34	**34**
Max	811	1133	**1133**
Confidence Level (95%)	86.2	33.1	**31.8**

Considering the above, the Sisimiut muskoxen used lower elevations than the Angujaartorfiup muskoxen. The Sisimiut mean was 310 m, median 240 m, mode 198 m, while Angujaartorfiup was mean 521 m, median 509, mode 772 (Table 4). The difference was statistically significant (t-Stat = -4.729, df = 28, P = 0.00006).

Calf production

Insufficient resources made a specific effort directed at obtaining accurate muskox demographics impossible. Nevertheless, we calculated a rough indication of calf percentage for Angujaartorfiup and Sisimiut combined. Of the 256 groups (n = 1,650 muskoxen) observed during DS (Table 2), calf absence/presence was recorded for 41 groups (n = 272 muskoxen). Demographic composition observed was not likely influenced by behavioral reaction by muskoxen to the helicopter fly-by, since calf presence did not predict a group's behavioral reaction ($P > 0.05$). Calf percentage was approximated from this small data subset that contained both group size and composition, i.e., number of calves (age < 1-year) and all others (age > 1-year). Calves were identified by their much smaller bodies relative to all other muskoxen. Of the 41 muskox groups with known composition, 71% (n = 29) contained calves. The groups with known demographics totaled 272 muskoxen including 50 calves, which suggests a possible 2018 calf percentage of ca. 18.4%.

Data processing for Distance Sampling analyses

The raw data set was in Excel format containing the survey variables, including region, sub-area, respective areas (km^2), transect identification, recorded distances, group size, and GPS coordinates. Sometimes included with muskox group observations were flight characteristics such as helicopter velocity, survey characteristics such as glare, shade, snow covering and depth. Owing to inconsistent categorization and recording, most of the latter were not included in the analysis. Data pertaining to habitat changes were removed because these concerned habitats exclusively i.e., there were no muskox observations associated. The remaining variables were properly restructured within R Statistical Software.

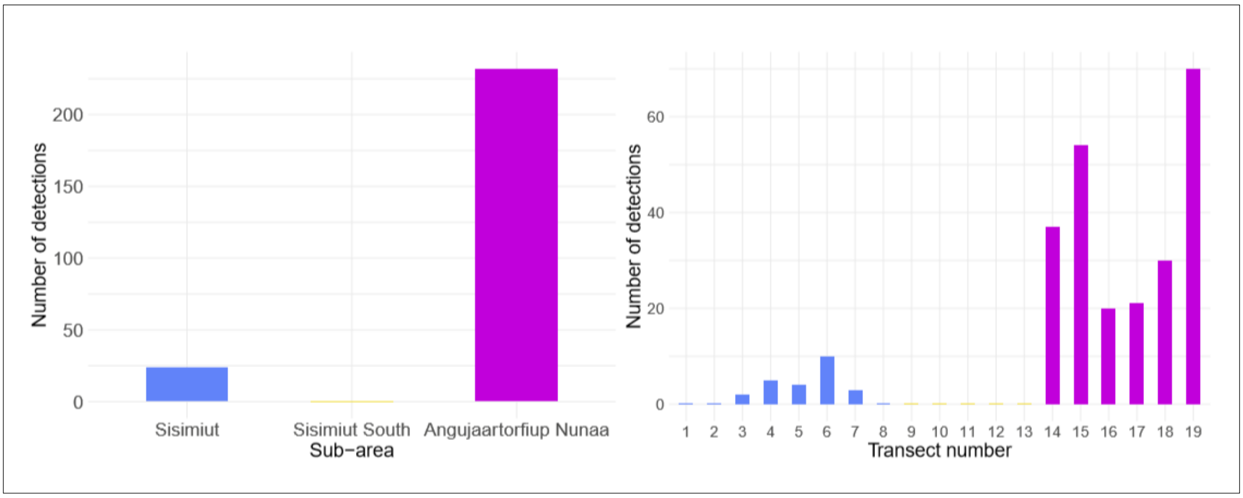

Figure 6. Muskox survey 2018: exploratory analysis plots for the non-truncated number of detections by sub-area (left), and number of detections per line transect by sub-area (right): Sisimiut (blue), Sisimiut South (orange) and Angujaartorfiup (purple). There were zero observations in Sisimiut South sub-area (line transects 9-13).

The data set was subject to some prior processing before analysis. Comment fields were deleted. Variable names were recoded to make them sensible in R. Only one (n=1) muskox group observation lacked a distance, and none lacked their group size value.

Given just one observation relative to the large amount the data, the actual impact of using any given distance value is minor. Thus, we used the average observed distance.

Preliminary analysis Distance Sampling

For reliable estimates of abundance, Buckland et al. (2001) suggests that sample size is at least 60 to 80 observations and from a minimum of 10 to 20 replicate line transects. The 2018 survey for muskoxen in the North region met these recommendations, since the sample size was 256 observations, i.e., detections of groups of (one or more) muskoxen, from a total of 19 parallel line transects separated by 15 km. Each transect took from as few as 30 minutes to several hours to be fully sampled. This depended on number of segments and total length. In the Angujaartorfiup sub-area, muskoxen were detected on all six of the line transects, but in the Sisimiut sub-area were detected on just Line transect number transects. No muskoxen were detected on any of the five line transects in the Sisimiut South sub-area. Of the three sub-areas, Angujaartorfiup dominated in observation frequency, i.e., number of detected muskox groups per sub-area (Fig. 6).

The detected objects of interest, i.e., muskox groups, averaged 6.4 animals, while the median was 4. The most observed group size was two animals (n=39 observations) (Fig. 7). Groups consisting of less than five individuals made up 52% of the observations, while groups counting less than ten individuals made up 77%.

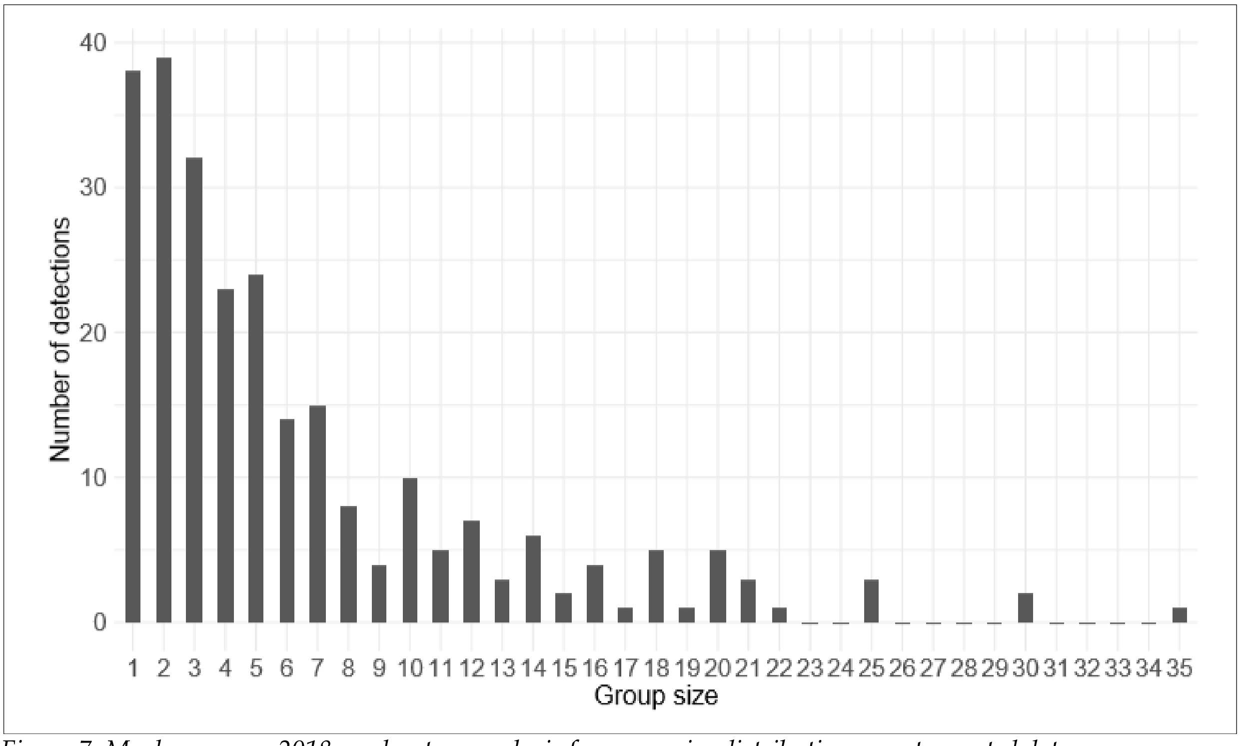

Figure 7. Muskox survey 2018: exploratory analysis for group size distribution, non-truncated data.

Regarding groups of muskoxen, the number of detections per unit transect length is the encounter rate. Considering the entire North region altogether, non-truncated data had a mean encounter rate of 0.016 muskox groups per kilometer. Specifically, the Sisimiut sub-area had a mean encounter rate of 0.003 muskox groups per kilometer, while the Angujaartorfiup sub-area had a mean of 0.026. No muskoxen were encountered in the Sisimiut South sub-area. Within the sub-area Sisimiut, encounter rates were zero for three line transects and sparse for the remaining five. For the Angujaartorfiup sub-area, the encounter rates were high in two possible hot spots, the east and west sides of the sub-area, and were least in the middle (Fig. 8).

Histograms examining observer effects (Fig. 9) were somewhat dissimilar and therefore this covariate will be investigated as to whether it influenced results for detectability. Other potential covariates, like sun glare or snow covering, were available but there were too many missing observations and/or inconsistency when referring to the categories for these to be used in the analysis.

The preliminary analysis provides the expectation of less precision in further analyses of detections within the Sisimiut sub-area, because of data variability. Precision is expected to be greater for Angujaartorfiup, as all line transects contained muskoxen. Nevertheless, the information agreed well with anticipated a priori, e.g., Angujaartorfiup sub-area would have more muskoxen than the other two sub-areas.

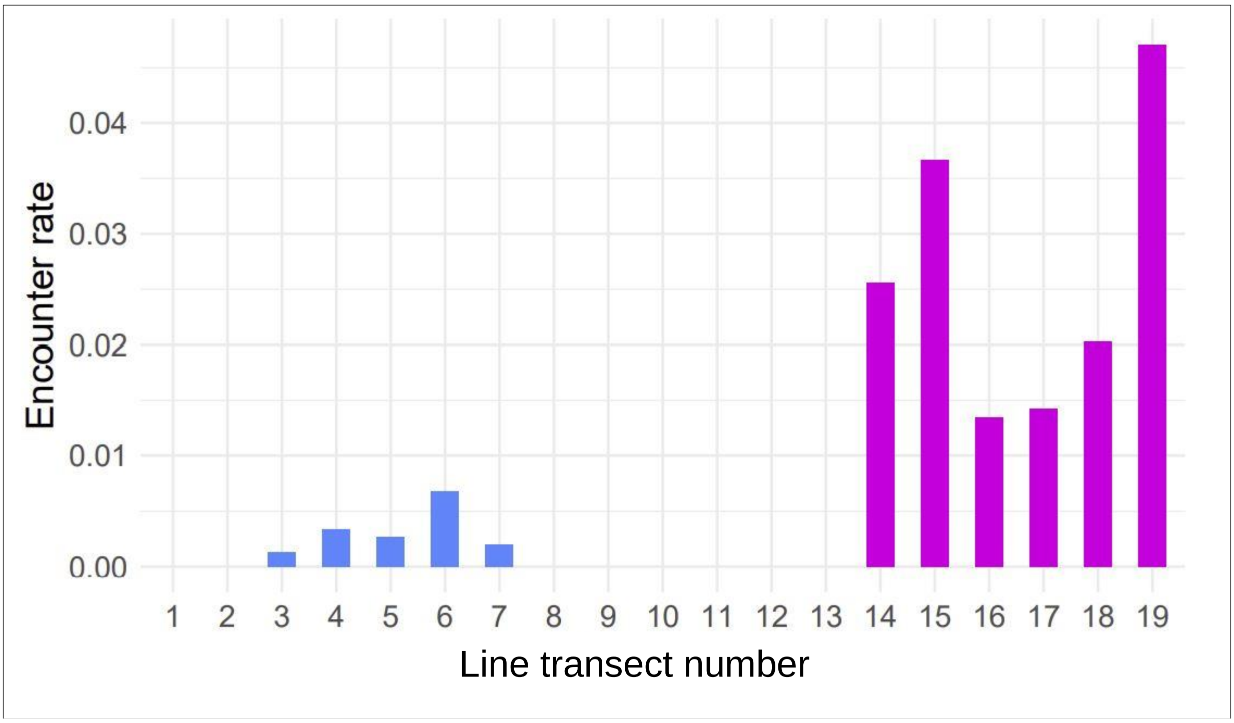

Figure 8. Muskox survey 2018: exploratory analysis of non-truncated data for muskox encounter rate (groups per km) per line transect using and illustrating sub-area: Sisimiut (blue, line transects 1-8), Sisimiut South (orange, line transects 9-13) and Angujaartorfiup (purple, line transects 14-19).

Distance Sampling analysis

Before conducting any modelling, an analysis of the observed distances was made to evaluate whether any major assumption violation occurred or other data-related issue,

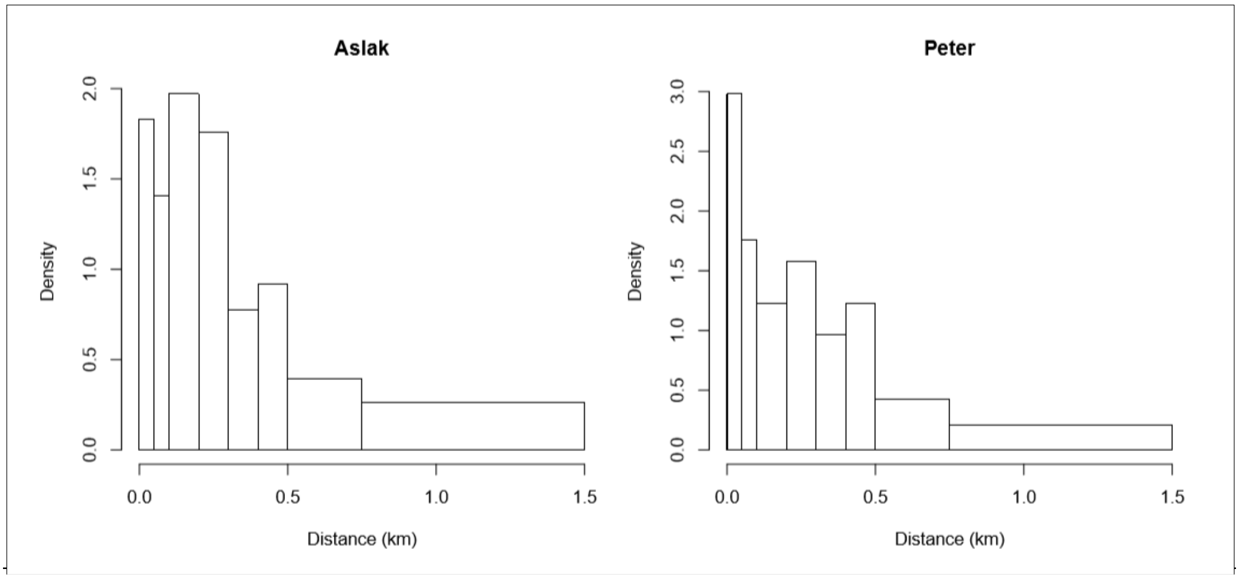

Figure 9. Observer effect: histograms illustrating detected distances for the two observers (a covariate with two levels). Density, y-axis, refers to the density of observations.

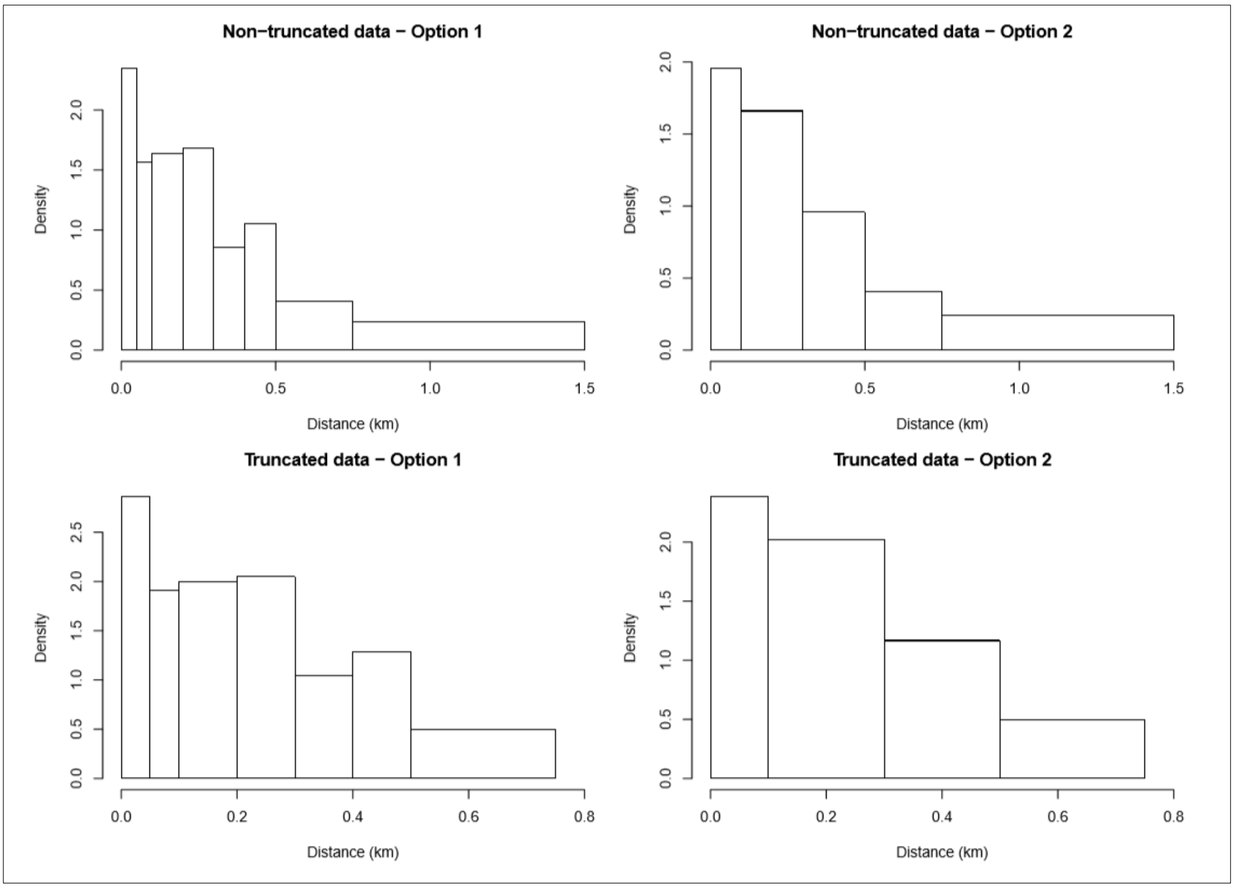

Figure 10. Histogram of the different binning options for the muskox distance data. Left: the original bins as collected on the survey. Right: an alternative binning to reduce the effect of heaping. The area of the rectangles is proportional to the number of points within each bin.

as stated in previous sections. These analyses are from Marques (2018). The histogram of observed distances with no defined truncation distance (non-truncated data) is like typical Distance Sampling data, perhaps showing some over-dispersion, with not-equally-spaced bins (Fig. 10). Given the histogram of binned distances, a strip half-width of w = 0.75 km was selected (i.e., all observations at distances beyond 750 meters were discarded). This truncation reduced the sample size from 256 to 210 muskox groups for the Distance Sampling analysis. Data truncation is a common procedure because otherwise extra adjustment terms may be needed to fit the long tail of the detection function. Further, little information is lost by truncation, since data observations located more than 0.75 km from each side of the line make a minimal contribution to the abundance estimate.

Truncated data

With the original binning Option 1 (Fig. 10), there seem to be less than expected observations on the 0.05-0.10 km and 0.30-0.40 km intervals, when compared to the 0.10-0.30 km and the 0.40-0.50 km bins. This suggests *heaping*, a phenomenon that occurs when observers tend to record some preferred values over others (Buckland *et al.* 2001) e.g., at round distances that are easily chosen in the absence of a rigorous distance measuring method, as often occurred in this study when rugged terrain forced observers to assign distance bins subjectively. The alternative binning Option 2, with less bins, reduces the influence of potential measurement errors in the observed distances. This alternative binning option includes bin cut points of 0, 0.10, 0.30, 0.50 and 0.75 km (Fig. 10).

Both binning options were considered in model fitting, albeit only Option 2 minimizes the effect of measurement error induced by heaping. Since binning Option 1 was not suitable for grouping, only the analyses whose fitted models consider the second binning option are illustrated below. The advantage for choosing the second binning option is that it results in more reliable detection functions. However, owing to fewer degrees of freedom, the small number of bins affects the χ^2 Goodness-of-Fit tests following model fitting. The regression analysis suggests that distance is not a statistically significant variable explaining group size (Table 5).

Table 5. Summary of the coefficient characteristics of the GLM between observed truncated distance and the muskox group size while considering a Poisson distribution.

Parameter	Estimate	Standard Error	z-value	p-value
Intercept	1.752	0.050	35.18	0.00000
Distance	-0.091	0.155	-0.58	0.55926

Note: AIC = 1564.2, Null Deviance = 879.5, Residual Deviance = 879.2.

Detection function models fitted with the first binning option did show poor fitting, including the best fit within this group, since these presented several adjustment terms, due to the heaping phenomena. Below, the detection functions are fitted to truncated data and considering the second binning option (Fig. 10), which improves the models.

Truncated data – Distance Sampling Models

For these models, every combination of key function and adjustment terms was tested. The only additional covariates assessed were observer and group size, considering w = 0.75 km. A summary of the information from each model fitted to the data (Table 6) provides a simple overview of several models, and includes the respective key functions, adjustment terms, model formula, χ^2 Goodness-of-Fit test p-value, estimates of the detection probability, respective standard error (se ($\hat{P}_a$)), and ΔAIC comparison between each model and the model with the lowest AIC. The best model fitted to the data possesses the lowest change in AIC value ($\Delta AIC = 0$). For the 2018 muskox survey data, the Half-Normal key function was selected because it was the most flexible key (AIC = 550.65). The second-best model was Uniform with cosine adjustment terms of order 1 (AIC = 550.692, i.e., ΔAIC = 0.042). The best fitted detection function parameters superimposed with the observed distances' histogram, indicates that neither group size nor observer were relevant covariates in detectability for the truncated data. (Table 6). The estimated averaged probability of detection for the North region was $\hat{P}_a$ = 0.557 (se = 0.033, Table 6).

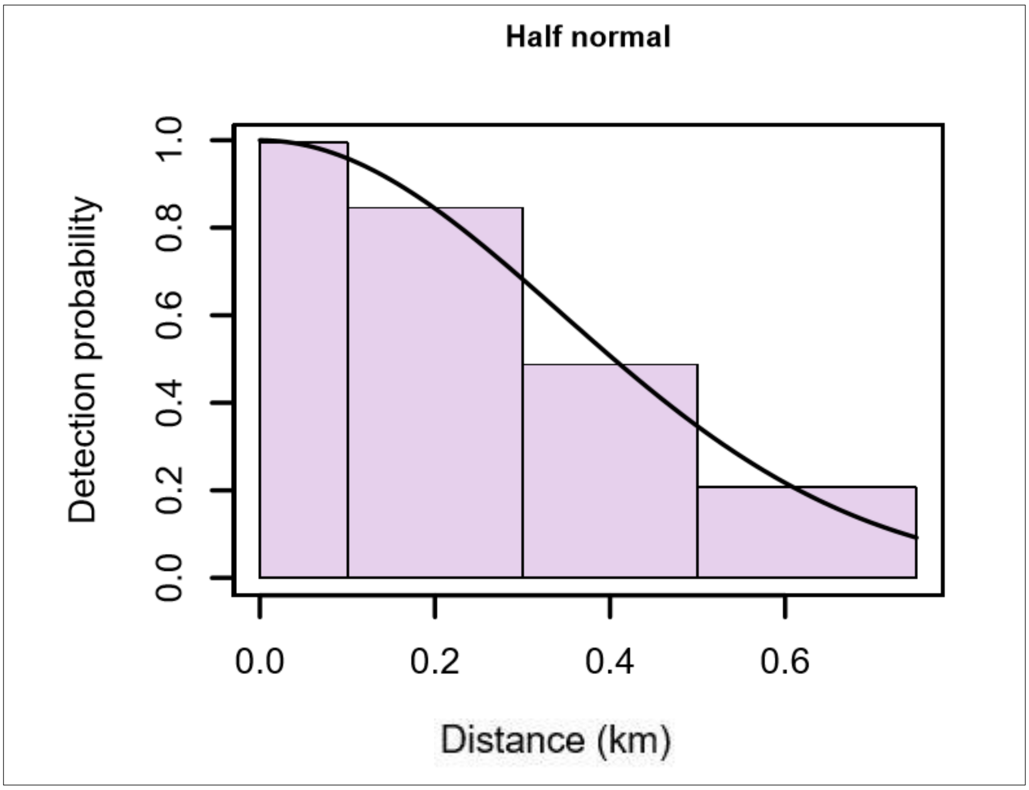

Figure 11. The detected distances truncated data with the estimated detection function overlaid, considering the binning option 2 that reduces the effect of heaping.

Each group size has its separate detection function, corresponding to different estimates for the probability of detection (Fig. 12). For non-truncated dataset, a group size of 2 muskoxen presents an estimated probability of detection of 0.273, a group size of 10 has an estimate of 0.45, a group size of 20 has an estimate of 0.74, while a group size of 30 has an estimate of 0.96 (Fig. 12). With increasing group size, the probability of detection also increases. For the truncated dataset, the probability of detection (0.557) was the same regardless of muskox group size. The Kolmogorov-Smirnov and Cramér-von Mises tests (Appendix 2) cannot be applied since the distances were represented as a discrete variable.

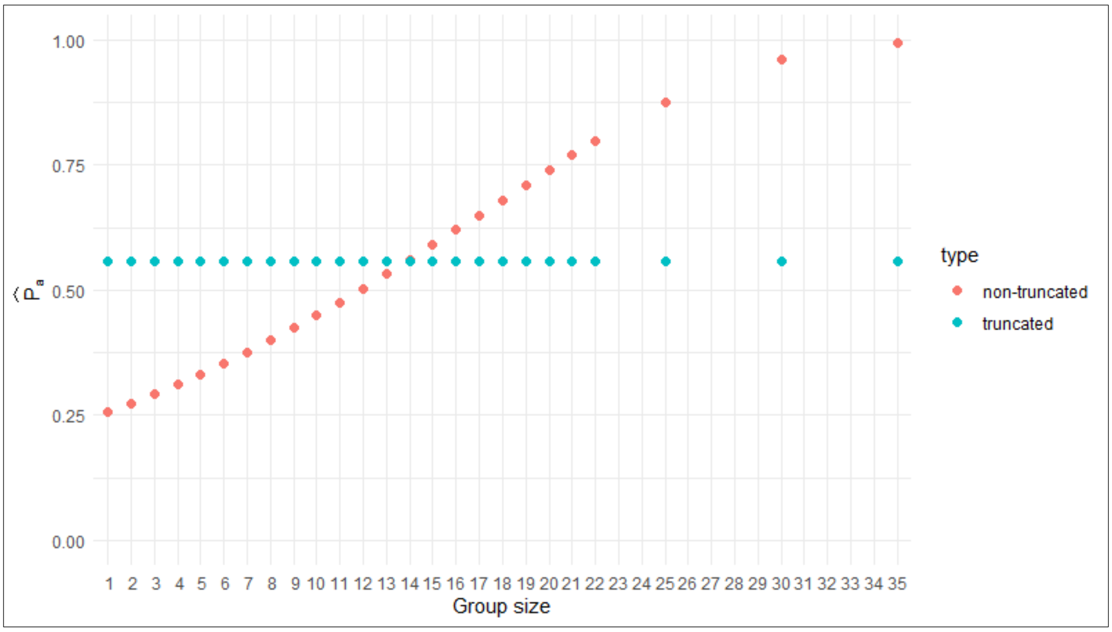

Figure 12. Estimated probabilities of detection, given non-truncated and truncated dataset, for each observed group size (muskoxen) obtained with the fitted model. Illustrates group size not important in truncated dataset.

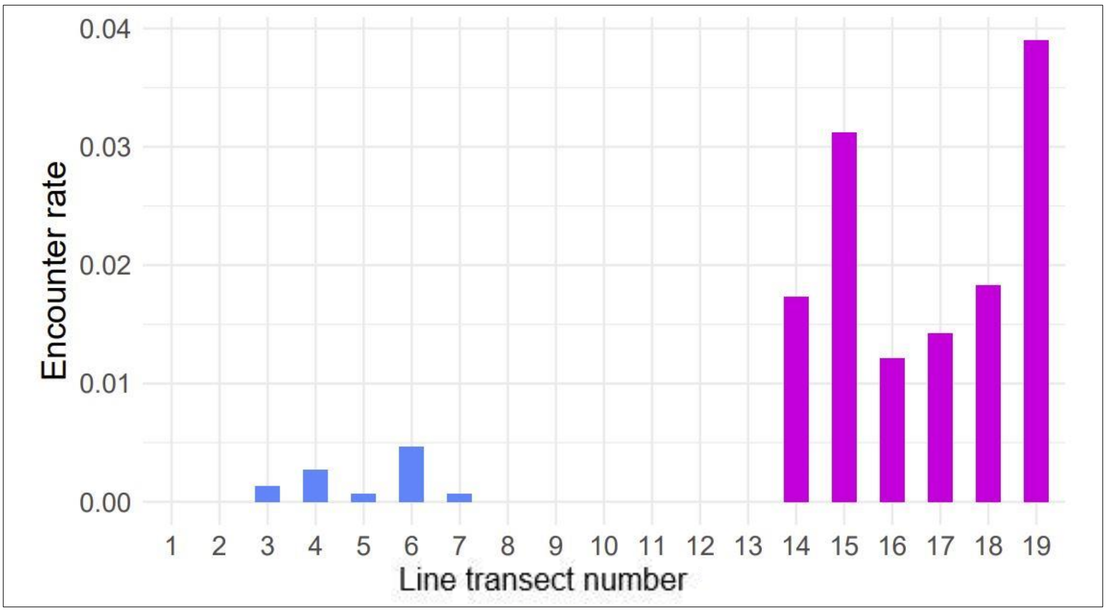

Figure 13. Muskox encounter rate (groups per km) per line transect, survey 2018: exploratory analysis of truncated data, illustrating sub-area: Sisimiut (blue), Sisimiut South (orange) and Angujaartorfiup (purple).

Encounter rate estimates suggest the Angujaartorfiup sub-area has the most muskoxen, since its estimate is larger than the other sub-areas (Table 7, Fig. 13). Visualization of the detected muskox distribution shows this was somewhat continuous only for line transects in the Angujaartorfiup sub-area, with two 'hot' spots, i.e., east, and western sides of the sub-area (Fig. 14). Muskox distribution in Sisimiut was sporadic and rare, and in Sisimiut South nonexistent. The DS design-based estimates for muskox abundance and density also reveal that Angujaartorfiup is the sub-area with the most muskoxen (Tables 8, 9, Fig. 15).

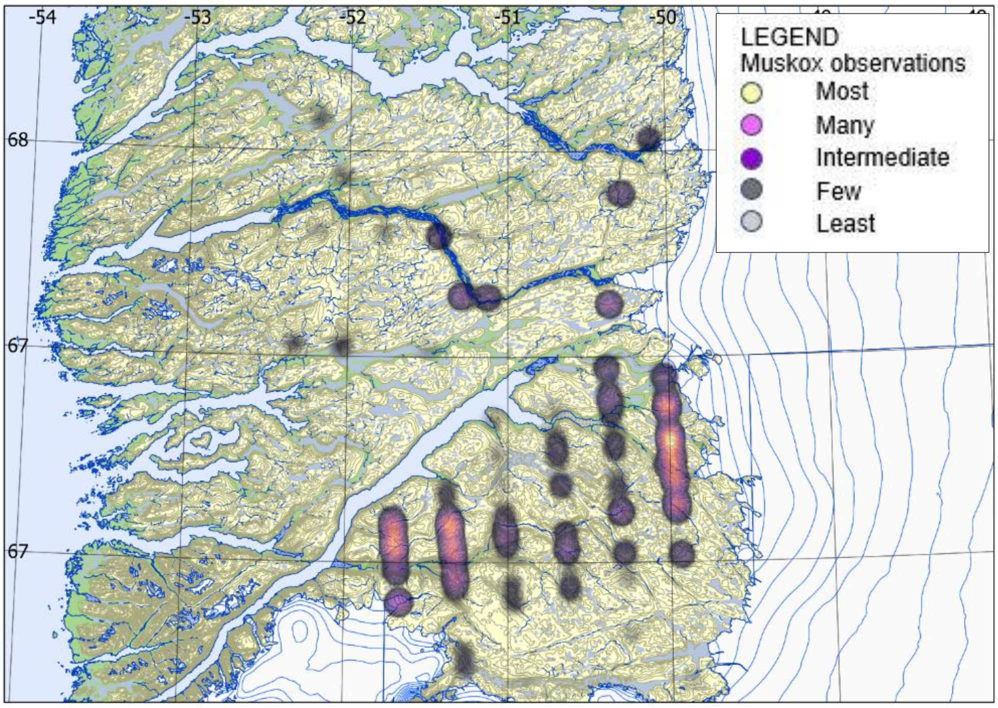

Figure 14. 'Heat' map illustrating relative distribution of muskoxen observations along the line transects in the North region, West Greenland. For interpretation of underlying map see Fig. 1.

In March 2018, the DS design-based population estimate for the combined Angujaartorfiup and Sisimiut sub-areas was approximately 21,746 muskoxen (95% CI: 11,061 – 42,751), with a CV of 28.5% (Table 8). The DS density estimate was 1.1 muskoxen per km^2, with 95% CI: 0.56 – 2.16 (Table 9, Fig. 15).

Separately, the Maniitsoq muskox harvest management area (Angujaartorfiup sub-area) had a DS design-based population estimate of 18,906 muskoxen (95% CI: 8,726 – 40,960), with a CV of 31.5%. Similarly, Sisimiut muskox harvest management area had a population estimate of 2,840 muskoxen (95% CI: 662 – 12,178), with a CV of 56.8%.

Table 6. Model comparison across the three Conventional Distance Sampling models and models considering muskox group size and observer as covariates.

Key function	Formula	χ^2 *p*-value	$\widehat{P}_a$	se ($\widehat{P}_a$)	Δ AIC
Half-normal (same result for Cosine/Simple Polynomial/Hermite)	1	0.932	0.557	0.033	0.000
Uniform with cosine adjustment terms of order 1	NA	0.913	0.565	0.025	0.042
Uniform with Hermite polynomial adjustment term of order 4	NA	0.448	0.604	0.024	1.509
Half-normal	Group size	0.717	0.557	0.033	1.673
Half-normal	Observer	0.709	0.557	0.033	1.953
Hazard-rate (same result for Cosine/Simple Polynomial/Hermite)	1	0.616	0.584	0.054	2.111
Uniform with simple polynomial adjustment terms of order 2,4,6	NA	0.498	0.577	0.047	2.325
Hazard-rate	Group size	NA	0.596	0.052	3.575
Hazard-rate	Observer	NA	0.589	0.053	4.004

Note: under Formula explanatory variables are as follows: Group size = group size as variable, 1 = for Uniform key, Observer = observer as variable, NA = no explanatory variables/covariates. There were not enough degrees of freedom for the χ^2 Goodness-of-Fit test, thus the 'NA' values. For each key function, all three series expansions (Cosine, Simple Polynomial, Hermite (Appendix 2, Table 15) were applied.

Table 7. Encounter rate (ER) estimates per sub-area for muskox groups considering truncated data, three sub-areas (strata), four bins, and a Half-Normal detection function fitted without covariates.

Surveyed Sub-area*	Muskox harvest Management area	Encounter rate	Standard Error (se)	Coefficient of Variance (cv)
Sisimiut	Sisimiut	0.020	0.007	0.360
Angujaartorfiup	Maniitsoq	0.414	0.092	0.222
TOTAL	Sisimiut + Maniitsoq	0.173	0.067	0.387

*Third sub-area, Sisimiut-South, does not appear in the table because there were no observations of muskoxen.

Table 8. March 2018, the Distance Sampling design-based muskox abundance estimates per stratum (sub-area) in the North region, considering truncated data, three sub-areas (strata), four bins and a Half-normal detection function with no covariates.

Sub-area*	Muskox harvest Management area	Population Size Estimate	SE	CV	95% Confidence Interval	
					Lower	Upper
Sisimiut	Sisimiut	2,840	1,613	0.568	662	12,178
Angujaartorfiup	Maniitsoq	18,906	5,948	0.315	8,726	40,960
TOTAL	Sisimiut + Maniitsoq	**21,746**	**6,194**	**0.285**	**11,061**	**42,751**

Note: SE = Standard Error, CV = Coefficient of Variance.
*Third sub-area, Sisimiut-South, does not appear in the table because there were no observations of muskoxen.

Table 9. March 2018, the Distance Sampling design-based muskox density estimates per stratum (sub-area) in the North region, considering truncated data, three sub-areas (strata), four bins and a Half-normal detection function with no covariates.

Sub-area*	Muskox harvest Management area	Density Estimate	SE	CV	95% Confidence Interval	
					Lower	Upper
Sisimiut	Sisimiut	0.224	0.127	0.568	0.052	0.962
Angujaartorfiup	Maniitsoq	2.650	0.834	0.315	1.223	5.742
TOTAL	Sisimiut + Maniitsoq	**1.099**	**0.313**	**0.285**	**0.559**	**2.160**

Note: SE = Standard Error, CV = Coefficient of Variance.
*Third sub-area, Sisimiut-South, does not appear in the table because there were no observations of muskoxen.

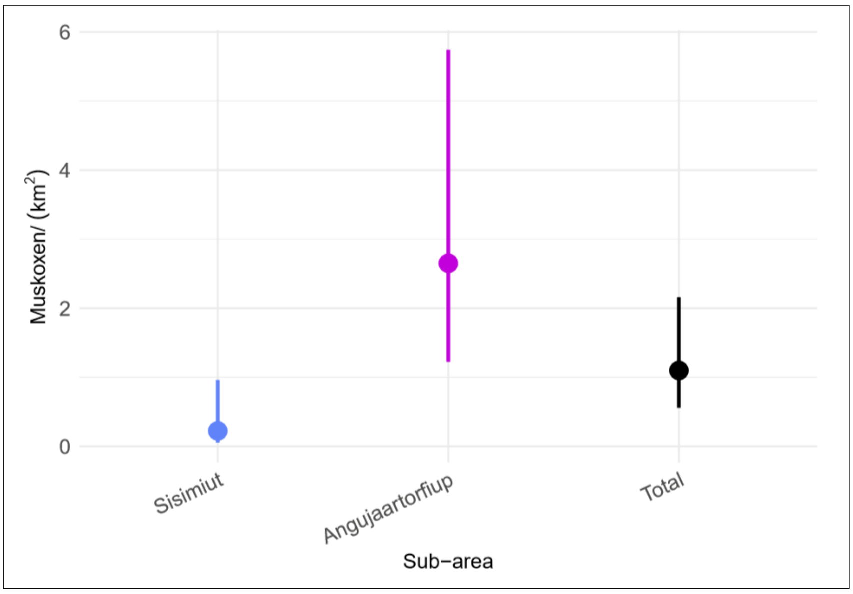

Figure 15. Distance Sampling design-based muskox density estimates with corresponding confidence intervals for the two sub-areas with muskoxen, Sisimiut and Angujaartorfiup, and finally for the total North region.

GAM & DSM

After splitting the transects into segments, their centroids were determined and intersected with the shapefiles concerning the spatial variables. These variables were GPS coordinates, vegetation, elevation, slope, and the aspect (geographical compass direction, which relates to sun exposure and temperature of a particular location) (Appendix 6). The vegetation covariate was excluded from the analysis since the current information available lacks the necessary resolution. Furthermore, a prediction data set was generated for the whole study region by converting the region into small 1.5 km sided square cells (i.e., 2.25 km^2, note w = 0.75 km).

Once the distance model was fitted, $\hat{P}_a$ could be determined for each group size and thus n_i, the number of muskoxen detected in group i, can be corrected as $\hat{n}_i = \frac{n_i}{\hat{P}_a}$. These predicted values for counts were then modelled using a GAM fitted to the spatial covariates along longitude (lon) and latitude (lat) considered jointly. Within the model, the previously estimate probability of detection was defined as the offset term along with the cell area of 2.25 km^2. The distribution considered in model fitting were Tweedie and Negative Binomial. These provide a flexible alternative to the quasi-Poisson distribution, which does not capture the response overdispersion.

Table 10. GAM model summary table relative to smooth terms for covariates and considering Tweedie distribution.

	Effective Degrees of Freedom	Chi-square	p-value
s(lon, lat)	19.235	9.021	0.0000
s(elevation)	4.024	4.238	0.0009

Note: R^2_{adj} = 0.378, Deviance explained = 63.6%.

Table 11. GAM model summary table relative to smooth terms for the covariates and considering a Negative Binomial distribution.

	Effective Degrees of Freedom	Chi-square	p-value
s(lon, lat)	19.667	159.429	0.0000
s(aspect)	1.000	4.215	0.0401
s(elevation)	3.692	15.404	0.0123

Note: R^2_{adj} = 0.091, Deviance explained = 67.6%.

Fitting GAM/DSM

The two distribution models, Tweedie, and Negative Binomial (Tables 10, 11) were fitted and the best model within each was selected for further work. The Tweedie distribution used longitude, latitude, and elevation. The Negative Binomial distribution (NegBin) used longitude, latitude, aspect, and elevation. The third best NegBin model was similar to the first (i.e., Table 11) but lacked elevation and the ΔAIC was low, 0.8799. The second best, which included all covariates, had a ΔAIC difference of 0.61. Thus, these models were almost identical.

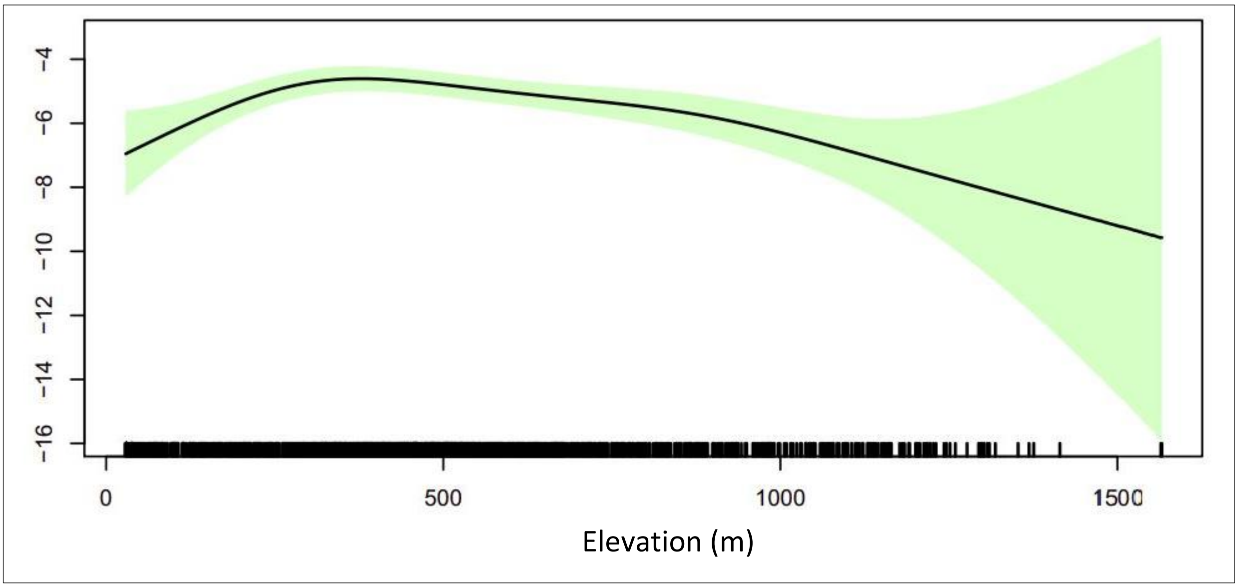

Figure 16. Fitted DSM plot corresponding to the fitted smooth of the elevation covariate (Y-axis is the fitted smoothing parameter). Green shading illustrates the standard error of the estimates, while the respective observations are represented on the horizontal axis.

Despite the similarity among results, the model considering the Tweedie distribution was chosen owing to its lower AIC value ($AIC_{Tweedie}$ = 1350.1 and $AIC_{NegBinom}$ = 1461.5). A larger Effective Degrees of Freedom (EDF) resulted for the bivariate smooth associated with the paired longitude and latitude relative to the other environmental covariates, since more basis functions are required to fit a surface than a line. Each of these environmental covariates does not appear to be linearly related with the response, since the respective EDF is larger than 1. Regarding the smooth functions, the relationship between the response variable and each explanatory variable appears to be non-linear for the elevations below 1000m (Fig. 16). Specifically, elevations from 300m to 700m seem to be preferred by the muskoxen in the early March period of the survey and density was positively correlated with elevation until around ca. 400 m when it began to fall slightly with elevation (Fig. 16). At high elevation, e.g., above 900m, variability was greater, and density fell. Muskoxen appear to prefer south-facing slopes (90°-270°), since these involved most observations and there was the least variability in the estimates. Furthermore, the results suggested that among south facing slopes, southwest aspects were most preferred by muskoxen.

Spatial prediction

The number of muskoxen within each cell was then predicted using the GAM model ($\hat{n}_i$) and spatially represented. The heat map presenting the prediction of muskox abundance in the North region indicates that muskoxen are scarce in most of the North region, excepting the Angujaartorfiup sub-area, which clearly illustrated the muskoxen distributed into two clusters (hot spots) at the time of the survey (Fig. 17). The GAM/DSM model-based approach produced a predicted mean muskox density value for the entire North region of 3.69 muskoxen/km^2 (95% CI: 2,87 – 4,74). The predicted range was from 0 to 125 muskoxen/km^2 (Fig. 17). The maximum value occurred rarely and only on a remote section of line transect 14, which was on the far west side of the Angujaartorfiup sub-area. This was one of the two hot spots of clumped distribution where most of the darker cells were in the range of 25-30 muskoxen/km^2. The clumping coincided with unusually high elevation.

The GAM/DSM model-based approach produced a population estimate of 23,256 (95% CI: 18,102 – 29,877) muskoxen for the entire North region. Additionally, a variability map was produced with the CV for each estimate in the survey region (Fig. 18), the CV estimate was 11.36%.

Table 12. Comparison of Distance Sampling design-based and GAM/DSM analyses, for entire North region.

Analysis	Population Size					CV for probability of detection
	Estimate	SE	CV	95% Confidence Interval		
				Lower	Upper	
Distance Sampling	21,746	6,194	0.285	11,061	42,751	5.98%
GAM / DSM	23,256		0.114	18,102	29,877	11.36%

Note: SE = Standard Error, CV = Coefficient of Variance.

To compare the model-based GAM/DSM to the design-based DS approach we used the CV for probability of detection of the muskoxen (i.e., not for abundance or density). The GAM/DSM had a probability of detection CV of 11.36% (like the estimate's CV), while the DS had a probability of detection CV of 5.98% (Table 12). For the overall analyses, i.e., DS and GAM/DSM, the probability of detection CV was 12.84%.

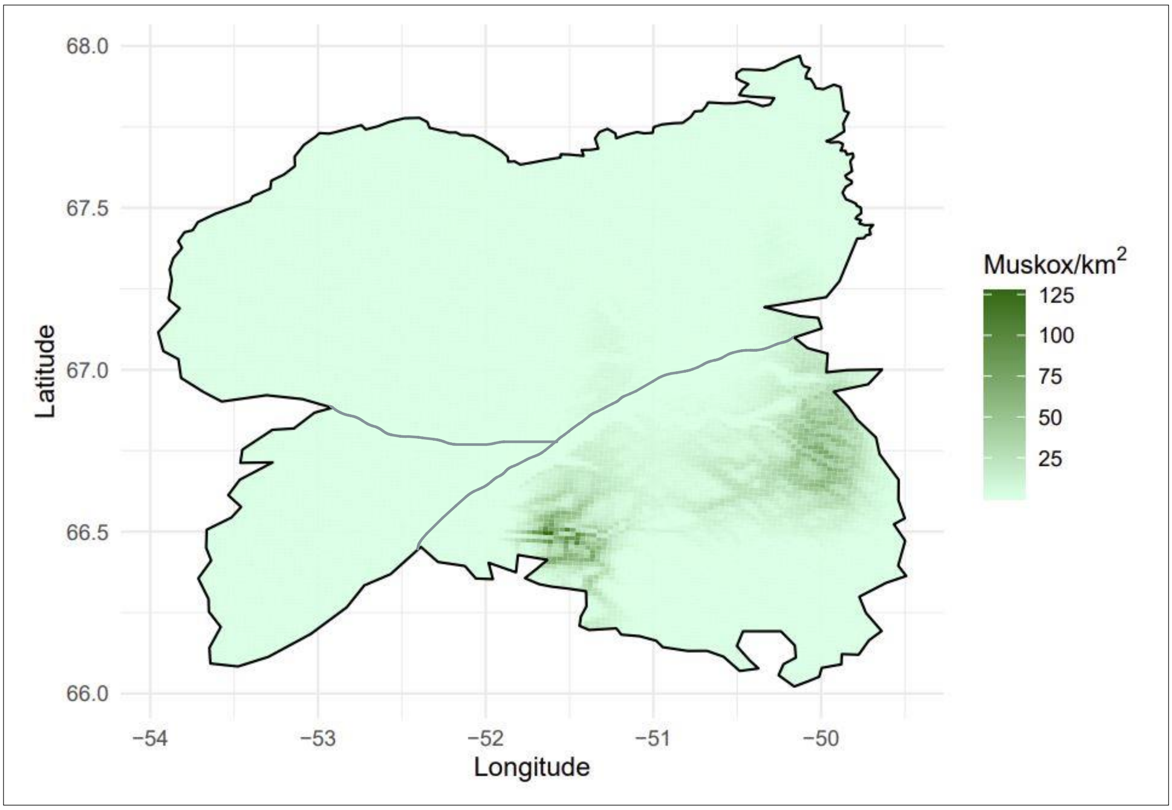

Figure 17. Predicted muskox density across silhouette map of entire North region. Grey lines illustrate approximate borders between the three sub-areas surveyed (see Fig. 3).

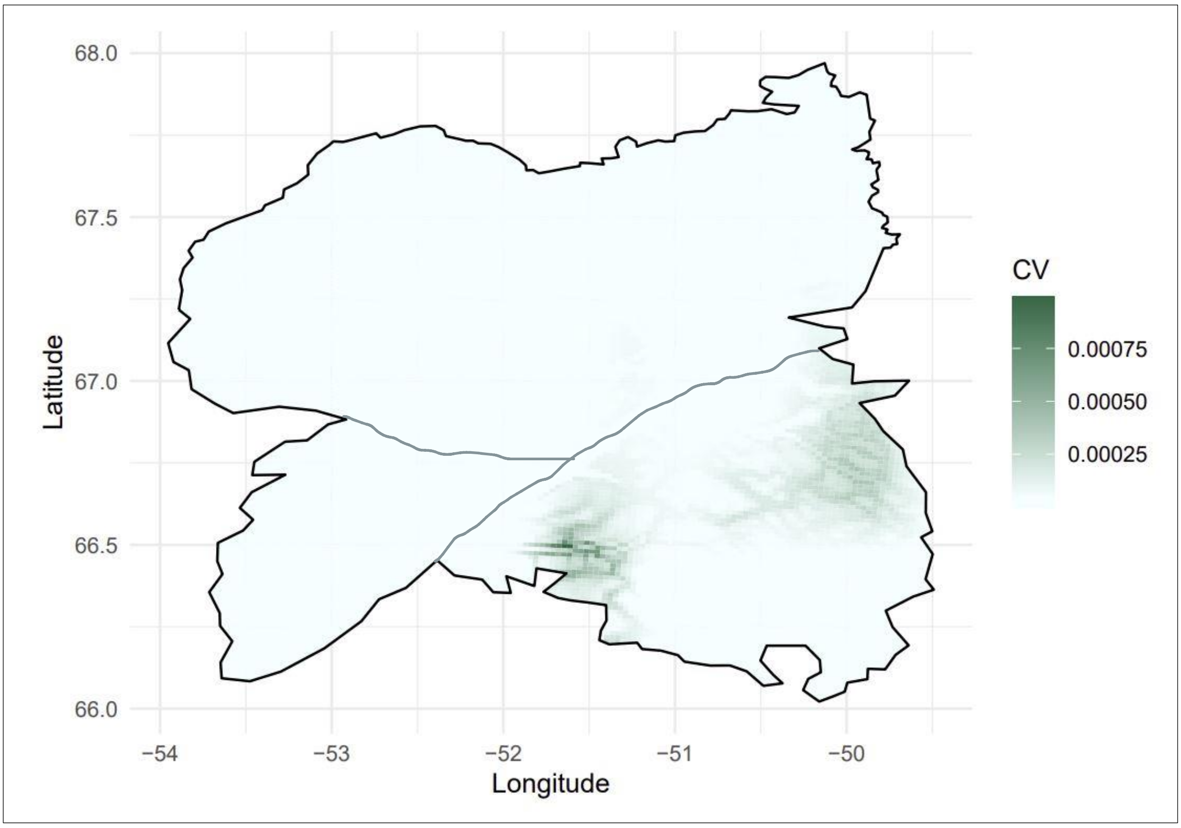

Figure 18. Fitted DSM variability on silhouette map of entire North region. Uncertainty associated with the respective density estimate increases with colour. The darkest colouring indicates the highest CV (uncertainty) associated with the respective density estimate. Grey lines illustrate approximate borders between the three sub-areas surveyed (see Fig. 3).

Discussion

Muskox detection & group movement in reaction to helicopter by-pass

Detection of animals can be made difficult by ground surface conditions that are common in the North region. These have been well illustrated in Cuyler et al. (2005, 2011, 2021) and include any one of the following or combinations thereof; incomplete or patchy snow cover, substrates (including grass, bushes, ground) or showing through a thin snow layer, rocky terrain, fog, alternating light/shadow and flat light (no shadows or horizon). These conditions were common in the surveyed Angujaartorfiup sub-area (Appendix 7). Further, all line transects in the Angujaartorfiup sub-area were oriented on an almost North-South axis. Although solar glare in the eyes of the observer could have made animal detection difficult when flying southward along transects, this study's typically overcast conditions and the use of polarized sunglasses resolved that issue. Meanwhile, the dark shape and large size of muskoxen gave the impression of being relatively easy to detect, owing to physical prominence in the terrain despite varying background conditions or presence of multiple large boulders (e.g., glacial erratics). Since flight responses by the muskoxen might influence detection, in 2018 the line transect data included whether the helicopter fly-by elicited any flight movement response from a muskox group or whether they were stationary, non-moving.

Over 3/4 of muskoxen groups exhibited no flight reaction to the relatively low altitude (40 m) helicopter fly-by. They simply stood and looked at the helicopter. Only 23% of muskox groups exhibited some type of flight movement, while 77% did not. That most muskoxen exhibit no flight response to a fly-by is expected to be common to populations elsewhere. Thus, a muskox survey detecting few stationary groups, relative to fleeing groups, might be underestimating population size. Group size appeared to have little or no influence on the reaction of the muskox group to the helicopter fly-by. In contrast, distance did make a difference. Not unexpectedly, groups of standing muskoxen were much further from the line transect (helicopter fly-by) than groups that ran away. The large proportion of stationary muskox groups, and their greater distance from the helicopter, indicates that lack of movement by the muskoxen did not appear to make their detection difficult for skilled observers. Further, this study's flying a helicopter slowly (< 100 km/hour) at low altitude (ca. 40 m) facilitated detection of muskox groups regardless of their behavior.

Elevation & Aspect

Schmidt et al. (2016) observed that elevation explained little about seasonal or daily movements in muskoxen in Northeast Greenland. It is well known that muskoxen are sedentary (Reynolds et al. 2002, Gustine et al. 2011, Schmidt et al. 2016), and generally forage in low lying valleys and coastal areas (Nellemann & Reynolds 1997, Nellemann 2011, Anderson & Fergusen 2016). Optimal muskox habitat is generally below 200 m elevation, while below 100 m elevation supports the highest densities of muskoxen (Thomas et al. 1981). Nevertheless, in Northeast Greenland, where winter snow depths make foraging difficult in lowlands, muskoxen may seek elevations of 200-600 m that have less snow cover (Beumer et al. 2019).

GAM/DSM analyses of the March 2018 muskox observations illustrated that in general the muskoxen preferred south facing slopes (90°-270°) and specifically, predominantly southwest facing slopes (180°-270°). In contrast to normal muskox foraging in low lying valleys and coastal areas, the GAM/DSM results for this March survey indicated a strong preference for elevations from 300-700m. Interestingly, the mode (most observations) elevation was 198 m for muskox groups in Sisimiut sub-area, while most groups of muskoxen in Angujaartorfiup sub-area were at the much higher elevation of 772 m (Table 4). This was despite that winter snow depths and cover are greater in the Sisimiut sub-area (Cover photo, Appendix 5) than in the xeric often virtually snow-free Angujaartorfiup sub-area (Fredskild 1996, Nellemann 1997) (Figs. 19, 20, 21, Appendix 7 - Fig. 40). Reasons for scant snow cover in the Angujaartorfiup sub-area are first that it is in the immediate precipitation shadow caused by the two ice caps Kangaamiut sermiat (Sukkertoppen) and Tasersiap sermia. Secondly, föhn winds coming down off the Greenland Ice Cap can cause extensive snowmelt (Hansen 1999), which produce large snow-free expanses (Fredskild 1996). Even lacking recent föhn winds, winter snow depths March 2018 were minimal in the Angujaartorfiup sub-area (Appendix 7).

Figure 19. Virtually snow-free terrain of the inner Umiiviit Fjord, Angujaartorfiup sub-area, April 2014. Photo from SW side Pinguarsuk highlands looking NW. Photo P. N. Hansen.

Figure 20. Virtually snow-free lowland (foreground <200 m) terrain of Angujaartorfiup sub-area, inner Ørkendalen, February 2014. View NW across the ponds near the cabin, Bioshytte. Photo H.S. Mølgaard.

Fig. 21. Large expanse of virtually snow-free terrain in Angujaartorfiup sub-area, early March 2005. View NW from Kiinnarissut Avannarliit highlands (foreground, elevation ca. 500-700m) towards the inner valley of Ørkendalen. Photo C. Cuyler

Beumer et al. (2019), studying NE Greenland, suggested muskoxen seek higher elevations when winter snow depths in lowlands make foraging there difficult. This likely applies elsewhere. Thus, muskoxen in Sisimiut sub-area might be expected to inhabit higher elevations than muskoxen in the Angujaartorfiup sub-area, since snow depths in the former are greater than those in the latter, as illustrated in Appendices (5, 7). However, muskoxen in Sisimiut sub-area used significantly lower elevations than muskoxen in the Angujaartorfiup sub-area. Further, the mode elevation of 772 m for muskoxen in the Angujaartorfiup sub-area is surprising, because specifically those muskoxen were documented to remain in lowlands under 400 m elevation throughout the year (Olesen 1993), where *Kobresia myosuroides* steppe had the highest muskox fecal pellet group densities, followed closely by shrub heath, indicating extensive use for foraging by muskoxen (Nellemann 1997). Those lowlands included those surrounding the town of Kangerlussuaq and several large valleys, i.e., Ørkendalen, around the Ammalortoq Lake, and Arnangarnup Qoorua (Paradisedalen) (Olesen 1993).

The lack of an extensive snow cover in the Angujaartorfiup lowlands combined with the muskoxen there preferring low elevations below 400 m for foraging, begs the question: Why were the muskoxen in the Angujaartorfiup sub-area unexpectedly using elevations of ca. 700 m in early March 2018? We suggest that the January-March hunting season is the primary factor disturbing the normal lowland distribution of muskoxen, causing them to inhabit elevations > 400 m in the Angujaartorfiup sub-area in winter.

In 2018, there was a muskox winter hunting season in the Angujaartorfiup sub-area but not in Sisimiut sub-area (hunting closed). The winter 2018 commercial and recreational hunting season for the Angujaartorfiup sub-area ended two weeks prior to the start of this study's helicopter survey (Appendix 8 - Table 16). However, muskox trophy hunting continued throughout March. The abnormally high elevation use exhibited by muskoxen in the Angujaartorfiup sub-area suggests that the two-week period, following the end of main winter harvest season, was insufficient for muskoxen to relax their vigilance and resume normal distribution, i.e., to forage at elevations below 400 m. Additionally, the March trophy hunting season on muskoxen seemed sufficient continued disturbance to keep muskoxen in the Angujaartorfiup sub-area at elevations > 400 m. This and given muskoxen in the Sisimiut sub-area utilized relatively low elevations in the absence of hunting despite extensive snow cover, suggests a strong avoidance of hunters by the muskoxen in the Angujaartorfiup sub-area.

Harvest of Maniitsoq muskox population in Angujaartorfiup sub-area

The Angujaartorfiup sub-area surveyed by this study corresponds to the Greenland Government's Maniitsoq muskox harvest management area, and consequently, animals there are currently known as the Maniitsoq muskox population (Table 1). Similarly, the surveyed Sisimiut sub-area loosely corresponds to the government's Sisimiut muskox management area and animals there are currently known as the Sisimiut muskox population.

Comparatively, harvest numbers are high for Maniitsoq muskoxen (Angujaartorfiup sub-area), while low for Sisimiut muskoxen (Sisimiut sub-area). The magnitude of the harvest on Maniitsoq muskoxen is reflected by the fact that for the past 30 years, those muskoxen accounted for a mean 84% ±6.0 of the entire Greenland muskox harvest for commercial and recreational hunters (Appendix 8 - Table 17). The Maniitsoq muskoxen also sustains most trophy hunting, and qiviut (muskox inner wool) production in Greenland.

The Maniitsoq muskox population normally used areas under 400 m elevation throughout the year (Olesen 1993) when harvests were about 200-400 muskoxen annually, and generally occurred near the town of Kangerlussuaq. In contrast, after 2002 harvested numbers rose quickly (Fig. 2; Appendix 8 - Table 17) and usually exceeded 2,000 muskoxen annually. Since 2015, harvest quotas for Maniitsoq muskoxen have typically been open (no limit) for both autumn and winter hunting seasons (Appendix 8 - Table 16). In contrast, harvest quotas for Sisimiut muskoxen are moderate, 400-520, and winter hunting seasons closed since 2017.

In the Maniitsoq muskox harvest management area (Angujaartorfiup sub-area), initially there were two hunting areas (Piniarfik/jagtområde 1 & 2) (Appendix 8 - Fig. 42). By the late 2000s, however, hunting activities encompassed an increasingly larger proportion of the Angujaartorfiup sub-area (Hans Mølgaard pers. comm.). Thus, from 2010 the Government of Greenland divided the Maniitsoq muskox management area into three hunting areas (Appendix 8 - Fig. 42) to permit harvest management through differential hunting periods and quotas (Nuka M. Lund pers. comm.). In 2019, a fourth hunting area was created (Appendix 8 - Fig. 43, Naalakkersuisut 2019). Current muskox harvest management allows hunting in most of the Maniitsoq muskox harvest management area except for two well marked areas where hunting is forbidden (Appendix 8 - Figs. 42, 43).

As restrictions on motorized vehicle use in the terrain relaxed for all hunters, earlier hunting by dogsled dwindled to a minimum, although common into the early 2000s. Meanwhile, the steadily increasing use of motor vehicle transport (e.g., snowmobiles, ATVs, belted-track vehicles, trucks (Hans S. Mølgaard & Nuka M. Lund pers. comm.), which granted hunters rapid access to previously remote or inaccessible areas of the Angujaartorfiup sub-area, likely contributed to the initial rapid rise in number of muskoxen harvested annually. Similarly, as harvesting muskoxen became increasingly lucrative, e.g., skin and trophy prices, it is not surprising that the number of participating hunters and trophy agents rose and with them the number of motor vehicles used (Nuka M. Lund pers. comm.). Given following the regular hunting season and during the March trophy season Maniitsoq muskoxen inhabited unusually high elevations, >700 m, we suggest that current anthropogenic disturbance associated with hunting may play a major role in causing muskox use of high elevations.

Consequences of winter foraging in sub-optimal habitat

Regardless of the cause(s), in 2018 most Maniitsoq muskoxen in the Angujaartorfiup sub-area foraged at elevations of 700-800 m in winter. This is suboptimal habitat. Given the latitude (ca. 67°N), winter forage available at 700-800 m elevation is inferior and less plentiful than that found in lowland valleys (Körner 2007), and specifically for the Angujaartorfiup sub-area high elevations are often fell field, abrasion plateaus and bare ground (Tamstorf et al. 2005). Foraging in poor habitat at high elevation could negatively affect winter body condition and ultimately survival of Maniitsoq muskoxen (see Appendix 9 for details). Further, it is common knowledge that among large herbivores most fetal growth occurs in late gestation and that this growth substantially increases maternal energy requirements. Muskox calves are usually born mid-April through June, with birthing dates as early as 05 April and as late as 19 June (Lent 1988) as there is no breeding synchrony as seen in caribou (Lent 1966). Depending on the date for parturition, late gestation for muskoxen ranges from February through May. Thus, Maniitsoq cows foraging at high elevation poor pasture could become nutritionally deficient in late gestation and birth weaker calves of low weight (Olesen et al. 1994).

Calf percentage

Forage quality varies widely seasonally, with winter associated with lowest forage quality (Dermanet et al. 2015). The Angujaartorfiup sub-area straddles the Arctic Circle (66°33′ N). At these latitudes, forage decreases rapidly with rising elevation (Tamstorf et al. 2005, Körner 2007). Muskoxen preferring to forage in lowlands year-round is therefore no surprise. We suspect that observed winter use of vegetation poor high elevations, 700-800 m, by muskoxen in Angujaartorfiup sub-area, could compromise their body condition, with negative consequences for body condition and finally winter survival and calf production. Since muskoxen are capital breeders (Desforges et al. 2019), cows rely on body reserves for parturition and early lactation. Thus, muskox cows entering parturition with low body condition may birth calves but lack sufficient reserves for milk production, which may reduce calf survival. Thus, the winter hunting season coinciding with late gestation is not expected to be compatible with a high percentage of calves. The general decline of calf percentage in the 2000-2010 period and additionally the March 2018 calf (age <1-year) percentage of ca. 18.4%, appears to support this. The March 2018 value is at the low end of the range 17-24% reported for expanding Alaskan and Canadian muskox populations (Jingfors & Klein 1982, Gunn et al. 1984). Further, it is well below the excellent 32% that characterized the Maniitsoq muskox population in the 1970's and into the late 1980's (Olesen 1993, Cuyler & Witting 2004, Appendix 9).

In addition to the possible role of the winter hunting season in reducing calf percentage, too many animals in an area relative to the available quality and quantity of forage can bring forth density-dependent factors that may reduce calf production in large herbivores (Kie & White 1985, Ouellet et al. 1997). Density-dependent factors are suspected of playing a role in the steady decline of Maniitsoq muskox calf percentage in the 2000–2004 period (Cuyler & Witting 2004). At that time, observed densities on preferred lowland winter forage averaged from 4 to 16 muskoxen/km² (Cuyler & Witting 2004), with maximums of 21-29 muskoxen/km² in valleys near the town of Kangerlussuaq (Cuyler et al. 2001). The minimum counts of 2000, 2001, 2002 and 2004 observed similar numbers of muskoxen (Cuyler & Witting 2004). Initial calf percentage was 26%, and dropped with each count, 25%, 21% and 18%, respectively. The latter two were also below those predicted by Bayesian modelling (Cuyler & Witting 2004). Meanwhile, the rough density of muskoxen in lowland elevations appeared to rise, being ca. 2.5/km² in 2000 and 3.1/km² in 2004 (Cuyler & Witting 2004). The high densities were observed prior to the winter hunting season and made density-dependent factors a plausible cause behind the declining calf percentages in 2000-2004. The observed decreasing winter cow rump fat depth and pregnancy rates for the same period support this, since not due to temporary factors, e.g., weather events, since similar weather conditions applied across years (Cuyler & Witting 2004). Further, winter harvesting may also have played a role in the falling calf percentages. Already from winter 2000, once snowmobile use commenced for winter hunting then most muskoxen left the valleys and moved into higher elevations (Cuyler unpublished). Given high elevation pasture is poor relative to lowlands and previous muskox densities in lowlands, this movement of muskoxen to higher elevations may have exacerbated the density-dependent factors suspected of already operating in the lowlands.

In winter 2018 most of the estimated population of 18,906 Maniitsoq muskoxen were observed at elevations above 700 m, which provide sub-optimal habitat for foraging. Since calf percentage was only approximately 18% calves, population growth is possible (albeit likely slow) but not certain. Under current harvest regimes that calf percentage may be insufficient for population size stability. With almost 19,000 Maniitsoq muskoxen on poor high elevation pasture in winter, density-dependent effects may be expected. Calf percentage might improve if Maniitsoq muskox cows were able to forage undisturbed in lowlands during late gestation.

Muskox population size & density

Survey coverage of the North region (23,303 km^2) was 10.6%, which is usually sufficient to facilitate reliable estimates. Both DS design- and GAM/DSM model-based approaches were applied to the dataset to obtain comparable estimates of muskox abundance and density. DS design-based estimates are based on the selected transects, which may or may not adequately represent every feature within the study region, as some features may be over-represented, while others under-represented. Meanwhile, GAM modelling considers the environmental covariates of the whole region, allowing the spatial representation of the estimates obtained and a visualization of patterns in abundance.

Most muskoxen were observed in the Angujaartorfiup sub-area (Maniitsoq muskox harvest management area), few in the Sisimiut sub-area (Sisimiut muskox harvest management area), and none in the Sisimiut South sub-area.

Considering the combined Angujaartorfiup and Sisimiut sub-areas, the DS analysis estimated muskox abundance at ca. 21,746 muskoxen (Table 12). That estimate, however, had a wide 95% CI (11,061 – 42,751), which indicates the range of possible abundance is broad. Further the CV was large, 28.5%, illustrating the magnitude of imprecision on the estimate. The GAM/DSM analyses produced a slightly larger estimate of 23,256 muskoxen, which had a tighter 95% CI (18,102 – 29,877) and a lower CV of 11.4%. The two abundance estimates may be considered similar because they differ by only 7-8% and 95%CIs overlap.

The DS population estimate was not precise as evidenced by the large CV. The main factor contributing to imprecision was the high variability within the dataset. For example, most transects flown had zero muskox observations while a few transects had many. Further, the number of muskox group observations was low (n = 210, truncated dataset) combined with a large range in the number of muskoxen individuals within groups. Specific to the Angujaartorfiup sub-area (Maniitsoq muskox harvest management area) was the unusual, clumped distribution of the muskoxen into two hotspots and few muskoxen elsewhere. Specific to the Sisimiut sub-area (Sisimiut muskox harvest management area) was the enormous area surveyed and the dominance of zero observations.

Considering the sub-areas surveyed, the DS estimate for the Angujaartorfiup sub-area was ca. 18,906 Maniitsoq muskoxen (95% CI: 8,726–40,960; CV = 31.5%) (Table 8). Similarly, the Sisimiut sub-area was ca. 2,840 Sisimiut muskoxen (95% CI: 662–12,178;

CV = 56.8%). For each sub-area, like with the overall estimate, the DS provided imprecise estimates with a broad range of possible population size.

At first glance, the GAM/DSM estimate for the entire North region appears best, however, to permit comparison of the DS and GAM/DSM approaches we used the CV for probability of detection of muskoxen within the entire region. The result was that DS was better than the GAM/DSM, with CVs of 5.98% and 11.36%, respectively (Table 12). This indicates that despite uncertainty the design-based DS approach provided a more reliable population estimate than the model-based GAM/DSM for this dataset.

Regarding harvest management decisions, we suggest using the design-based DS estimates for abundance, albeit fully aware of large imprecision. The DS also provides estimates specific for each population, i.e., Maniitsoq and Sisimiut, which can be helpful for applying population specific harvest management. Given the uncertainty in the estimates, erring towards caution is suggested regarding abundance, i.e., consider values in the lower range of the 95% CIs.

Regarding muskox density, the design-based DS density estimates are assumed more immediately usable than those from the GAM/DSM. The design-based DS estimate for the combined Angujaartorfiup and Sisimiut sub-areas was 1.1/km^2 (95% CI: 0.56 – 2.16). Specifically, the Angujaartorfiup sub-area density was ca. 2.65 muskoxen/km^2 and the Sisimiut sub-area ca. 0.22 muskoxen/km^2. These muskox densities intuitively match observer experience. However, density estimates from the model-based GAM/DSM approach did not. The GAM/DSM density estimate for the entire North region was 3.69 muskoxen/km^2 (95% CI: 2,87 – 4,74), which although not realistic is reasonable given the high concentration of muskoxen at two hot spots. Similarly improbable, estimated GAM/DSM densities had a maximum of 125 muskoxen/km^2 (Fig. 17) for rare high elevation locations in the Angujaartorfiup sub-area. We do not suggest a literal interpretation. Instead, the maximum GAM/DSM value reflects the extreme degree muskox distribution was clumped in the Angujaartorfiup sub-area during the survey period. It is inherently harder to estimate abundance and density when clumping is severe. This dataset had enormous variability, which in addition to clumping also included highly variable group size. Additionally, it is important to consider the variability in the density data associated with the covariates (lon, lat, and elevation). The hotspot with the highest densities was associated with elevations that typically ranged from 300 m to 500 m. However, the second hotspot was associated with lower elevations, which made the density estimates lower, albeit the densities were still large (e.g., 70 muskox/km^2). Further, the Sisimiut sub-area has extensive terrain with elevations from 300 m to 500 m (Appendix 6 - Fig. 32), but no hotspot occurred. Instead, muskox detections were sparse in Sisimiut, and the absence of an estimated hot spot is based on the muskox observations. Finally, the largest estimated GAM/DSM densities in the hot spots are associated with the highest uncertainty (Figs. 17, 18). The above makes estimating abundance and density difficult. Nevertheless, the GAM/DSM density pattern (Fig. 17) clearly illustrates the clumping of Maniitsoq muskoxen into areas remote from human influence.

As there is less precision on the GAM/DSM density and the CIs from the two approaches do not overlap, we suggest giving the GAM/DSM density less 'weight', although values in the lower CI range may be relevant at specific locations. We expect the design-based DS densities are closer to actual densities and recommend their use in management decisions.

In 2018 the Maniitsoq muskox population in the Angujaartorfiup sub-area had a density, 2.65/km^2. Elsewhere in the Arctic (Canada's Northwest Territories and Nunavut, and Northeast Greenland), muskox densities are typically much lower, having a range from 0.02 to 1.8/km^2 and averaging ca. 0.86 muskoxen/km^2 (Cuyler et al. 2001). In the period 2000-2004 Maniitsoq muskoxen density in lowland elevations <400 m was ca. 4-5/km^2 (Cuyler et al. 2001, Cuyler and Witting 2004). These values, however, applied only to the northern portion of the Angujaartorfiup sub-area. Regardless, both present and past Maniitsoq muskox densities are relatively high, which attests to the habitat suitability of the Angujaartorfiup sub-area for muskoxen. This is further illuminated by the extreme densities encountered in the 2000-2004 period for muskoxen foraging in lowland elevations <400 m. Examples from core winter grazing areas included, 21.6 muskox/km^2 in the valley, Ørkendalen (n=589 muskoxen in area of 20.25 km^2), and 29.1 muskox/km^2 in the lowlands and river valleys surrounding the Ammalortoq Lake (n = 876 muskoxen in area of 40.5 km^2) (Cuyler & Witting 2004). The falling calf percentages of the 2000-2004 period, suggest that, at those densities, density-dependent factors may have begun negatively affecting the population.

A study to examine the current herbivore carrying-capacity of the Angujaartorfiup sub-area's lowland grass/sedge *Kobresia* steppe is warranted, as is a similar study for elevations of 700-800 m. Specifically, examining the effect of foraging and trampling on vegetation at current muskox density, while considering that föhn winds create expanses of snow-free winter pastures where the vegetation is exposed to harsh conditions including temperatures well below zero and powerful winds.

Muskox population trend

From the 2018 survey, the DS and GAM/DSM analyses provided population size estimates for muskoxen in the North region. These are the first population size estimates based on aerial survey data. Alone, the 2018 estimates cannot indicate current population trend, because this would require at least two additional aerial survey estimate points using similar methods. Additional future surveys will be needed. In the past, Maniitsoq muskoxen (Angujaartorfiup sub-area), received ground-based minimum counts (Appendix 1: Table 13, Appendix 9). However, these cannot be used for comparison to the 2018 aerial estimate, primarily because those counts report only the number of animals observed and do not estimate population size. Regardless, the 2018 estimates of muskox population size clearly illustrate an immense population growth since 27 individuals were translocated to the area over 50 years ago.

For the Maniitsoq muskoxen, population growth appears to have been steepest in the late 1980's and early '90's (Appendix 9). In the 2000-2020 period, ground-based winter minimum counts observed that total muskox number and number of groups became fewer, while simultaneously group size, calf percentage and calf recruitment decreased (Appendix 9). Combined, these indicate a declining Maniitsoq population since the mid-2000s, as does the plot of observed muskoxen from minimum counts for the Angujaartorfiup sub-area (Fig 22).

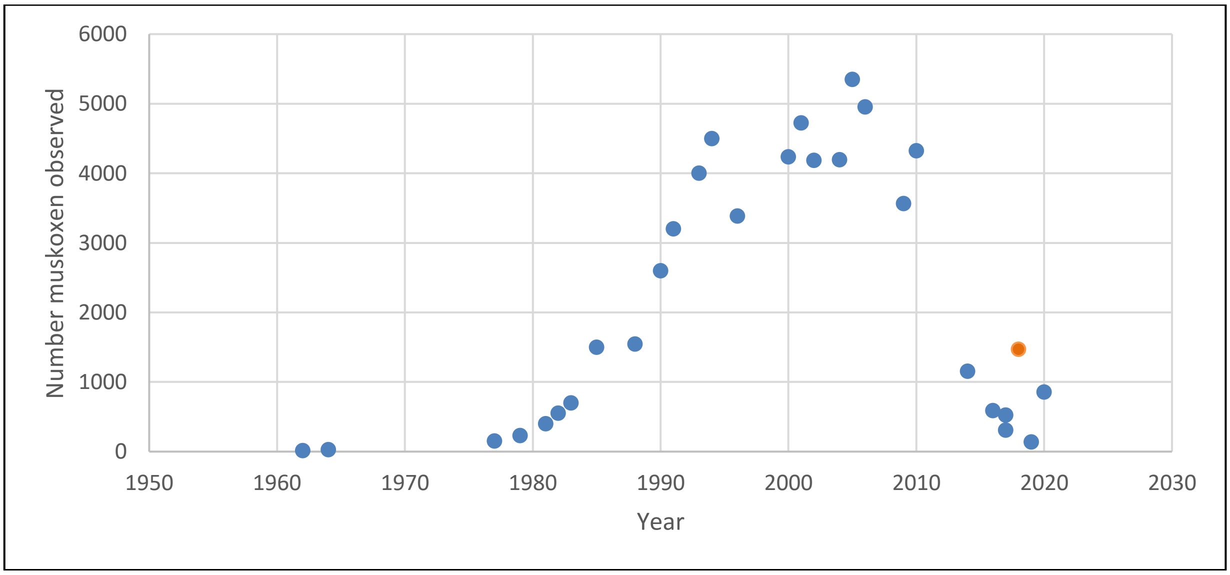

Figure 22. *Index of Maniitsoq muskox abundance in the Angujaartorfiup sub-area since translocation to the region in 1963-65. Data are minimum counts of only those individuals observed and cannot be interpreted as estimates of population size. All but 2018 are ground counts. All are of varying timing, effort, and area coverage. Beginning 2000, all are pre-calving counts from either winter or late winter. Those from 2000 to 2010 were pre-harvest, while those 2014-2020 were post-harvest. In the latter muskoxen were avoiding preferred lowlands. The actual number of individual muskoxen observed during the March 2018 helicopter survey (●) has been included as a type of minimum count, which effort and coverage were the most comprehensive relative to any other minimum count presented. (From Cuyler 2020).*

Reported harvests also suggest declining muskox numbers. Harvest increased after 2002, the peak was in 2008 and generally has declined ever since (Fig. 2, Appendix 8: Table 17). The declining harvests following 2008 (Fig. 2) are reflected in the declining index of muskox abundance starting from about the mid-2000s (Fig. 22). Bayesian analyses of the 2000-2004 minimum counts in the Angujaartorfiup sub-area concluded that harvesting more than ca. 1600 muskoxen annually would likely reduce Maniitsoq muskox population size and harvests that large would not be sustainable over the long term (Cuyler & Witting 2004). Nevertheless, reported annual harvest from 2004 to 2016 always exceeded 1600 muskoxen (Appendix 8: Table 17). Seven of those years exceeded 2000 muskoxen annually. Then, the harvests in 2017 and 2018 were the lowest in over a decade, falling below 1600 muskoxen. Since hunter effort for the winter harvest has remained high and even increased while reported harvests diminished, this supports the 2004 prediction that harvests over 1600 animals would not be sustainable, likely owing to population decline. Alternately, with most muskoxen in high inaccessible terrain in winter, as in March 2018, that would not facilitate hunter success either.

Meanwhile, sex-biased harvesting may have occurred. For the period 2011-2013 the commercial and recreational harvests as per *særmeldingsskemaerne* (special reporting forms, which involve only a portion of the Piniarneq reported harvest) were sex-biased towards cows, i.e., 54.5% cows and 44.2% bulls (Cuyler & Raundrup 2014). Whether this cow-biased harvesting among commercial and recreational hunters continued, or changed has not been investigated, nor whether the sex-biased results from the *særmeldingsskemaerne* can be applied to the entire harvest, i.e., Appendix 8: Table 17. Obviously, if annual harvests repeatedly took more cows than bulls then population decline could be expected.

This century has seen a rapid expansion of local and international demand for qiviut and qiviut products. This motivation likely played a role in raising numbers harvested since 2000, specifically because prices paid for raw skins have skyrocketed and are higher than ever before. By 2017, the increasing worldwide demand for qiviut resulted in international buyers willing to pay Greenland hunters up to DKK 9.500,00 ($1,500 US / 1,280 EUR) for one winter skin (Fernando Alvarez pers. comm.). Since 2014, intact skinless carcasses have been discovered despite attempts to hide them (Cuyler unpublished 2014 field report). Illegal skin-only harvest is an additional mortality of unknown magnitude, which might contribute to possible population decline.

Regarding Maniitsoq muskox calf percentage, the 2018 value of 18.4% (albeit a rough approximation) means they are less productive than before 2000, when calf percentage typically was above 25% (Roby 1978, Thing et al. 1984, Olesen 1993, Cuyler & Witting

2004, Appendix 9). Already in the 2000-2004 period, calf percentage decreased from ca. 26% to ca. 18% (Appendix 1, Table 13). In that period, muskox densities were often exceedingly high in the lowland elevations, which suggests negative density-dependent factors could have been involved. It may be coincidence that over the same period reported harvest more than doubled from 716 to 1614 muskoxen annually (Appendix 8, Table 17) and muskoxen were noted to move into inaccessible high elevations once the winter hunting season began. Thereafter, excepting 2005, calf percentages continued to decline, 15.5% in 2006, 11.0% in 2009 and ca. 12% in 2010. Again, harvests were heavy, but now muskox densities had fallen i.e., density-dependent factors would have had less affect. Calf percentages from 14.6% to 16.5% in North American caribou populations do not permit population size increase because that level of calf recruitment equals adult mortality, while below those decline is inevitable (Bergerud et al. 2008). Meanwhile for muskoxen, calf percentages of 17-24% can facilitate population growth (Jingfors & Klein 1982, Gunn et al. 1984). The 2018 Maniitsoq calf percentage of 18.4% is in the low end of that range, specifically given the absence of large predators. Predation is not pressing calf production down for Maniitsoq muskoxen. Under current conditions, interpreting whether a value of 18.4% calves is sufficient for population stability or growth is difficult. Future population trend is not obvious.

We suspect that a factor behind low calf production is poor cow body condition. Muskoxen are generally not as productive as caribou, and the importance of cow body condition begins already prior to the late summer rut. Muskox cows require 22% body fat to have a 50% probability of pregnancy, while caribou need only 7% body fat (Crête et al. 1993, Adamczewski et al. 1998, Pachkowski et al. 2013). This is important because the probability of successful breeding during the rut increases with the body mass of cows (Rowell et al. 1997, White et al. 1997). Thus, muskox cow pregnancy rates are sensitive to nutritional influences, which if poor lead to reproduction declines (Adamczewski & Flood 1997, White et al. 1997, Adamczewski et al. 1998). Everything that makes vegetation/forage inaccessible, ultimately reduces cow body reserves and thus calf production. For example, winter hunting activities in the vegetation rich lowlands, appear to cause muskoxen to forage at high elevation where vegetation quantity and quality are low. Coinciding with late gestation, cow body condition is likely negatively affected and may be reflected in lower calf survival. With factors(s) causing current 18.4% calves unresolved, the chance for that value to facilitate stability or growth for the Maniitsoq muskox population is debatable.

Circumstances for winter harvesting in the past decade may have resulted in a hunting pressure that was not compatible with sustainable use of this renewable resource. The combined results from past counts, densities, harvests, and calf percentages present the possibility of some muskox population decline already having occurred. If true, the Maniitsoq muskox population may in the past have been larger than the current 2018 estimates. There is no indication that abundance grew since 2010. We suggest future population decline is possible and may already be in progress. Given the above, a future stable or growing Maniitsoq muskox population is not certain.

This report's population size estimates, specifically for Maniitsoq muskoxen, are larger than any previous estimate for muskox populations anywhere in Greenland, while the Maniitsoq muskox DS density is much higher than elsewhere in the Arctic. If considering only elevations <400 m that density becomes even greater. It is well known that high animal density can increase exposure of individuals to infectious pathogens (diseases, parasites). Thus, population growth is perhaps not to be recommended given possible density-dependent influences at current population size. Whether the 2018 Maniitsoq muskox population size (ca. 19.000) and density (ca. 2.65/km^2) for the Maniitsoq muskox harvest management area (Angujaartorfiup sub-area) are within the current herbivore carrying-capacity of the pasture/range remains to be seen.

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Appendix 1

Minimum counts 2000-2014 for Maniitsoq and Sisimiut muskoxen

Winter counts for muskoxen were obtained while driving snowmobile through the lowlands for a limited portion of the area available for each population. Typically, the counts occurred in January prior to the onset of the winter hunting season for commercial and recreational hunters. In brief, the counts employed two snowmobiles and two observers recording muskox number using binoculars and telescopes. The counts provide the actual number of muskoxen observed for specific year in the portion of the region covered and must not be confused with estimates of population size for the entire region.

Table 13. Maniitsoq and Sisimiut muskoxen 2000-2014: winter minimum counts, which were typically ground-based (snowmobile), but included one aerial minimum count of 2010 (in Italics) that supplemented the 2010 ground count.

Year	**Muskox Minimum Count**		**Reference**
	Sisimiut[1] (calf %)	Maniitsoq[2] (calf %)	
2000	---	4235 (26.1 %)	Cuyler & Witting 2004
2001	391 (24.0 %)	4721 (24.7 %)	Cuyler & Witting 2004
2002	480 (19.0 %)	4186 (21.4 %)	Cuyler & Witting 2004
2003	---	---	---
2004	432 (19.9 %)	4236 (17.9 %)	Cuyler & Witting 2004
2005	155	5092 (20.6 %)	Cuyler unpubl., Cuyler & Witting 2004
2006	---	4951 (15.5 %)	Cuyler & Mølgaard unpubl.
2009	---	3564 (11.0 %)	Cuyler & Mølgaard unpubl.
2010	260 (15.2 %)[a]	2417* (12.2 %) + 1113[b] (12.7 %)	Cuyler & Mølgaard unpubl.
2014	---	1151** (21.8 %)	Cuyler & Hansen unpubl.

[1] Corresponds with Sisimiut sub-area and Greenland government's Sisimiut muskox harvest management area.
[2] Corresponds with Angujaartorfiup sub-area and Greenland government's Maniitsoq muskox harvest management area.
[a] Value obtained from count of muskoxen observed in Sisimiut sub-area during March 2010 aerial survey for caribou.
[b] Value obtained from count of muskoxen observed in Angujaartorfiup sub-area during March 2010 aerial survey for caribou, specifically in areas far removed from those surveyed during the January-February ground count by snowmobile.
* Weather and lack of snow curtailed ground area that could covered. Count effort was much reduced relative to previous years.
** In contrast to previous counts, this one occurred in April. Although winter hunting season for commercial and recreational hunters had finished. The low number of muskoxen observed may be explained by the trophy hunting season continuing through the April count period. The muskoxen were typically observed in inaccessible high elevations.

Table 14. Rough densities for Maniitsoq muskoxen in the Angujaartorfiup sub-area.

Year	Maniitsoq muskox density per square kilometre			Source
	Angujaartorfiup[1]	<400m elevations[2]	Core lowland[3]	
1986	0.22			Olesen 1993
1987	0.2			Olesen 1993
1988	0.3			Olesen 1993
1989	0.3			Olesen 1993
1990	0.4-0.51	1.8	2	Olesen 1993, Pedersen & Aastrup 2000
1993	0.32			Pedersen & Aastrup 2000
1994	0.35 – 0.39			Pedersen & Aastrup 2000
1995	0.33 - 0.41			Pedersen & Aastrup 2000
1996	0.4			Pedersen & Aastrup 2000
2000	0.61	4.5		Cuyler et al. 2001
2001	0.7	5.0	21.6 - 29.1	Cuyler et al. 2001
2018	2.6			This study

[1] Angujaartorfiup sub-area has a total area of 7,133 km^2 (Fig. 3).
[2] Area < 400 m was estimated at ca. 950 km^2 (Cuyler et al. 2001).
[3] Core lowland involves areas of extreme muskox density with elevations <400m and within the Government of Greenland hunting areas 1 and 2 (Fig. 42, 43).

Appendix 2

Statistical methods behind Distance Sampling

This appendix presents the basic building blocks and reasoning behind Distance Sampling (DS) methods, followed by some details. This summary of statistical methods is from Correia (2020).

Fundamental concepts

Before entering into the detailed theory behind the Distance Sampling methodology, we present a simpler design, which is quadrat or plot sampling (Buckland et al. 2001; Marques, 2009).

In plot sampling, a region of interest with total area A, is divided into small plots of area a_{plot} (Fig. 23). Some of these small plots are randomly chosen for sampling and the total number of individuals within these, n_{plot}, is recorded.

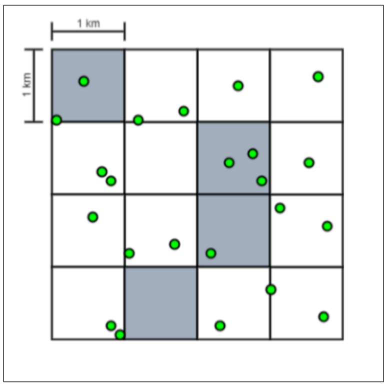

Figure 23. Plot sampling grid example of total area A divided into smaller plots of area a_{plot}.

The density within each plot, D_{plot}, is the number of individuals per unit area for the respective plot so, by definition, it is given by

$$\widehat{D}_{plot} = \frac{n_{plot}}{a}, \qquad \text{Equation (1)}$$

where a is the total area sampled within A. (i.e., $a = 4 \cdot a_{plot} = 4km^2$ for Fig. 23) Since a random design was used, the density is a representative estimate, by design, for the total area A. Hence, an estimate for the abundance, $\hat{N}$, can be obtained by simply multiplying $\hat{D}_{plot}$ by the total area A,

$$\widehat{N} = A \cdot \widehat{D}_{plot} = A \cdot \frac{n_{plot}}{a}. \qquad \text{Equation (2)}$$

The DS methodology is an extension of quadrat-based sampling methods. The detail that creates the bridge from one methodology to the other is the fact that the method described above assumes that every individual of interest is detected (Miller et al. 2016). Frequently, this assumption cannot be met, specifically if among the individuals of interest there are animals impossible to observe owing to low sightability. Several factors cause low sightability, including topographical barriers, weather conditions, ground surface conditions and many others related to observer training and survey design. The proportion of individuals that were not detected can be estimated using the detection function fitted to the observed distances (Thomas et al. 2002). Once this proportion is estimated, it can be considered to obtain more accurate estimates and then, an extrapolation for a wider region can be done similarly as shown in Equation (2).

In Distance Sampling, this proportion of detected objects in the area a is defined as the probability of detection, P_a. Therefore, a density estimate can be obtained as per Equation(1) by adjusting n_{plot} by P_a, i.e., by correcting the detections for those that were missed. Since the latter cannot be known, in general, an estimate must be also obtained, thus

$$\widehat{D} = \frac{\frac{n_{plot}}{\widehat{P}_a}}{a} = \frac{n_{plot}}{2wL\widehat{P}_a}, \qquad \text{Equation (3)}$$

where $\hat{P}_a$ is an estimate of P_a obtained from the distance data, and a is the area of the sampled region. Usually $a = 2wL$, with w as the truncation distance, for both sides of the centreline, and the total transect length $L = \sum_{j=1}^{k} l_j$, where l is the length of transect j. Abundance can be determined using a reasoning analogous to that above (Equation 2). The truncation distance is defined as the distance beyond which distances are not recorded. This can be defined in the field or at the analysis stage.

The coefficient of variation of $\widehat{D}$, $cv(\widehat{D})$, is related with two random components referred above, encounter rate (n_{plot}/L), and $\hat{P}_a$, plus a third one that is the estimate of the expected size of detected clusters ($\hat{E}\ (s)$). Assuming independence between there, the former is given by

$$(cv(\widehat{D}))^2 = \left(\frac{se(\widehat{D})}{\widehat{D}}\right)^2 = (cv(n_{plot}/L))^2 + (cv(\widehat{E}(s)))^2 + (cv(\widehat{P}_a))^2.$$

Equation (4)

An approximation of the standard error of $\widehat{D}$, $se(\widehat{D})$, is defined as

$$se(\widehat{D}) = \widehat{D} \cdot \sqrt{(cv(n_{plot}/L))^2 + (cv(\widehat{E}(s)))^2 + (cv(\widehat{P}_a))^2}.$$

Equation (5)

Once these are obtained, an approximate $100(1-\alpha)\%$ confidence interval (CI) can bedetermined by

$$\widehat{D} \pm z_{1-\frac{\alpha}{2}} \cdot se(\widehat{D}), \qquad \text{Equation (6)}$$

Where $z_{1-\frac{\alpha}{2}}$ is the quantile of the $N(0,1)$ distribution $(z_{1-\frac{\alpha}{2}} = z_{1-\frac{0.05}{2}} = z_{0.975} =$ 1.96 for a 95% confidence interval). However, the distribution of the $\widehat{D}$ is positively skewed, thus an interval assuming that $\widehat{D}$ is log-normally distributed has better coverage. According with Buckland et al. (2015), a 100(1-alpha)% confidence interval can be given by

$$\left(\widehat{D}/C, \widehat{D} \cdot C\right), \qquad \text{Equation (7)}$$

where

$$C = \exp\left\{z_{1-\frac{\alpha}{2}} \cdot se\left[\log_e(\widehat{D})\right]\right\} \qquad \text{Equation (8)}$$

and

$$se\left[\log_e(\widehat{D})\right] = \sqrt{\log_e\left[1 + \left(cv(\widehat{D})\right)^2\right]}. \qquad \text{Equation (9)}$$

For further details see Buckland et al. (2001) and Buckland et al. (2015).

Probability of detection

Given the above, the probability of detecting an object, giving that it is within the areacovered by the transects, $\hat{P}_a$, needs to be estimated. For this project, the object of interest consists in muskox groups.

To illustrate the importance of this probability, consider that an observer walks across a large patch of tundra and detects 8 muskoxen (Fig. 24). While discussing with the local biologist, and considering the biologist's experience, he/she will state that, on average, only one third of all muskoxen present are detected (i.e., $\hat{P}_a = 1/3$) meaning that probably there were around 24 muskoxen within that patch of tundra and 16 have been missed. That is where Distance Sampling is useful, since it allows a rigorous framework for the estimation of P_a and then an estimate of abundance can be obtained as shown in Equation (3).

Distance Sampling methods

The detection function, $g(y)$, describes the probability of detecting an object of interest given that it is at a distance y, from the centreline (also known as 0-line), thus being a non-increasing function of y (Buckland et al. 2015).

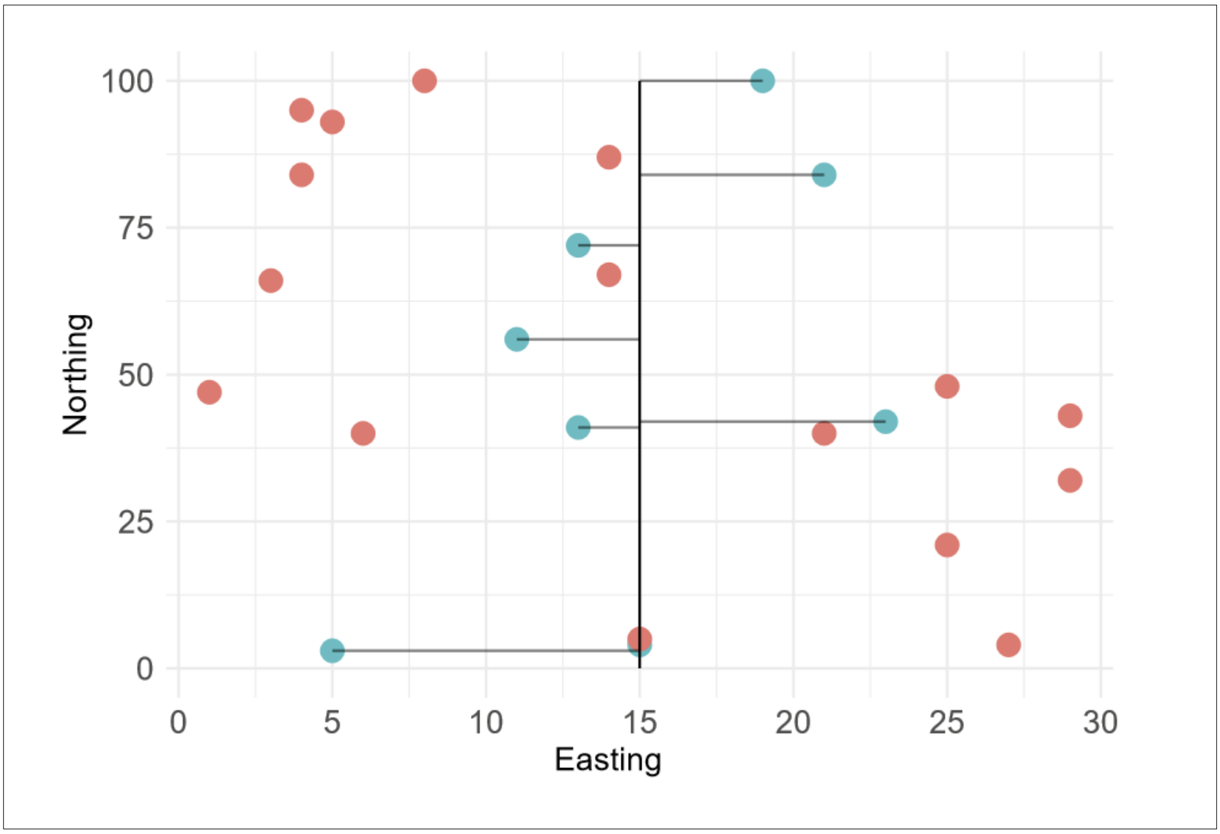

Figure 24. Example of a patch of tundra with the transect in the middle. Blue dots represent eight observed muskoxen, while orange dots represent the 16 undetected ones. The lines perpendicular to the transect represent the recorded distances.

For line transects, y is the perpendicular distance from the 0-line to the detected object. Within Distance Sampling methods, the probability of detection is explained recurring to these observed distances (Buckland et al. 2001). Sometimes covariates may be added to explain their relationship with the detection probability. In this situation, we are within the Multiple Covariate Distance Sampling (MCDS) framework (Buckland et al. 2001).

Conventional Distance Sampling

Conventional Distance Sampling (CDS) occurs when no additional covariates are added to the model. Once the detection function is estimated, $\hat{P}_a$ can be obtained via the following equation

$$\widehat{P}_a = \int_0^w \hat{g}(y) \cdot \pi(y) dy, \qquad \text{Equation (10)}$$

where $\pi(y) = \frac{1}{\omega}$ and, therefore, used to estimate density using Equation (3). For $g(y)$ it is also specified a flexible semi-parametric model, composed by a key function and some additional series expansions, known as adjustment terms, and their parameters are estimated (Marques et al. 2007).

To obtain robust estimates of density, flexible models for $g(y)$ are needed with the form (Buckland et al. 2001)

$$g(y) = \frac{k(y) \cdot [1 + s(y)]}{k(0) \cdot [1 + s(0)]}, \qquad \text{Equation (11)}$$

where $k(y)$ is the parametric key function and $s(y)$ represents the additional adjustment terms (Table 15).

Table 15. Commonly used key functions and series expansions for the detection function. Adapted from Buckland (2001).

Key function		Series expansion	
Uniform	$1/w$	Cosine	$\sum_{m=2}^{M} a_m cos(m\pi y_s)$
Half-normal	$\exp[-y^2/2\sigma^2]$	Simple Polynomial	$\sum_{m=2}^{M} a_m (y_s)^{2m}$
Hazard-rate	$1 - \exp[-(y/\sigma)^{-b}]$	Hermite	$\sum_{m=2}^{M} a_m H_{2m}(y_s)$

Note: If Uniform key, $m = 1, ..., M$. $H(x)$ denotes Hermite function.

The uniform key function has no parameters, while the half-normal and the hazard-rate functions include a scale parameter, σ, which determines the rate at which the function decreases with increasing distance (Fig. 25). Furthermore, the hazard-rate function also includes a shape parameter, b, that provides greater flexibility to this function comparing to the others (Buckland et al. 2001).

It is not always necessary to include adjustment terms, and in such cases, these models are referred to as "key only" models. When the key functions are not enough for fitting $g(y)$, some series expansions terms may be added to modify its shape (Fig. 26). These terms can be either cosine, simple polynomial or Hermite polynomial (Table 15).

It is important to note that these adjustment terms do not depend directly on y but on y_s which is a scaled value of y, where $y_s = \frac{y}{\omega}$ with ω being the truncation distance. This allows independence between the shape of the series expansion and the units used for y (Marques et al. 2007).

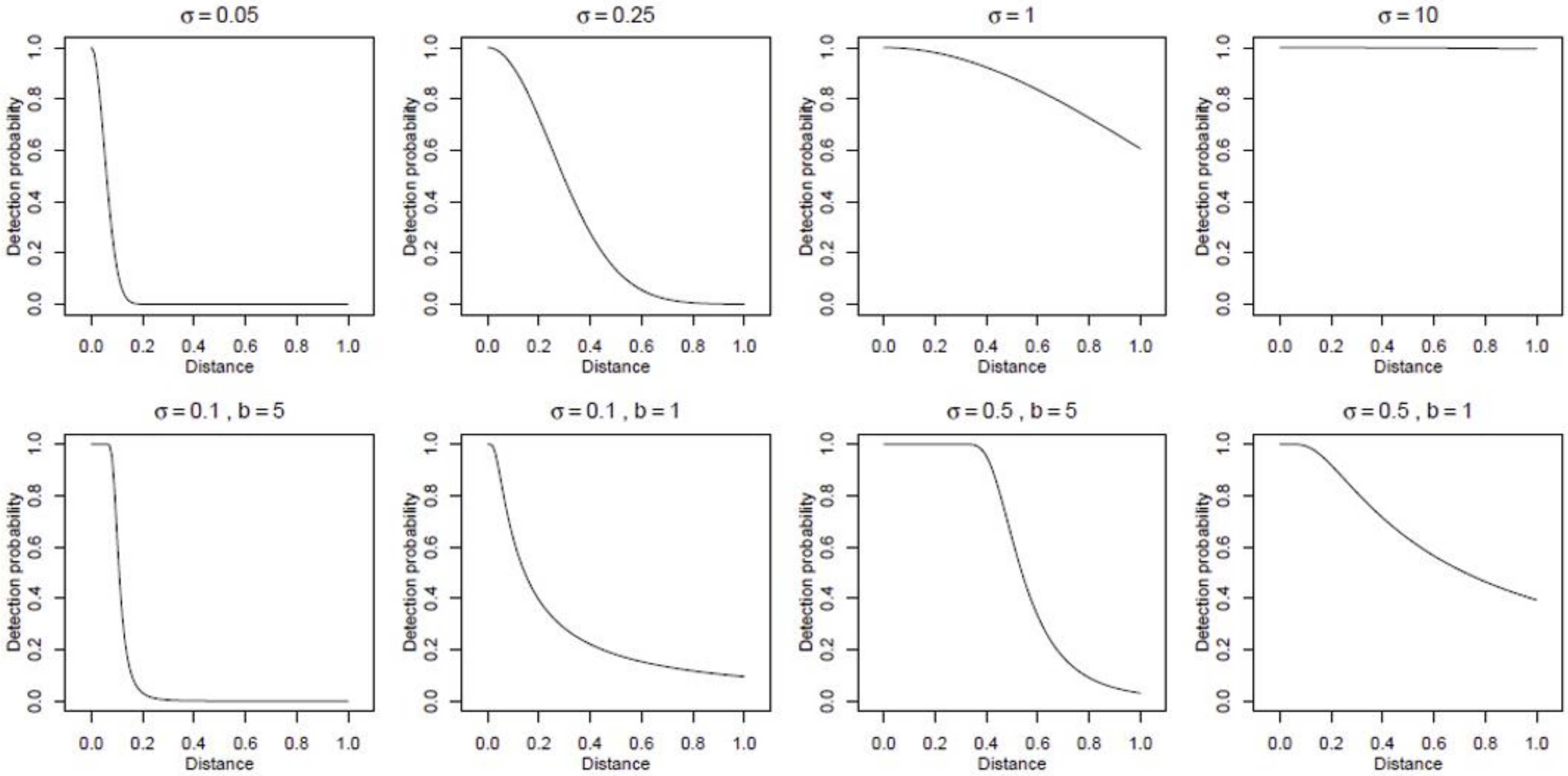

Figure 25. Half-normal (top row) and hazard-rate (bottom row) detection functions without adjustments, varying scale (σ) and, only for hazard-rate, shape (b) parameters. Values tested are presented above the plots. On the top row from left to right, the study species becomes more detectable (higher probability of detection at larger distances). The bottom rows show the hazard-rate model's more pronounced shoulder. Adapted from Buckland et al. (2001).

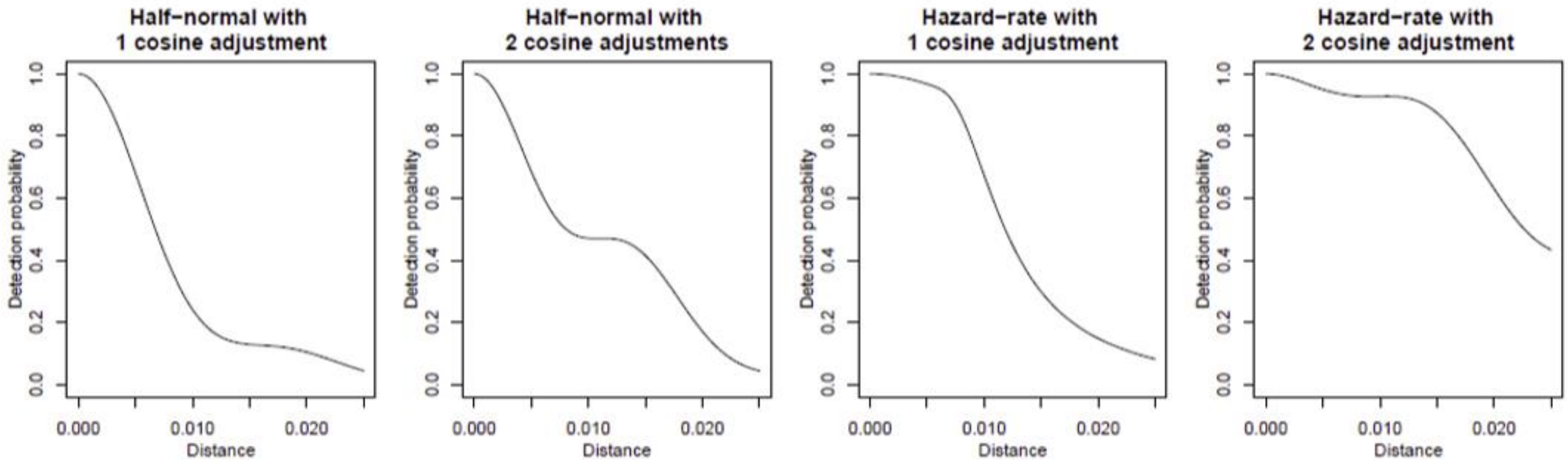

Figure 26. Possible shapes for the detection function when cosine adjustments are included for half-normal and hazard-rate models. Adapted from Buckland et al. (2001).

Right truncation of the data, or the removal of the largest distances, is a common procedure that aids model fitting. Some precision might be lost with truncation; however, it is usually slight. On the other hand, precision is increased since the data is easier to model and, consequently, fewer parameters and adjustment terms are required to model the detection function (Couturier et al. 2018).

Multiple Covariate Distance Sampling

CDS methods can be extended to MCDS, so that $g(y)$ is modelled as a function not only of distance, but also of a vector of J additional covariates for each of the n objects of interest,

$\mathbf{z_i} = z_{i1}, ..., z_{iJ}, i = 1, ..., n$. Accordingly, the function that describes the probability of detection at a given distance, is represented by $g(y, \mathbf{z})$. These additional covariates can either be discrete or continuous, such as observer and group size, and are assumed to affect only the scale, σ, of the detection function (Marques et al. 2007; Miller et al. 2016). For line transects, $P(\mathbf{z_i})$, i.e., the probability of detecting the i-th object of interest given its respective vector of covariates $\mathbf{z_i}$ can be estimated using the formula presented in Equation (12).

$$\widehat{P}(\mathbf{z_i}) = \int_0^w \hat{g}(y, \mathbf{z_i}) \cdot \pi(y) dy, \qquad \text{Equation (12)}$$

with $\pi(y) = \frac{1}{\omega}$. Considering the three key functions previously presented, only the uniform key is excluded from MCDS since it does not have a scale parameter. Half-normal and hazard-rate functions can have their scale parameter written as a function of the covariate values as

$$\sigma(\mathbf{z_i}) = \exp\left(\beta_0 + \sum_{j=1}^{J} \beta_j z_{ij}\right), \qquad \text{Equation (13)}$$

Where $\beta_0$and all the β_j's are the J + 1 coefficients to be estimated with J being the total number of covariates. The estimation of the parameters for both CDS and MCDS is typically done via maximum likelihood (Marques et al. 2007).

Once the detection function is estimated, according with (Buckland et al. 2004), density can be estimated as

$$\widehat{D} = \frac{1}{a} \sum_{i=1}^{n} \frac{1}{\widehat{P}(\mathbf{z_i})}, \qquad \text{Equation (14)}$$

where a is the total area surveyed, $\hat{P}(\mathbf{z_i})$ is the estimated probability of detecting the i-th object of interest given its respective vector of covariates $\mathbf{z_i}$.

Finally, Marques et al. (2007) states that MCDS methods potentially offer improved inference in four situations, when comparing to CDS methods:

1. when a subset of data is used to estimate density, e.g., by strata, where this information can be introduced as a factor covariate. In CDS, the strategy is more complex, either to estimate P_a for each stratum and thus, stratum-level estimates for density or to use a global estimate for the probability of detection, but this second introduces bias, for example, if one stratum favours the animals when compared to other strata which uses fewer parameters than a fully stratified detection function model;
2. where pooling robustness does not hold for CDS analyses, e.g., when survey intensity varies according with pre-defined strata to increase efficiency, or when the detection probability faces extreme heterogeneity due to different object habitats or behaviors, for example, showy males contrasting with cryptic females in animal surveys;
3. reduces the variance of density estimates by modelling the heterogeneity in the detection function;
4. if there are covariates of interest to be included in the model.

Model selection

Since the estimator of density is closely linked to the detection function, it is of critical importance to select models for the detection function carefully. Three properties desired for a model for $g(y)$ are, in order of importance, model robustness, a shape criterion and estimator efficiency (Buckland et al. 2001, 2015; Miller et al. 2016).

The most important property of a model for the detection function is model robustness. According with Buckland et al. (2001, 2015), this means that the model is a general, flexible function that can take a variety of plausible shapes for the detection function. The concept of pooling robustness is also included here. Models of $g(y)$ are pooling robust if the data can be pooled over many factors that affect detection probability and still yield a reliable estimate of density. A model is pooling robust if, for example, a stratified estimation for density, $\widehat{D}_{st}$, and a pooled estimation for density, $\widehat{D}_p$, are approximately the same. In the first scenario, the data is stratified by factors, such as observer or habitat type, and an estimate for density in each stratum is made. Then these estimates are combined into $\widehat{D}_{av}$, an average density estimate. In the second scenario, all data could be pooled, regardless of any stratification, and a single estimate computed, $\widehat{D}_p$. A model is pooling robust if $\widehat{D}_{av} \approx \widehat{D}_p$.

According to Buckland et al. (2001), the shape criterion consists in the fact that the detection function should have a 'shoulder' near the line (Fig. 27), i.e., detection remains nearly certain at small distances from the sampling unit's track line ($g'(0) = 0$). This allows the reliable estimation of object density (Thomas et al. 2002). Generally, good models for $g(y)$ will satisfy the shape criterion near the zero-distance track line, which is especially important in the analysis of data where some heaping at zero distance is suspected.

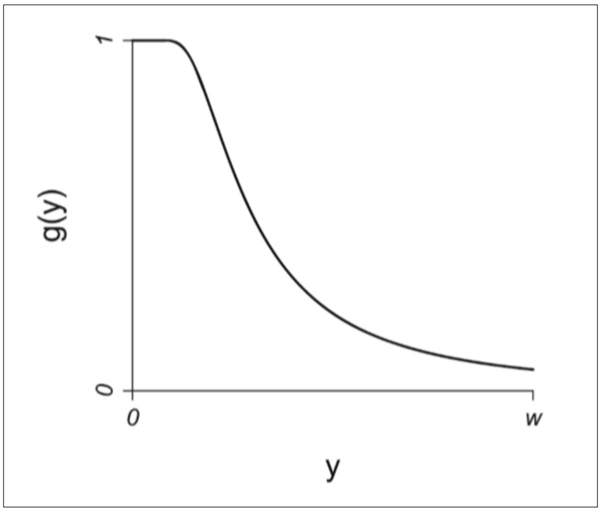

Figure 27. A good model for the detection function should have a shoulder, with probability of detection staying at or close to one at short distances from the centreline or point. At larger distances, it should fall away smoothly. The truncation distance ω corresponds to the strip half-width (for Line Transect Distance Sampling). Adapted from Buckland et al. (2001).

Estimator efficiency is the third most important property (Buckland et al. 2001), which means that it is desirable to select a model that provides estimates that are relatively precise, i.e., that have small variance. This property is of benefit only for models that are model robust and have a shoulder near zero distance, otherwise the estimation might be precise but biased.

Besides these three criteria, the model should be a monotonic function of distance from the line, that is, the probability of detection at a given distance cannot be greater than the probability of detection at any smaller distance (Fig. 27) (Buckland et al. 2001).

There is no fixed standard method to select the best fitting model, i.e., choosing the most appropriate key function and series expansion (Marques et al. 2007). It is usually done by applying the Akaike's Information Criterion (AIC), Kolmogorov-Smirnov test, Cramér-von Mises test and the χ^2 Goodness-of-Fit test (GOF test). The likelihood ratio test can also be used but, since it is only applicable for nested models, AIC is the recommended method (Marques et al. 2007). A proper model should be simple with an adequate fit without overfitting the data.

Akaike Information Criterion

The relative fit of alternative models may be evaluated recurring to AIC, or AICc, in case of small samples, providing a small sample bias correction (Buckland et al. 2001). These criteria can be determined as follows

$$AIC = -2 \cdot \ln(\mathcal{L}) + 2q, \text{ and} \qquad \text{Equation (15)}$$

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$$AICc = AIC + \frac{2q(q+1)}{n-q-1}, \qquad \text{Equation (16)}$$

where $\mathcal{L}$ is the likelihood function, q is the number of estimated parameters in the model, and n is the sample size. This measure provides a trade-off between bias and variance. AIC includes two terms, one related with the fitted model, and the other working as a penalty considering the excess of parameters in the model (Brewer et al. 2016).

Kolmogorov-Smirnov test

The Kolmogorov–Smirnov test is one of the tests that can be applied to the detection function to assess model fit (Buckland et al. 2004). This test is only applicable for continuous data, being preferable to the χ^2 GOF test for MCDS methods.

Considering the cumulative distribution function (c.d.f.) $F(x) = P(X \leq x)$ and the empirical c.d.f. (e.d.f.) $S(x)$, the null hypothesis to be tested is $H_0 : F(x) = F_0(x), \forall x$. The alternative hypothesis states that both functions differ for at least some value of x. In practice, $F(x)$ is replaced by its estimate, and $H0$ states that the assumed model is the true model for the data (Buckland et al. 2004). The largest absolute difference between $\hat{F}(x)$ and $S(x)$, denoted D_n, is the test statistic (Gibbons & Chakraborti 2011). The corresponding p-value can be approximated by

$$p = 2 \cdot \sum_{i=1}^{\infty} (-1)^{i-1} \exp(-2ni^2 D_n^2). \qquad \text{Equation (17)}$$

Cramér-von Mises test

Similar to the Kolmogorov-Smirnov test, the Cramér-von Mises test shares the same null hypothesis and basis on differences between c.d.f. and e.d.f. However, instead of considering only the largest difference between the two functions, this test is based on their entire range (Buckland et al. 2004). The test statistic can be given by

$$W^2 = \frac{1}{12n} + \sum_{i=1}^{n} \left[\widehat{F}(x_{(i)}) - \frac{i-0.5}{n} \right]^2. \qquad \text{Equation (18)}$$

Chi-square Goodness-of-Fit test

The χ^2 Goodness-of-Fit test (Buckland et al. 2001, 2015) compares the observed frequencies, n_i, with the expected frequencies under the model $E(n_i)$ and it is given by

$$X^2_{obs} = \sum_{i=1}^{n} \frac{\left[n_i - E(n_i)\right]^2}{E(n_i)} \sim \chi^2_{(u-q-1)}, \qquad \text{Equation (19)}$$

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under the null hypothesis (H_0) of good model fitting, i.e., the difference between the observed (n_i) and expected ($E(n_i)$) counts is close to zero. In Equation (19), n is the total number of observations, u is the number of groups (or bins) within the distance data, and q is the number of model parameters estimated. Reject H_0 if $X^2_{obs} > X^2_{1-\alpha;(u-q-1)}$, with the latter representing the 1–α quantile from a χ^2 distribution with u - q - 1 degrees of freedom.

As the number of parameters of the fitted model increases, the bias decreases, but the sampling variance increases (Buckland et al. 2001). While the Goodness-of-Fit test results should be considered in the analysis of distance data, they will be of limited value in selecting a model since these tests are sensitive to heaping. Therefore, care is needed in choosing suitable distance intervals.

If data are collected with no fixed ω, it is possible that a few extreme outliers will be recorded. These values are not useful, and the data should therefore be truncated. This can be checked using the distances' histogram, and whether there is evidence of heaping or not (Buckland et al. 2001; Couturier et al. 2018).

Goodness-of-Fit tests allow formal testing of whether a detection function model provides an adequate fit to the data. Since the GOF test cannot be used on continuous data, unless grouped, it is of limited use for testing MCDS models (Buckland et al. 2015), being useful for testing models using CDS methods. However, if distances are not grouped, they must first be categorized into groups to allow the test to be conducted. Thus, there is a subjective aspect to the test, and different analysts, using different group cut points, may reach different conclusions about the model adequacy. In contrast, the Kolmogorov–Smirnov and Cramér–von Mises tests can only be applied to continuous data (Buckland et al. 2015).

Appendix 3

Statistical methods behind Generalized Additive Model (GAM) & Density Surface Model (DSM)

This appendix presents the basic building blocks and reasoning behind GAM and DSM methods, followed by some details. This summary of statistical methods is from Correia (2020).

Generalized Additive Model (GAM)

Generalized Additive Models are an extension to Linear Models (LM) and Generalized Linear Models (GLM) where non-linear responses with smoothing functions can be fitted to the data. So, to define a GAM, first LM and GLM will be briefly introduced.

In LM, and considering a total of n observations, a response variable Y_i, with mean value $\mu_i = E(Y_i)$ is expressed as the sum of a function of linear combinations of M independent variables X_m, $m = 1, 2, ..., M$, and a random error ϵ,

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_M X_{Mi} + \epsilon_i, \quad i = 1, \ldots, n, \tag{20}$$

where the β's are the unknown parameters, with β_0 representing the intercept and β_M the parameter associated with the M-th predictor. It is assumed that the random errors ϵ are independent and identically distributed, following a $N(0, \sigma)$ distribution (Wood, 2017).

GLMs are an extension of LM where there can be a non-linear relationship on the response scale between the dependent variable and the independent variables (Wood, 2017), considering that the former follows a distribution from the Exponential family and using a link function, $g(.)$. Therefore, the equation of the model is given by

$$g(E(Y_i)) = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots + \beta_M X_{Mi}. \tag{21}$$

Finally, GAM are a GLM extension where the linear predictor includes smoothing functions of covariates, $f(.)$ (Wood, 2017). As happens with GLM, Y_i must belong to the Exponentialfamily and a link function, $g(.)$, is specified. A GAM is expressed as

$$g(E(Y_i)) = \beta_0 + f_1(X_{1i}) + f_2(X_{2i}) + f_3(X_{3i}) + \ldots + f_M(X_{Mi}). \tag{22}$$

These smoothing functions need, therefore, to be defined and predetermine how flexible or smooth they should be. Another advantage of working with this type of functions is the possibility of combining covariates into a single smoothing function. Thus, by combining, for example, the covariates X_1 and X_2, the above formulation would look like

$$g(E(Y_i)) = \beta_0 + f_1(X_{1i}, X_{2i}) + f_3(X_{3i}) + \dots + f_M(X_{Mi}). \quad (17)$$

Therefore, GAM are more adequate since these are able to fit smoothing functions through the data, which provides flexibility in describing complex non-linear relationships (Wood, 2017).

Furthermore, if Y_i is described by a Poisson distribution, the surveyed area is defined as the offset variable. This variable can be added to the model with its regression coefficient known to be 1. Equation (22) can then be rewritten as

$$g(E(Y_i)) = \beta_0 + f_1(X_{1i}) + f_2(X_{2i}) + f_3(X_{3i}) + \dots + f_M(X_{Mi}) + \log(offset) \quad (18)$$

During this project, the offset term considered to explain the number of observations in each area was the effective sampling area, obtained in the first stage via Multiple Covariate Distance Sampling (MCDS).

Density Surface Model (DSM)

Conventional Distance Sampling methods provide average estimates of abundance over a region but no information about the distribution of the objects of interest within the survey region. One possible option is to divide the study area into progressively smaller and smaller strata to try to detect patterns in spatial distribution. However, a more efficient approach is to build a spatial model. These models incorporate spatially-referenced environmental covariates, thus modelling part of the spatial variability of the data (Katsanevakis, 2007; Miller et al. 2013). Density surface modelling uses the GAM framework (Wood, 2017) to build models of abundance/density as a function of environmental covariates, typically as part of a two-stage method. In the first stage we model the detectability via distance sampling and in the second stage we model the counts, corrected for detectability, over space. To propagate the variance, the GAM model parameters' distribution can be used to generate replicate abundance estimates, and the uncertainty from the estimated detection function can be incorporated as an additional random effect term (Miller et al. 2013).

Generally, very little information is lost by taking this two-step approach as the transects are very narrow when compared with the width of the study area. So, provided no significant density variation takes place across the lines' width or within the point, there is no information in the distances about the spatial distribution of animals (Miller et al. 2013).

Additionally, DSM can be used to predict abundance and density over an area of interest, given the other environmental covariates (Miller et al. 2013). In our work, the provided covariates of interest included aspect, elevation, slope, and vegetation. Although relevant, the latter was discarded since available data lacked the necessary resolution for the analysis.

After fitting the DS model, the counts within the defined offset are adjusted with the estimated probability of detection and, with this new data set including the offset, a GAM is fitted. A prediction map can then be created once a spatially georeferenced data set used for prediction is obtained. Furthermore, it would be better to include the uncertainty associated with each mapped estimate, since these estimates alone can be less informative. Within this project, a map representing the coefficient of variation (CV) associated to each estimate was obtained resorting to the packages mentioned in the previous chapter, even though there are other possible methods (e.g., varying each prediction's pixel size according with the associated uncertainty, within a single map).

Using QGIS, the whole study region was converted into small cells. Centred on each point, a 1.5km × 1.5km square shaped buffer zone was created and intersected with the sampling points and spatial covariates. For each square, the mean of each covariate was determined, along with the respective central pair of coordinates. This information was converted into a data set to create the GAM model.

Appendix 4

Distance Sampling Assumptions – short summary

Line transect Distance Sampling assumptions and design are described in Buckland et al. (1993) and a summary of the assumptions for large herbivore survey in Greenland provided below are from Cuyler et al. (2016).

1. All muskoxen on the 0-line are detected. This must be true.
2. Muskoxen are randomly distributed. (Lacking this will not bias abundance estimates because the line transects were randomly placed.)
3. Detection of muskoxen is independent. (Although detection was dependent in our survey, the line transects had random start-end points, so this assumption is not violated).
4. No muskoxen movement prior to detection. The method is a 'snapshot' method. In practice this assumption is not violated if the observer moves faster than the animal, e.g., if movement of muskoxen to the next line transect to be surveyed is rendered impossible, which it was.
5. Distance measurements are exact. Provided distance measurements are approximately unbiased, bias in line transect estimates tends to be small in the presence of measurement errors. In our survey we binned the observations into distance intervals which decreases measurement error.
6. Group size for muskox groups close to the 0-line are accurate.
7. Other assumptions include those for other survey types, e.g., that each population is closed, being confined within a clearly defined area.

Appendix 5

Sisimiut sub-area inland, within 40 km of the Ice Cap, March 2018: Some muskox groups and snow cover observed. Photos by C. Cuyler

Figure 28. Group of 30 muskoxen, which may have included 2-3 calves (age ca. 10-months).

Figure 29. Group of 38 muskoxen, which may have included 3 calves (age ca. 10-months).

Figure 30. Group of 23 muskoxen, which may have included 1-2 calves (age ca. 10-months).

Figure 31. Group of 38 muskoxen, which may have included 7-8 calves (age ca. 10-months). Eight adults kept themselves somewhat separated from the main group.

Appendix 6

Maps illustrating elevation, aspect, and slope in the North region

Elevation

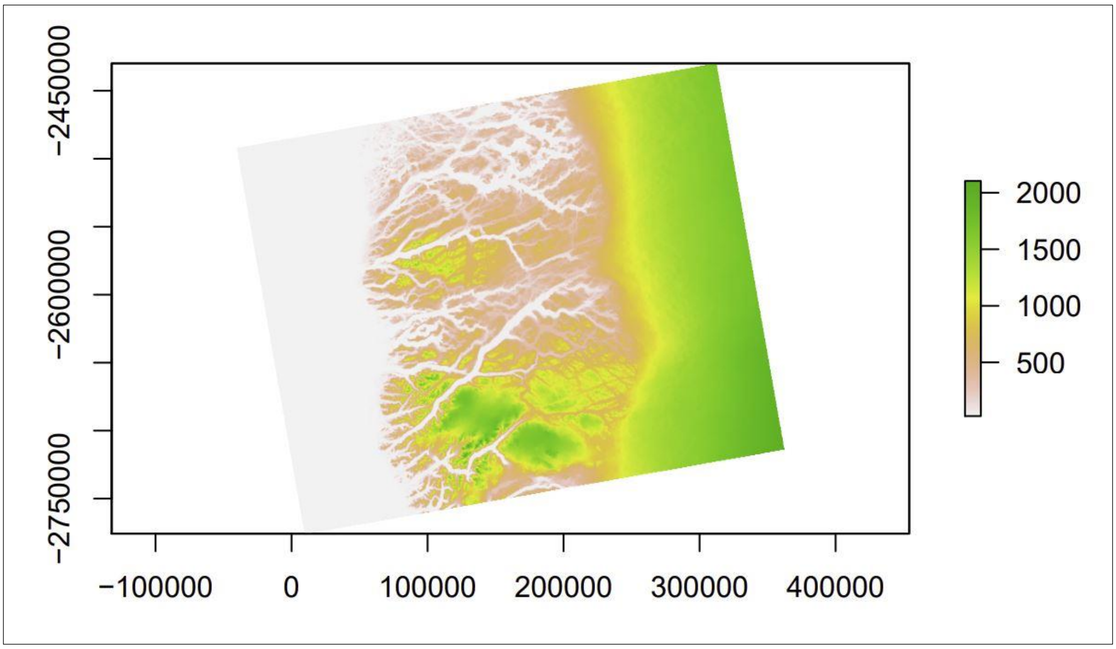

Figure 32. Map illustrating elevation in the surveyed area. Legend colour codes the elevation.

Aspect

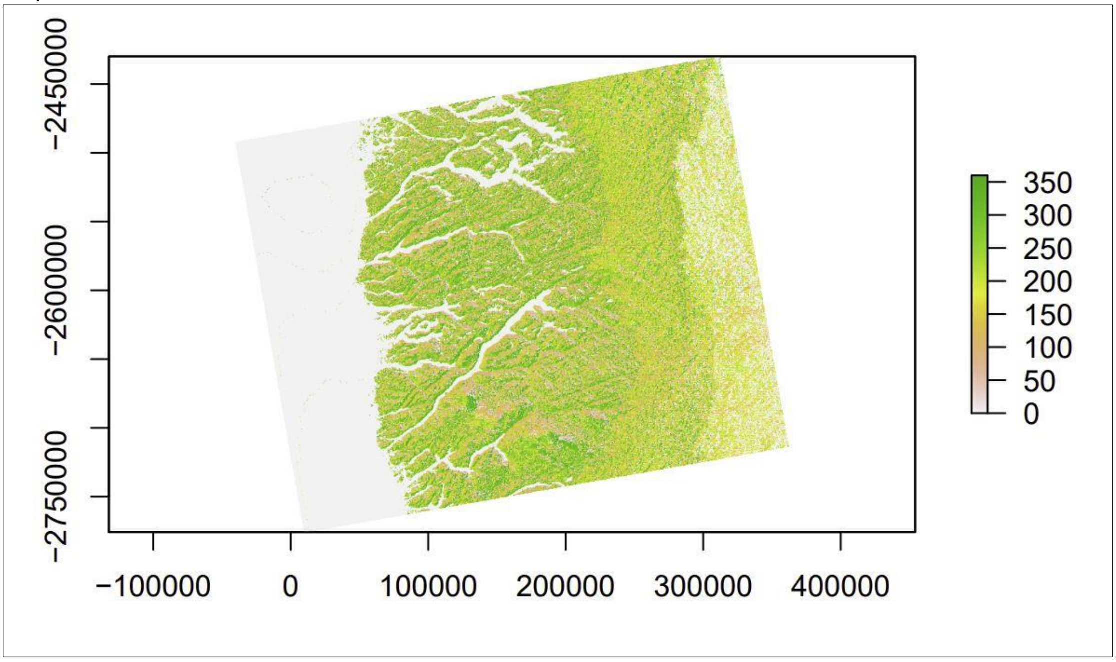

Figure 33. Map illustrating aspect in the surveyed area. Legend colour codes the compass headings for aspect.

Slope

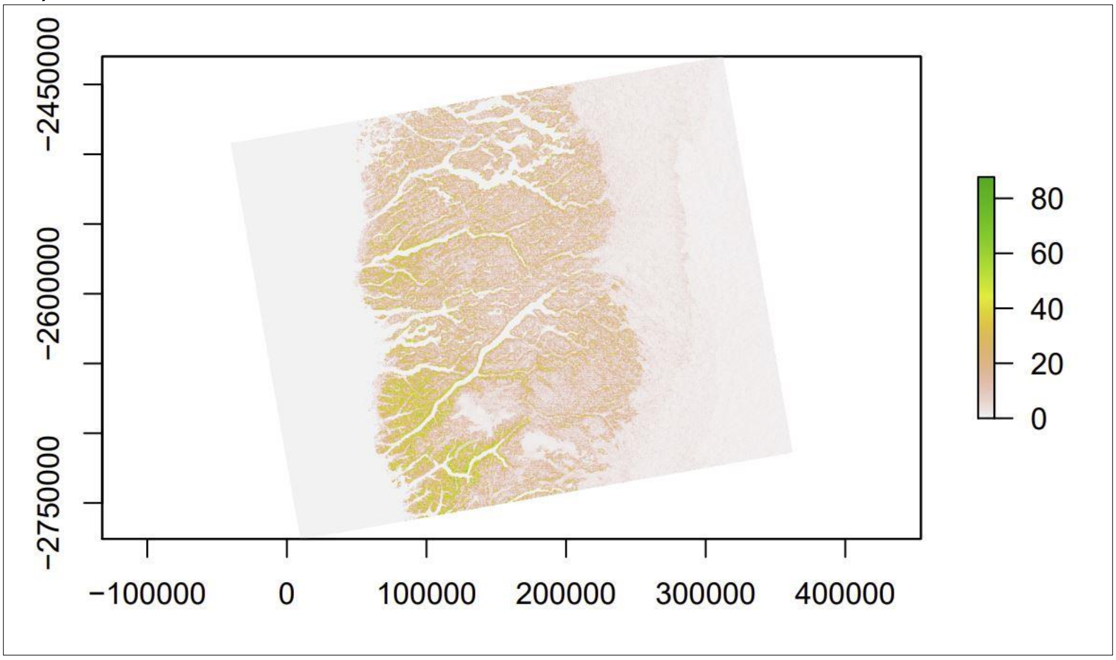

Figure 34. Map illustrating slope in the surveyed area. Legend colour codes the angle of slope.

Appendix 7
Angujaartorfiup sub-area, March 2018: Photos of survey conditions and snow cover observed. Photos by C. Cuyler

Figure 35. View from surface of lake ice during a pause between survey lines, illustrating lack of snow common in the Angujaartorfiup sub-area. Also illustrating flat-light (no shadows).

Figure 36. View as helicopter flew over surface of lake ice, illustrating the typical sparse snow cover on the ground ahead, line transect 18 Angujaartorfiup sub-area. Also illustrating flat-light (no shadows).

Figure 37. View while flying line transect 17, illustrating sparse snow-cover common to the Angujaartorfiup sub-area. Also illustrating flat-light (no shadows).

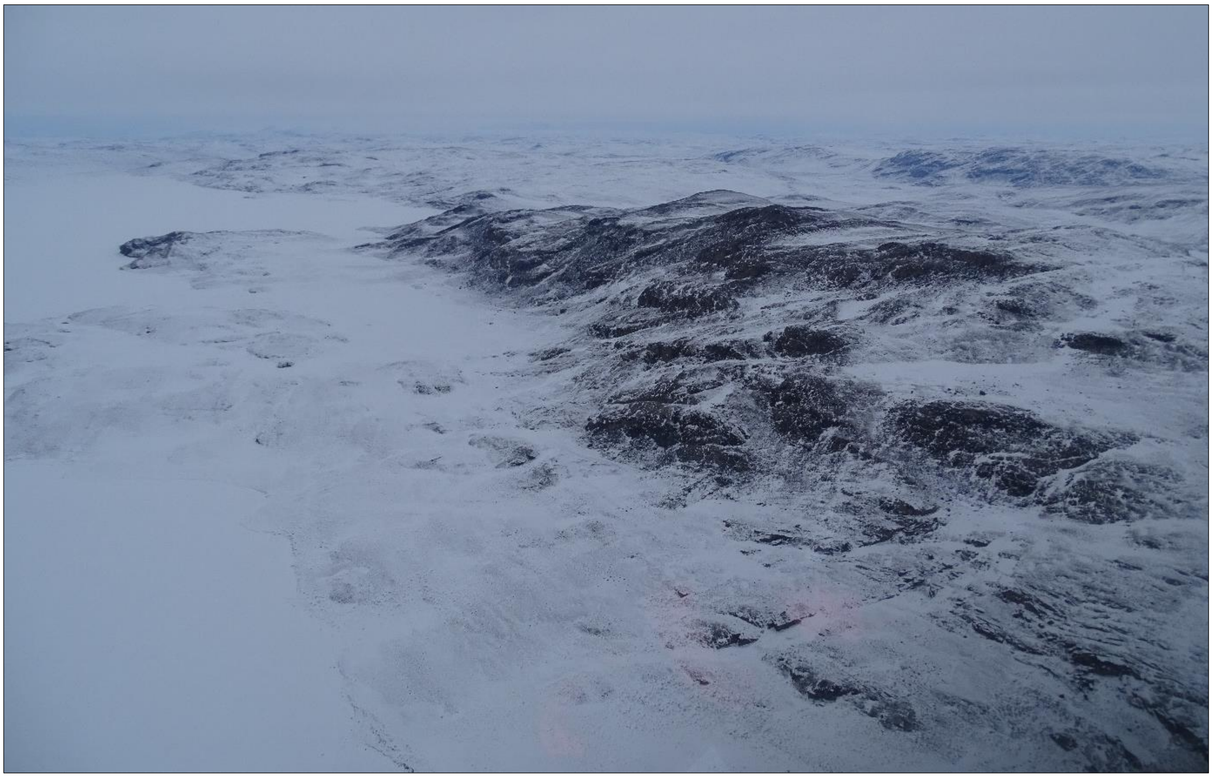

Figure 38. Overview of the north side of Tasersuaq Lake (large flat white surface on left: lake elevation 312 m), illustrating flat-light (no shadows) and sparse snow-cover common to the Angujaartorfiup sub-area.

Figure 39. Overviews illustrating flat-light (no shadows) and the windswept terrain with sparse snow-cover common to the Angujaartorfiup sub-area. Horizontal white surfaces are lake or fjord ice.

Figure 40. Minimal March snow cover typical of lowland valleys in Angujaartorfiup sub-area. View NW into the Maniitsut Atannguisa Kuussuat river valley from line transect 19. Valley bottom elevation <100 m.

Figure 41. Observation platform for aerial survey: AS350 helicopter on terminal moraine with Greenland Ice Cap in background, illustrating windswept rocky terrain with sparse snow-cover.

Appendix 8

Hunting seasons, quotas and reported harvests, primarily for the Maniitsoq muskox management area.

Table 16. Muskox hunting seasons and quotas for the Sisimiut and Maniitsoq muskox management areas in the 2015-2020 period (commercial and recreational combined) (Nuka M. Lund pers comm (Ministry for Fisheries & Hunting: APN). Trophy hunting seasons and quotas not included. Maniitsoq muskox management area corresponds to the Angujaartorfiup sub-area surveyed by helicopter in March 2018, and the Sisimiut management area corresponds to Sisimiut sub-area surveyed.

Muskox management area	Hunting area[1]	WINTER HUNT		AUTUMN HUNT	
		Season	Quota	Season	Quota
Maniitsoq					
2015	1	10 January – 10 March	Open	1 August – 15 October	Open[2]
	2	Closed	0	Closed	0
	3	10 January – 10 March	Open	1 August – 15 October	Open
2016	1	10 January – 10 March	Open	1 August – 15 October	Open
	2	Closed	0	Closed	0
	3	10 January – 10 March	Open	1 August – 15 October	Open
2017	1	10 January – 10 March	Open	1 August – 30 September	Open
	2	22 January – 31 January	400	Closed	0
	3	10 January – 10 March	800	1 August – 30 September	Open
2018	1	10 January – 15 February	Open	1 August – 15 October	Open
	2	Closed	0	Closed	0
	3	10 January – 15 February	800	1 August – 15 October	Open
2019	1	25 January – 15 February	Open	1 August – 15 October	Open
	2	Closed	0	Closed	0
	3	25 January – 15 February	Open	1 August – 15 October	Open
	4	25 January – 15 February	Open	1 August – 15 October	Open
2020	1	25 January – 14 February	100	1 August – 15 October	Open
	2	Closed	0	1 August – 15 October	Open
	3	25 January – 14 February	1200	1 August – 15 October	Open
	4	25 January – 14 February		1 August – 15 October	Open
Sisimiut					
2015	---	10 January – 10 March	520	1 August – 15 October	400
2016	---	10 January – 10 March	520	1 August – 15 October	400
2017	---	Closed	0	1 August – 15 October	400
2018	---	Closed	0	1 August – 15 October	400
2019	---	Closed	0	1 August – 15 October	400
2020	---	Closed	0	1 August – 15 October	400

[1] See Figures 40-41 for the Greenland government's muskox management hunting areas for Maniitsoq (Angujaartorfiup sub-area surveyed).

[2] Open = No limit on the number of muskoxen that may be harvested.

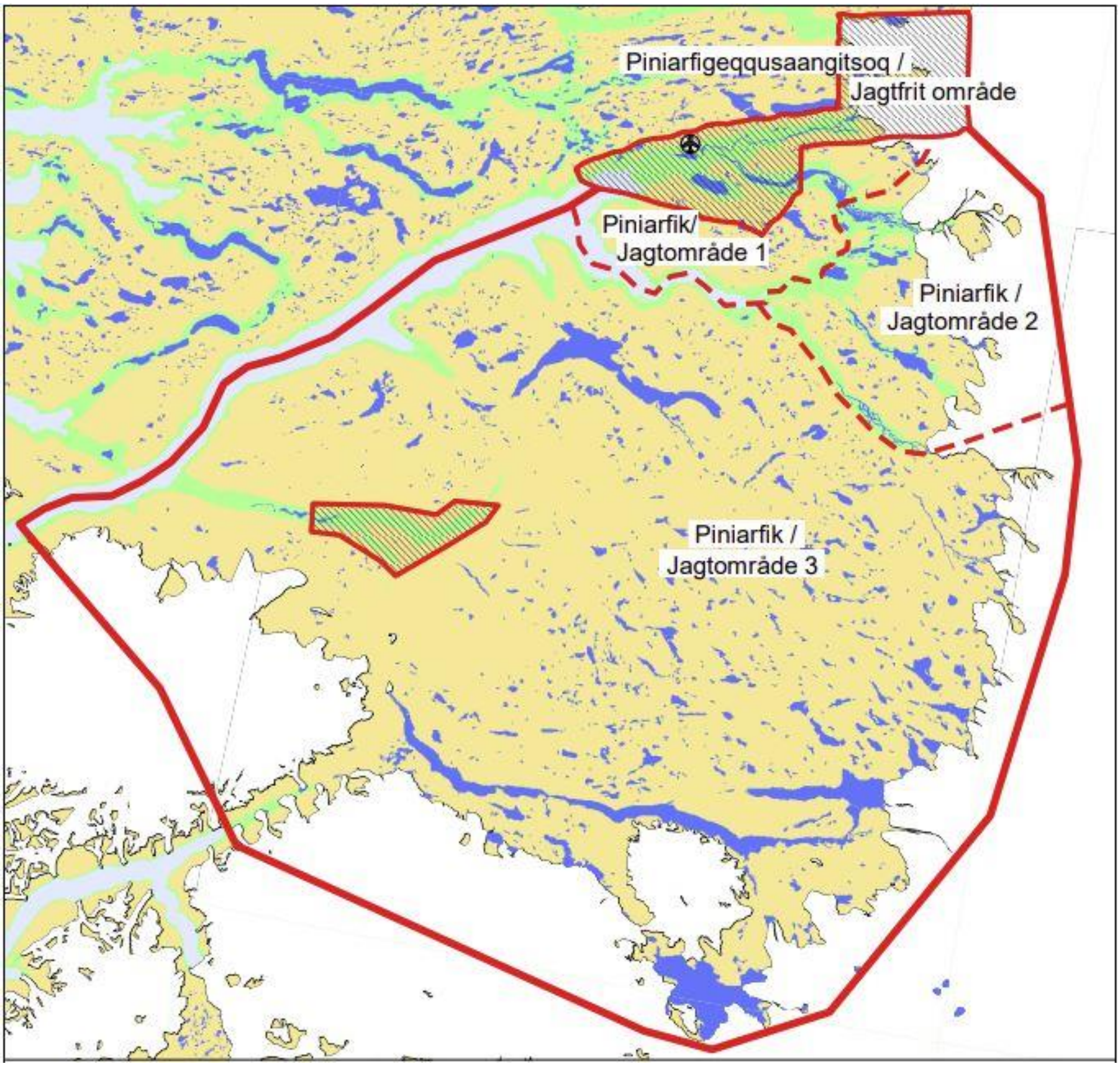

Figure 42. Map for the 2010-2019 period illustrating the Government of Greenland's Maniitsoq muskox harvest management area with specific hunting areas for regulating harvest of the Maniitsoq muskox population. Hunting areas are separated by stippled lines and labelled with "Piniarfik/Jagtområde" and a number. Areas where hunting is prohibited are marked with diagonal lines and/or the label, "Piniarfigeqqusaangitsoq/Jagtfrit område". The largest encompasses the airport town of Kangerlussuaq and near vicinity including Lake Ferguson, the beginnings of Ørkendalen and the Sandflugtdalen river valley up to and including the Inland Ice Cap. The smaller and triangular area encompasses the inner portion of the valley, Arnangernup Kuua (Paradisdalen) and its side valleys (Naalakkersuisut 2019).

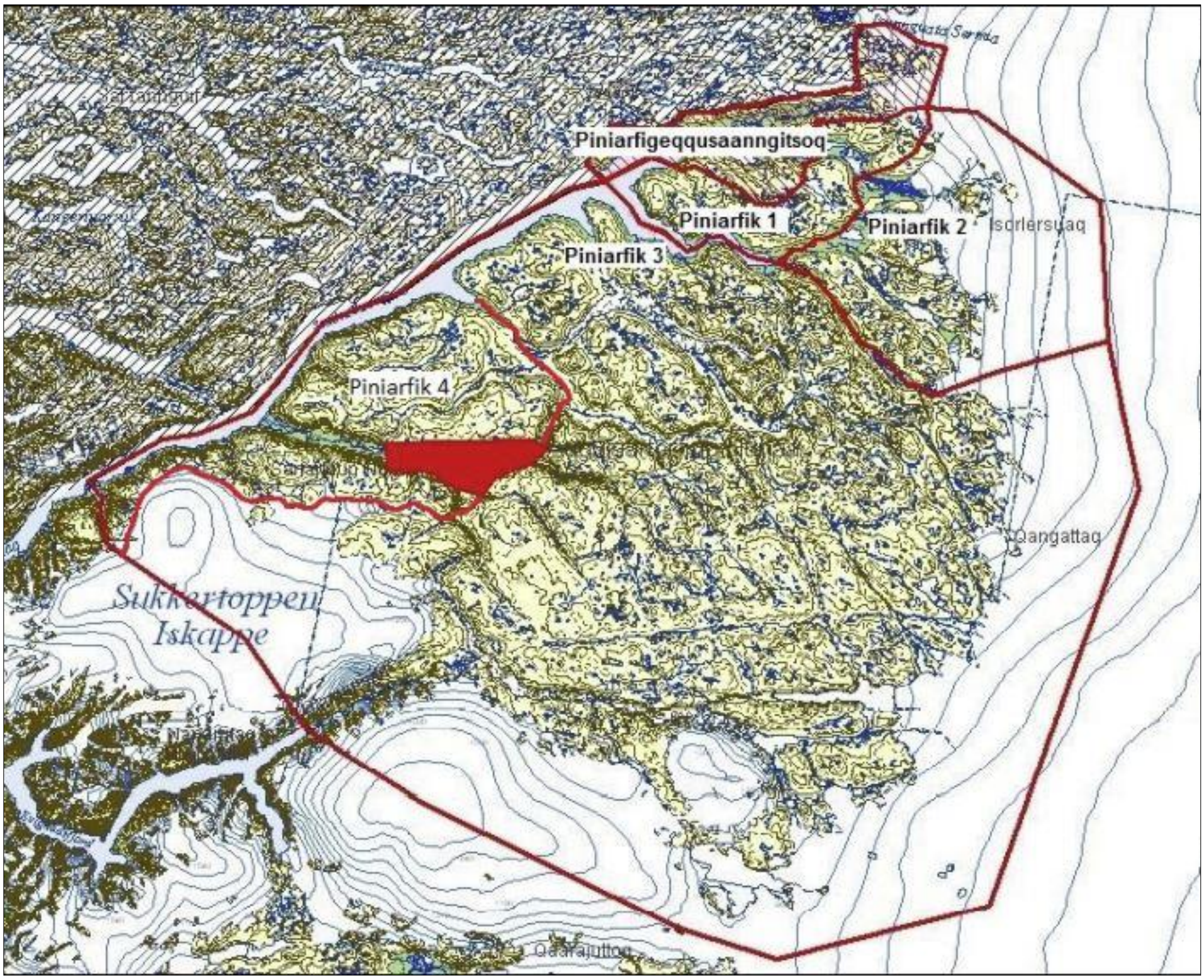

Figure 43. Map illustrating the entire Maniitsoq muskox harvest management area with the current hunting sub-areas for regulating harvest of the Maniitsoq muskox population in the Qeqqata municipality. The hunting sub-areas are defined by the Government of Greenland. Hunting areas are labelled with "Piniarfik" and a number. Hunting area 4, established in 2018, was first implemented from summer 2019 (Naalakkersuisut 2019, bilag 4). Areas where hunting is prohibited are either marked with diagonal lines and the label, "Piniarfigeqqusaangitsoq", or are a solid red colour. Since 1984, hunting has been prohibited in the inner portion of the valley, Arnangernup Kuua (Paradisdalen), which is indicated by the solid red within Piniarfik 4. (Naalakkersuisut 2020).

Table 17. Reported number of muskoxen harvested by commercial (PIN) and recreational (FRI) hunters in the Maniitsoq muskox management area since translocation of 1962/65 relative to total annual muskox harvest for all of Greenland. Trophy harvest is not included. Maniitsoq muskox management area corresponds to the Angujaartorfiup sub-area surveyed. Data is from Government of Greenland's Piniarneq records.

Year	Hunter category reported muskox harvest Maniitsoq		Max killed per harvest report[1] (category)	Reported muskox harvest Maniitsoq[2]	Reported muskox harvest all Greenland	% Greenland muskox harvest from Maniitsoq
	PIN	FRI				
1962-1987	0	0	0	0	---	---
1988	---	---	---	200	---	---
1989	---	---	---	300	---	---
1990	---	---	---	350	---	---
1991	---	---	---	400	---	---
1992	---	---	---	446	---	---
1993	501	25	20 (PIN)[?]	526	611	86.1
1994	414	80	12 (FRI)[?]	494	563	87.7
1995	417	39	11 (PIN)[?]	456	560	81.4
1996	284	52	10 (PIN)[?]	336	472	71.2
1997	346	74	10 (PIN)[?]	420	553	75.9
1998	305	108	36 (FRI)[?]	413	590	70.0
1999	680	138	30 (PIN)[?]	788	953	82.7
2000	530	186	17 (FRI)	716	833	86.0
2001	579	85	19 (PIN)	664	797	83.3
2002	1109	244	25 (PIN)	1353	1478	91.5
2003	1018	472	19 (PIN)	1490	1669	89.3
2004	1134	480	18 (PIN)	1614	1780	90.7
2005	1142	606	43 (PIN)	1748	1955	89.4
2006	1488	673	33 (PIN)	2161	2397	90.2
2007	1741	606	79 (PIN)	2347	2546	92.2
2008	1895	648	220 (PIN)	2543	2833	89.8
2009	1833	508	150 (PIN)	2341	2675	87.5
2010	1515	599	132 (PIN)	2114	2485	85.1
2011	1963	517	195 (PIN)	2480	2760	89.9
2012	1464	434	90 (PIN)	1898	2134	88.9
2013	1423	416	108 (PIN)	1839	2244	82.0
2014	1638	335	150 (PIN)	1973	2394	82.4
2015	1553	364		1917	2386	80.3
2016	1779	387		2166	2656	81.6
2017	885	330		1215	1568	77.5
2018	1148	301		1449	1772	81.8

? Hunter category may be typographical error in Piniarneq records.
¹ Maximum number reported killed per harvest report, which may represent kill by one hunter.
² Care taken to assign harvest to muskox population correctly, however, values are approximate. All harvest in the Government of Greenland's Piniarneq is based on the municipality of residence for the hunter and not the animal population the animal was removed from. Further, specifically the Maniitsoq muskox population may be harvested by hunters regardless of residence. Following ca. 2005, muskox harvest seasons were opened on new muskox populations, e.g., Naternaq and Sigguk. Thus after 2005, the number of Maniitsoq muskoxen reported killed may include a few muskoxen shot in the new muskox regions.

Appendix 9

2020 Supplementary materials to the biological advice for caribou and muskoxen harvest in 2020 are from Cuyler (2020).

Only those portions of the 2020 supplementary materials pertaining to muskoxen in the North region are included in this appendix. For complete materials see Cuyler (2020).

Supplementary materials to the biological advice for caribou and muskoxen harvest in 2020

Christine Cuyler

14 May 2020

Left: Muskox bull, Cape Atholl region – photo by C. Cuyler
Right: Caribou cows with neonate calves, Central region (Akia-Maniitsoq caribou) – photo by C. Cuyler

Contents supplementary materials

General for caribou & muskoxen

A not overly biased sex ratio in caribou and muskox populations benefits genetic diversity / robustness, and thus armours future generations with resilience to meet challenges including impacts of climate change. Meanwhile, protecting cows with calves is expected to benefit to calf survival.

Significance of unstable / extreme weather on caribou & muskox abundance

Undoubtedly, there is always uncertainty in the natural fluctuations of animal populations (Clutton-Brock et al. 1997; Clutton-Brock and Coulson 2002; Gaillard et al. 1998) and causes typically remain poorly understood (Krebs 2002). Nevertheless, the climate is changing globally, and changes are particularly evident in the Arctic (Cuyler et al. 2020). One of the consequences of these changes is increasingly unstable weather, which also applies to Greenland (Cuyler 2019a). It is therefore expected that there will be more periods of so-called extreme weather in the future. Such events are unpredictable. Consequences, including increased mortality among herbivores, will depend on the severity, frequency, and extent of the event (Cuyler et al. 2020). Negative influences on caribou and muskox abundance in Greenland could be spread across several years or occur abruptly within a single season (Cuyler et al. 2016. Cuyler 2019b). Extreme weather events could make harvest yields uncertain and require mitigating management measures.

In the summer, extreme or unstable weather can include periods of drought, prolonged high air temperatures or alternately freezing temperatures and snow. Prolonged droughts can kill summer plant growth, which herbivores rely on to replenish body reserves lost in the previous winter and to build up reserves for the coming winter. Furthermore, desiccated / dead vegetation cannot provide the necessary quality and quantity of forage for herbivores in the coming winter. Air temperatures below the freezing point that bring persistent snow cover in summer can have some similar effects. High temperatures in the absence of wind increases insect harassment on caribou and muskoxen and may also lead to hyperthermia and possible death owing to pre-existing conditions (Ytrehus et al. 2008).

In winter, extreme, or unstable weather can result in multiple periods with temperatures above freezing and possibly rain. When the temperature subsequently falls below 0°C, icing can form preventing access to the forage vegetation herbivores depend upon. Thick icing can completely block access to vegetation. Unstable or more extreme weather can also cause excessively deep snow and delayed, sometimes very late, snow melt in spring. High winds accompanied by freezing rain-sleet at spring calving may occur. Common to the expected increasingly unstable weather is the risk of pronounced negative effects (e.g., reduced calf production, greater natural mortality) for caribou and muskoxen.

Winter and spring (ca. 01 January until final spring melt) are decisive for caribou / muskoxen survival, primarily because usually forage quality, quantity and availability are low. These can also have negative effects on cow body condition and reproduction. Winter survival strategies include choosing optimal winter habitat, minimizing daily activity/movements, and employing rumination periods long enough to break down typically poor-quality winter forage, thus permitting absorption of nutrients. At any time of year, disturbance of caribou / muskoxen can result in more energy used (flight responses causing greater daily movements), less time available for energy intake (grazing) and ultimately less nutrient absorption (rumination / digestion). Specifically, winter hunting creates disturbance that produces these negative effects at a time when the opposite is essential for survival. If a large area of winter habitat and high number of individuals are affected, it can weaken a population's general health. Winter hunting using motor vehicles may exacerbate the above. Furthermore, it may cause animals to avoid otherwise preferred essential winter habitat and to seek refuge in poorer quality habitat less suitable for survival, e.g., because animal densities may be too high relative to the forage quality, quantity, and availability. Cow body condition may decrease, which would negatively affect calf survival and calf production the following spring. Furthermore, high animal density can increase exposure of individuals to infectious pathogens (diseases, parasites). In winters with repeated periods of unstable or extreme weather, winter hunting clearly adds further negative effects to already beleaguered caribou and muskoxen populations. A typical mitigating management measure is the cessation of winter harvesting.

All the above are important because the probability of successful breeding increases with the body mass of cows (Rowell et al. 1997; White et al. 1997). Everything that makes vegetation / forage inaccessible, ultimately reduces cow body reserves and thus calf production. This is specifically true for muskox cows, which require 22% body fat to have a 50% probability of pregnancy (Adamczewski et al. 1998). In contrast, only ca. 7% body fat is needed for reindeer cows (Crête et al. 1993; Pachkowski et al. 2013). Stock density, lactational status and quality / quantity / availability of forage also affect the likelihood of pregnancy (Pachkowski et al. 2013). Poor cow body condition can result in non-annual breeding (White et al. 1997), and muskox cows often calve at intervals of 2-3 years, probably because they did not regain enough body reserves during a single summer season after pregnancy and milk production (Reynolds 2001).

General Caribou – (see Cuyler 2020)

General Muskoxen

Native muskoxen occur only in North and Northeast Greenland. Muskox harvest is prohibited in Washington Land and the National Park, although hunters travelling through those regions by dog team are permitted to take a few for feeding the sled dogs. Meanwhile, annual quoted harvests in East Greenland are permitted in Jameson Land and Inner Kangertittivaq Fjord (Figure 3).

There are several well-established translocated muskox stocks in western Greenland, and only one, Inglefield Land, is a mixture of introduced and native muskoxen (Figure 3). Expansion since introductions has formed two additional stocks of muskoxen, which are Sisimiut and Nuuk. Nuuk muskoxen are presumed a tiny stock and hunting remains prohibited.

Nanortalik (South Greenland) received 19 translocated muskoxen six years ago, in 2014, and therefore is still in its establishment phase and hunting remains prohibited.

Muskox calves are usually born mid-April through June, with birthing dates as early as 05 April and as late as 19 June (Lent 1988) and unlike caribou there is no breeding synchrony (Lent 1966).
Regarding optimal muskoxen habitat, generally this is below 200 m elevation, while elevations below 100 m support the highest densities of muskoxen (Thomas et al. 1981). In the 1980's -90's Greenland's Maniitsoq muskoxen remained in areas below 400 m elevation throughout the year where their densities were unchanged (Olesen 1993).
The Greenland Department of Fisheries, Hunting and Agriculture (APNN) manages harvest seasons and quotas for 9 muskox regions / populations, while the total number of stocks is 13 (Table 2). Greater detail is provided for the Maniitsoq, Cape Atholl and Nuuk muskox populations.

Table 2. APNN's muskox management areas, north to south, with population names and where relevant hunt-area numbers. Government regulated harvest most populations.

APNN management area	Population name	Hunt-area no.	2019 Harvest
Western Greenland			
Qaanaaq	Inglefield- & Prudhoe Land	-	Yes
	Cape Atholl	-	Yes
Uummannaq/Upernavik	Sigguk/Svartenhuk	-	Yes
Diverse[1]	Naternaq/Lersletten	-	Yes
Sisimiut/Kangaatsiaq	Sisimiut	-	Yes
All Greenland communities	Maniitsoq	1, 3, 4	Yes
		2	No
-	Nuuk	-	No
Ivittuut	Ivittuut	-	Yes
Nanortalik	Nanortalik	-	No
North and Northeast Greenland			
Washington Land	Washington Land	-	No
National Park	National Park	-	No
Ittoqqortoormiit	Jameson Land & Liverpool Land	-	Yes
	Inner Kangertittivaq / Scoresbysund Fjord	-	Yes

[1]Diverse includes the following communities: Aasiaat, Qasigiannguit, Kangaatsiaq, Ilulissat and Qeqetarsuaq.

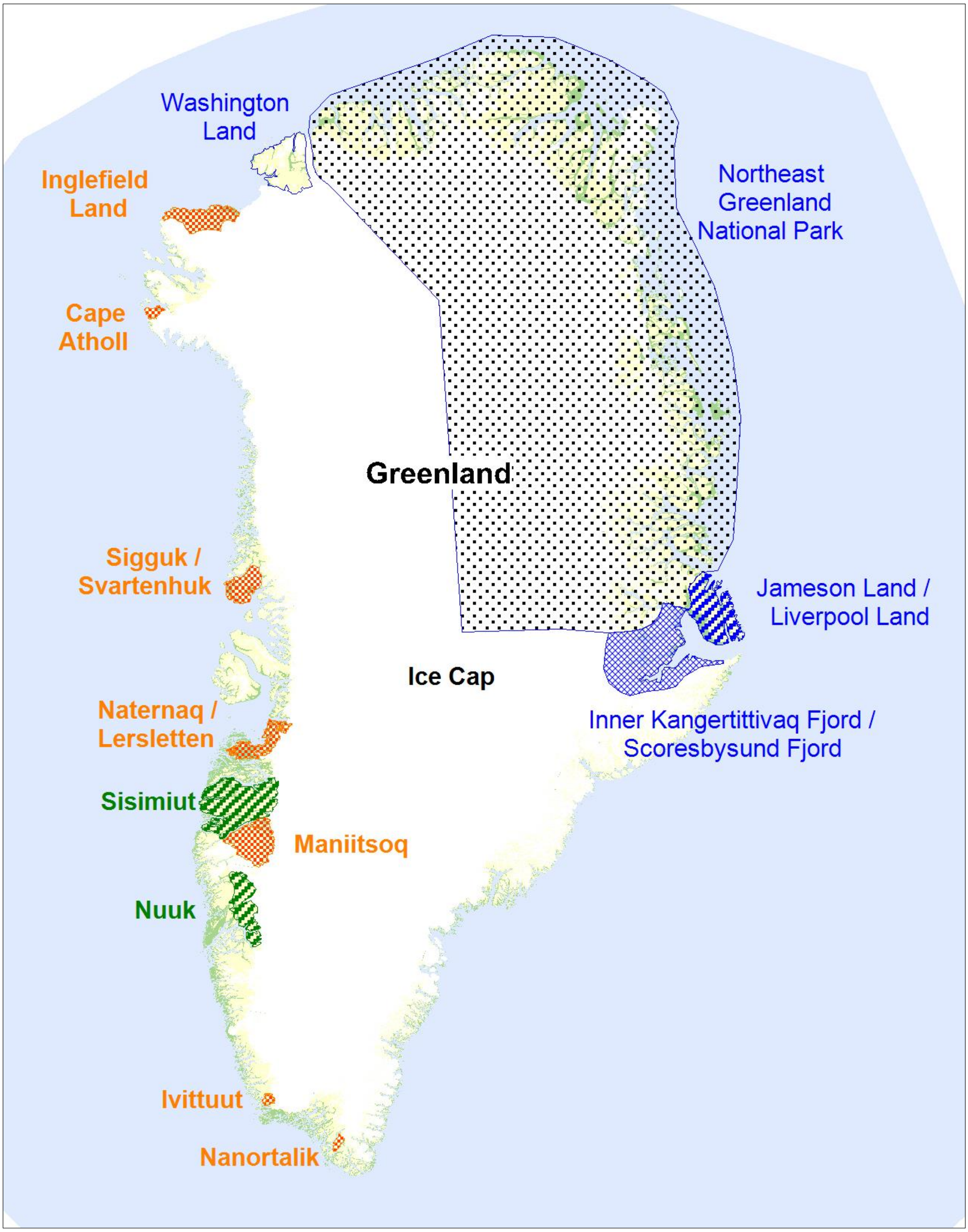

Figure 3. Muskox populations in Greenland. Native populations (blue) are in North and Northeast Greenland. Inglefield Land muskoxen are a mix of native and translocated stock. In western Greenland, specifically from Cape Atholl to Nanortalik, all populations are either translocated (orange) or the result of expansion (green) from a neighbouring translocation. Population borders are approximations and size does not reflect animal abundance, e.g., Greenland's largest muskox population, Maniitsoq, inhabits a relatively small area. Boundary of the National Park in northeast Greenland is indicated. Currently, regulated harvest is permitted on most populations, however hunting is prohibited in Washington Land, National Park, Nanortalik and Nuuk.

Maniitsoq muskox population

In 1963 and 1965, 27 juvenile muskoxen were translocated from East Greenland to the area south of the Kangerlussuaq (Søndre Strømfjord) International airport in West Greenland. Previously, this population was commonly called the Kangerlussuaq muskoxen (Cuyler & Witting 2004), but hereafter will be referred to as the Maniitsoq muskoxen as per APNN (2019a). All hunting was prohibited for 25 years, first harvest was 1988, and by 1990 the muskox population was considered well established (Olesen 1993).

Already in the 1980's, the muskoxen clearly selected lowland elevations under 400 m. At that time, this included the lowlands surrounding the Kangerlussuaq (Søndre Strømfjord) international airport and several large valleys, i.e., Ørkendalen (Bioshytte), Ammalortoq Lake, and Paradisedalen (*Arnangarnup Qoorua*) (Olesen 1993). The total area available to Maniitsoq muskoxen is 7,853 km^2, (corrected area from this study is 7133 km^2), however only ca. 950 km^2 is habitat under 400 m elevation (Olesen 1993). Calf production indicated that lowland habitat within the 7,853 km^2 region was well suited to muskoxen. Although neither is normal for muskox populations elsewhere, in the 1970-80's, calves accounted for 24-28% of the Maniitsoq muskox population, while many cows produced a calf every year (Roby 1978, Thing et al. 1984, 1987, Olesen 1993).

To manage the Maniitsoq muskox harvest, APNN subdivided the region into four hunting management areas. Initially (2010) there were three hunting management areas (Piniarfik 1, 2, 3) but a fourth was added in winter 2018 and first implemented in summer 2019 (Figure 4).

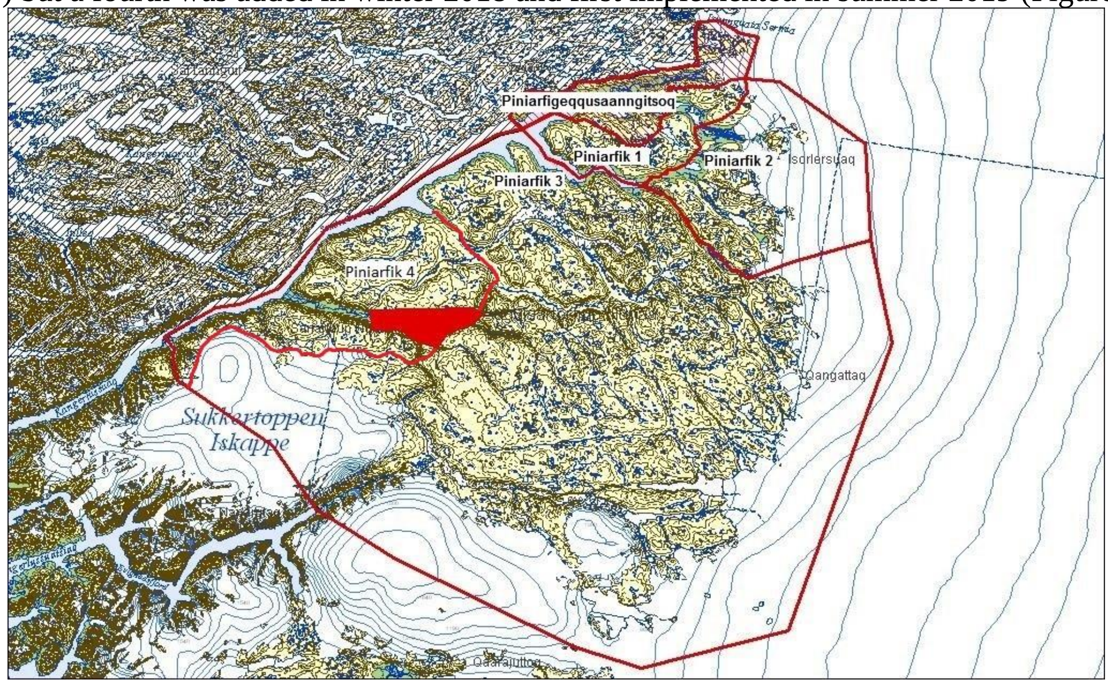

Figure 4. APNN's four hunting areas (Piniarfik 1, 2, 3, 4) for harvest management of the Maniitsoq muskox population in Qeqqata municipality (APNN 2019b). Top right and indicated by red diagonal lines is the hunting-prohibited area (Piniarfigeqqusaanngitsoq) that surrounds the Kangerlussuaq (Søndre Strømfjord) international airport and includes Sandflugtdalen Valley and Isunngua areas. Hunting has always been prohibited in the inner Paradise Valley, indicated by solid red.

Current population trend, Maniitsoq muskoxen

A 2018 helicopter survey provided a population size estimate of ca. 20,334 muskoxen (95% CI 9,386 – 44,055; SE 6397; CV 0.31) for the Maniitsoq muskox population (Marques 2018). This number cannot be compared with previous ground-based minimum counts, because it is the first and only estimation of total abundance of muskoxen in the entire area south of the Kangerlussuaq international airport. The high 2018 estimate provides evidence of the explosive increasing trend for abundance that occurred since 27 individuals were translocated to the area in the 1960's. The steep growth curve in the 1980's and '90's (Figure 5) supports this. Regardless, alone the 2018 estimate cannot indicate current population trend. Instead, past, recent, and current trends are indicated by the minimum count and calf percentage data gathered over a 40-year period (Figures 5, 6). These suggest the current trend is steady decline in abundance since 2010. The most recent minimum count, in 2020, also supports that population size and production have decreased. The abundance in the 2000-2010 period might have been greater than the 2018 aerial survey estimate of ca. 20,334 muskoxen. Below follows a brief discussion of the minimum counts, calf production, 2018 aerial survey, muskox density, and disturbance.

Minimum counts 1963 – 2020, Maniitsoq muskoxen

Since the initial release of 27 muskoxen in 1963-65, ground-based minimum counts from the 1980's to 2020 provide indices of abundance. Although not population size estimates, they illustrate general population trends (Figure 5). Minimum counts in this area are usually done by two observers travelling by skidoo in the January-April period and using binoculars and telescopes recording all muskoxen seen. The 2018 minimum count was the actual number of muskoxen seen during a helicopter survey for caribou. Certainly, the inconsistent timing, effort and coverage of the diverse minimum counts makes comparisons across time less reliable. For example, the 1977-1995 minimum counts were carried out before the hunting season and covered hunting areas 1 and 2 (see Figure 4). Minimum counts in 2000-2010 occurred also prior to winter harvesting, but typically covered most of hunting areas 1, 2, 4 and northern portion of area 3. In 2010, lack of snow and sea ice limited the minimum count to hunting areas 1 and 2 and a small portion of 3, while 4 was impossible to cover. Meanwhile, winter harvest influenced minimum count results post-2014 because counts were during or after the winter hunting season. During these counts, animals had probably moved to less accessible terrain, which prevented their detection. Furthermore, 2014-2020 area coverage was highly variable and often much reduced. The exception being the 2018 minimum count from helicopter, which had the greatest effort and coverage of any count to date. Owing to different timing and effort, muskox abundance trends should be considered with caution. Nevertheless, general trends are apparent.

The index of muskox abundance illustrates a general rapid expansion in the 1980's and early 1990's, a possible peak from the mid 1990's until 2010, and a decline thereafter (Figure 5). Neither the magnitude nor slope of the decline are likely as steep as they appear, since minimum counts after 2014 occurred after hunting had altered the distribution and detectability of the animals. Regardless, the suggested declining trend in population size since 2010 is supported by simultaneous declining number of muskox groups observed, maximum group size, as well as a ca. 37% reduction in calf recruitment (Appendix 2). Furthermore, minimum count data from hunting area 2 (Appendix 3), which received consistent effort and coverage on all ground-based counts, although timing varied, similarly supports an abundance decline in the Maniitsoq population since 2010.

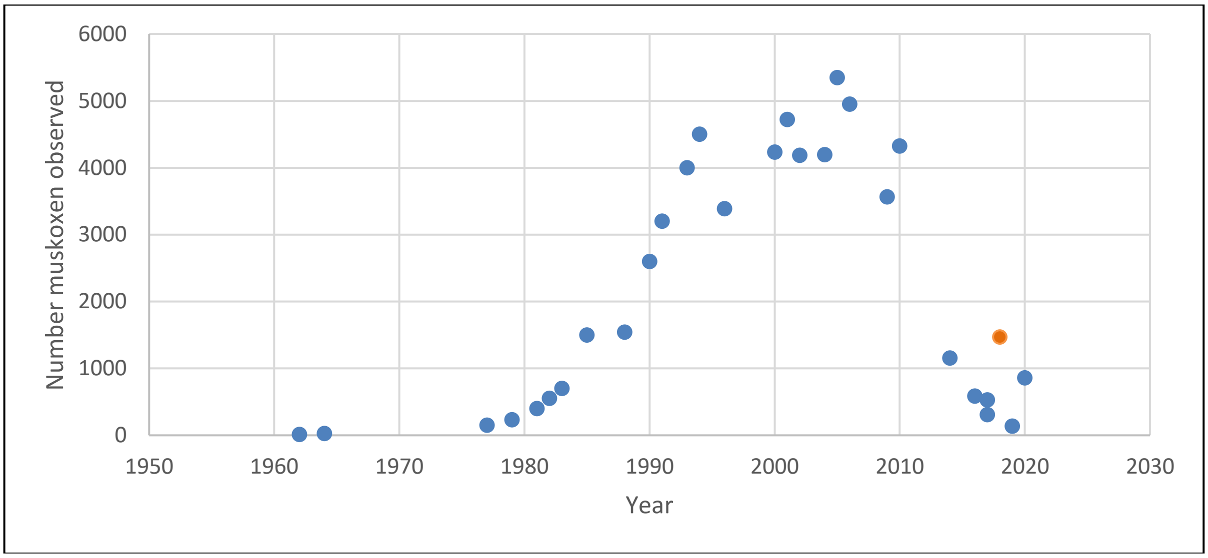

Figure 5. Index of Maniitsoq muskox abundance since translocation to the region in 1963-65. Data are minimum counts of only those individuals observed and cannot be interpreted as estimates of population size. All but 2018 are ground counts. All are of varying timing, effort, and area coverage. Beginning 2000, all are pre-calving counts from either winter or late winter. Those from 2000 to 2010 were pre-harvest, while those 2014-2020 were post-harvest. In the latter muskoxen are avoiding lowlands owing to recent hunting. The actual number of individual muskoxen observed during the March 2018 helicopter survey (●) has been included as a type of minimum count, which effort and coverage were the most comprehensive relative to any other minimum count. (Data from Roby 1978, Thing et al. 1984, Olesen 1993 and Cuyler unpublished).

Calf production 1977-2020, Maniitsoq muskoxen

Until at least 1981 calf percentage for Maniitsoq muskoxen was excellent (Figure 6) resulting in the highest recorded population growth rate, 35%, for any muskox population globally (Thing 1984, Olesen 1993). Population growth for Maniitsoq muskoxen was above the 17-24% reported for a similarly translocated population in Alaska (Jingfors & Klein 1982) and the 21% from Queen Maud Gulf, Canada (Gunn et al. 1984). Maniitsoq's population increment, ca. 30%, continued almost unabated until 1990 (Olesen 1993), and even into 2000-2001 (Cuyler et al. 2001). Beginning in 2002 however, calf percentages declined and have not recovered to pre-2000 values (Figure 6). Calf percentage seemingly improved since the 2010 minimum count, however, the 2014-2020 period involved only post-harvest counts. Resulting calf percentages may just be an artifact of hunters shooting all except calves, thereby reducing the total number while calf number remained the same, which artificially raised calf percentage in the counts. Specifically, the 2014 value is likely unreliable and artificially high because the count was post-harvest, no-hunting zones did not yet exist and the small size of surveyed area, which was easily accessible to hunters. In the 2016-2020 period, a no-hunting zone was established, and minimum count effort was concentrated there. Thus, the ca. 15% calves for this period provides the best current expected calf percentage, which is ca. 40% below the pre-2000 values and supported by the ca. 37% known decline in calf recruitment (calves per 100 cows; Appendix 2).

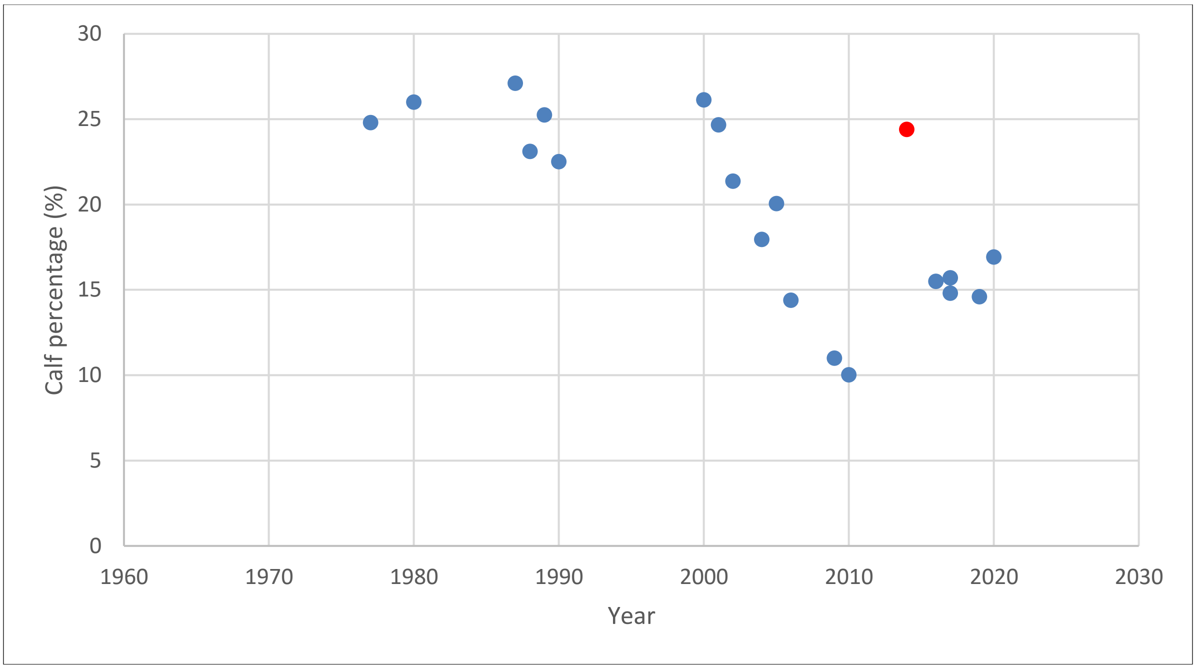

Figure 6. Calf percentages in the Maniitsoq muskox population from 1977 to 2020. All results are from ground counts. Beginning 2000, all results are from winter (pre-calving) counts, 2000-2010 pre-harvest and 2014-2020 post-harvest. The April 2014 outlier value (•) is likely unrealistic and artificially elevated, primarily owing to the timing of the count, which was post-harvest, and count effort involved a limited area easily accessible to hunters. Thus, while total muskox number was reduced calf number remained the same (not shot), which artificially raised calf percentage. (Data from Roby 1978, Thing et al. 1984, Olesen 1993 and Cuyler unpublished).

The 1980's and 1990's were associated with rapid population growth, when the percentage of calves was usually ca. 25% (Figure 6) of the total number of muskoxen observed. In 1990, near Kangerlussuaq (Søndre Strømfjord) international airport, Ørkendalen Valley (Bioshytte/Bios cabin) and Ammalortoq Lake, density was almost 2 muskoxen/km^2 at elevations under 400 m, however, density was greater in the most commonly used valley areas, and yet there were no observations of density-dependent mortality i.e. no increased calf mortality had been observed even in the areas of highest densities (Olesen 1993). This suggests that for Maniitsoq muskoxen, a density of ca. 2 muskoxen/km^2 in lowland habitat was no impediment to calf production. By winter 2001, density grew to at least 4-5 muskoxen/km^2 in the same area (Cuyler et al. 2001). Again, because winter grazing was often concentrated, some valley locations had much higher densities, e.g., ca. 29 muskoxen/km^2

near Bios cabin Ørkendalen (589 muskoxen in 20.25 km^2) and ca. 22 muskoxen/km^2 around Ammalortoq Lake (876 muskoxen in 40.5 km^2) (Cuyler et al. 2001). Even at those densities, calf percentage was ca. 25% and annual population growth ca. 30% (Cuyler et al. 2001), which indicates that the carrying capacity of that lowland habitat was excellent. However, something changed in the period 2001-2004, because calf percentage decreased each year and this trend continued until 2010 (Figure 6).

Typical causes for poor calf production include predation, disease, adverse weather, and maternal body condition. Elsewhere, large predators (Reynolds et al. 2002, Marquard-Petersen 1998) and fatal disease outbreaks (Ytrehus et al. 2008) can negatively affect calf percentages. However, for Maniitsoq muskoxen, large predators are absent and fatal disease has not been observed. This leaves poor cow body condition and adverse weather as primary factors. Given the relative stability of the xeric continental climate of the region, weather conditions or events are not expected to explain the observed continuous decline in calf production in the 2000-2010 period, or the relatively stable but low values thereafter. This makes cow body condition the likely primary factor. Causes of poor cow body condition would include muskox densities too high for the forage quantity, quality, and availability in the region, and excessive disturbance preventing cows from regaining body reserves in summer or maintaining those reserves through winter.

Simultaneously with the declining trend for calf percentages, in the period 2001-2004 there occurred a significant (p<0.05) reduction in cow rump fat depth, and pregnancy rates (cows bearing a foetus) fell from 74.6% to 61.5% (Cuyler & Witting 2004). Poor cow body condition (fat reserves) suggests the possibility of density-dependent effects and/or excessive disturbance. Regarding the former, the high densities observed in 2000 and 2001 did not appear to change calf percentage. Regarding disturbance, at least for the 2001-2004 period we know harvests doubled (Cuyler & Witting 2004). It may only have been coincidence that calf % dropped just as harvesting increased, specifically winter harvesting. On the other hand, the increased disturbance occasioned by winter hunting activities may have negatively influenced cow body condition and ultimately calf production.

Winter hunting began in 1994 and initially harvest disturbance was minimal. For example, the first six years winter quotas were small, averaging 227 muskoxen, or about half the annual quota. The harvests involved a small number of commercial hunters from only the towns of Sisimiut and Maniitsoq, hunting was only in what are now referred to as hunting areas 1 and 2, and Sisimiut hunters used almost exclusively dog sleds for transport. Maniitsoq hunters had a government granted dispensation to use skidoos. In the period 2000-2010 several things occurred. The Maniitsoq winter harvest quotas began at 500 muskoxen and rose quickly thereafter. The harvest continued to involve a growing but still limited number of commercial hunters, still mostly from Sisimiut and Maniitsoq. Many Sisimiut hunters replaced dog-teams with motorized vehicles. Sport hunters were admitted. Finally, by the end of the period a third hunting area was added, which meant winter hunting now occurred over the entire region, excepting Paradise Valley and the near airport area. In sharp contrast to the early days, since ca. 2010 and continuing today, winter harvest involves large numbers of commercial and sport hunters, using many and diverse motorized vehicles, which penetrate deeply into the region and specifically all lowlands. Meanwhile, trophy harvesting has always been permitted into April, ending just as muskox calving begins. In the beginning the trophy harvest involved few agents and hunters. Like the regular harvesting, however, today the trophy harvest industry is greatly expanded involving multiple actors and concession districts covering much of the region.

Muskox calving normally begins in mid-April and lasts to past mid-June (Lent 1988). Disturbing parturient cows in late gestation is not expected to be compatible with good calf production. The current January-February harvest likely disturbs normal winter distribution, as well as foraging and rumination time for muskoxen. Likely this also applies to the March-April trophy harvest. Each winter since 2000, hunting appears to cause Maniitsoq muskoxen to avoid lowlands and seek vehicle-inaccessible terrain at relatively high elevations (Cuyler unpublished). Avoiding areas accessible to hunters was apparent during the March 2018 aerial survey (Figure 7). Although 2 weeks after the end of the regular 2018 winter hunting season, most muskoxen had not returned to lowlands, and the hunting of trophy bulls was still on-going at the time. Avoiding essential lowland habitat in winter likely has a negative effect on the winter body condition of pregnant cows. Thus, winter harvest may have influenced the steep decline in calf percentage in the 2000-2010 period (Figure 6).

Finally, the 2020 minimum count involved only hunting areas 1 and 2, which contain the 950 km^2 under 400 m elevation described in Olesen (1993). The 2020 post-harvest count yielded 16.9% calves, and a density of 0.9 muskoxen/km^2 in Olesen's lowlands (Cuyler & Mølgaard unpublished). Both are well below the 2000 values: 26% and 4-5 muskoxen/km^2 respectively (Cuyler et al. 2001).

Although elsewhere in the Arctic muskox densities are typically lower, for Maniitsoq muskoxen the relatively high 2000-2001 densities of 4-5 muskoxen/km^2 in lowland habitat (under 400 m elevation) did not appear to influence calf percentage, which remained high. This suggests that today's 2020 post-harvest density of 0.9 muskoxen/km^2 is unlikely to be a limiting factor to population growth, prerequisite on that cows can utilize lowland habitat as they did prior to and including 2000-2001. Instead, harvest may be the primary limiting factor, specifically its associated disturbance, which causes muskoxen to avoid lowland habitat, although total catch is likely also important.

Improving cow body condition would promote calf production. Strategies would include reducing the duration of human disturbance. Shorter hunting season(s) could increase undisturbed foraging in optimal habitat. A shorter summer hunting season, e.g., beginning after mid-August, would likely facilitate rebuilding cow body condition lost during the winter and due to calving and lactation, resulting in more cows achieving the prerequisite 22% fat for ovulation during the rut. Regarding the winter harvest, a shorter winter season ending well before parturition would likely facilitate successful gestation and birthing. Furthermore, the magnitude of disturbance associated with an otherwise shorter seasons might be minimized if fewer persons and motorized vehicles were involved than is currently normal.

2018 survey Maniitsoq muskoxen

March 2018 was the first ever systematic transect distance sampling aerial survey for Maniitsoq muskox abundance and distribution in the region south of the Kangerlussuaq international airport in West Greenland. The 2018 population size estimate for Maniitsoq muskoxen was ca. 20,334 muskoxen (95% CI: 9,386 – 44,055; SE = 6,397; CV = 0.31). The large Coefficient of Variance (CV) reflects poor accuracy on the population estimate. This estimate cannot provide population trend, because it was the first using this method, and there are no other estimates for comparison.

The March 2018 aerial survey occurred two weeks post-harvest (albeit trophy harvest continued) and muskoxen were still avoiding lowlands and other areas easily accessible to hunters. This is likely the primary factor causing the nonuniform distribution observed across the region (Figure 7). Few muskoxen (n=8, 0.5%) were observed in the southernmost portion of the region near the Sukkertoppen Ice Cap, likely because that area is characterized by barren high elevations of around 1000 m or more. Despite the large area of lowlands in the north only a few muskoxen (n=81, 5.5%) utilized that area. This is remarkable, given that lowlands are the preferred habitat for muskoxen. This area is, however, within easy reach for hunters coming from the Kangerlussuaq international airport town. Many muskoxen (n=200, 13.6%) were in an area halfway between the airport and the Sukkertoppen Ice Cap. Meanwhile, the majority concentrated in two subareas on either side of the region. Most (n=632, 43.1%) were in the east near the Greenland Ice Cap and the rest (n= 546, 37.2%) were in the west. This was not surprising because in the winter 2018, muskox hunting was prohibited in hunting areas 2 and 4, while motor vehicles were prohibited in hunting area 1. These restrictions coincide with the two greatest concentrations of muskoxen post-harvest. Regardless of where they were observed, few muskoxen were utilizing lowlands.

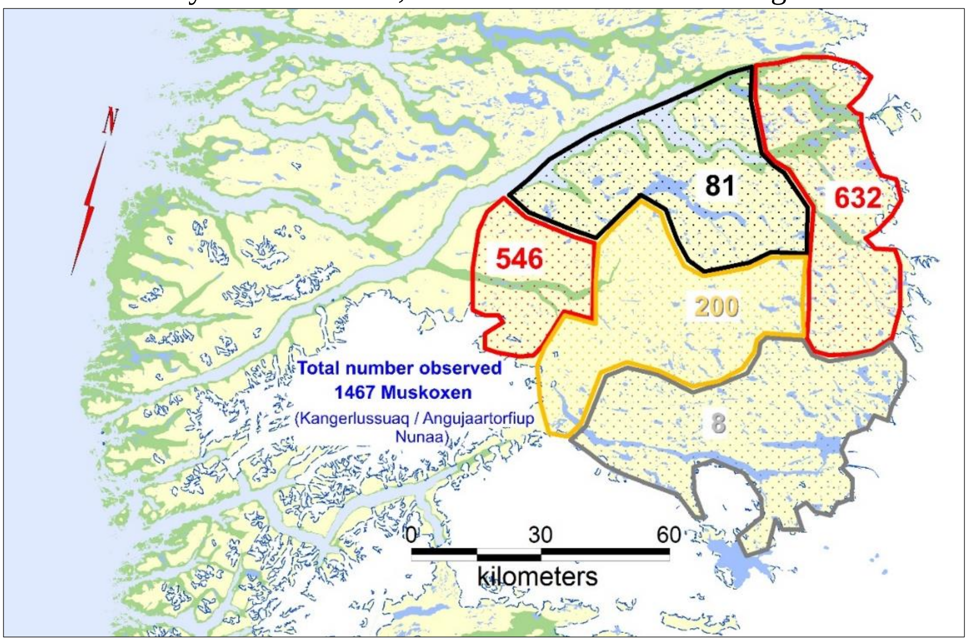

Figure 7. March 2018 distribution of the 1,467 muskoxen observed two weeks post-harvest (albeit still trophy-bull season) during the aerial survey of the Maniitsoq muskox population. Boundaries are approximate. (Cuyler unpublished).

Supplementary Materials Cuyler (2020: Appendix 2)

Maniitsoq muskox population

Population trends, 2000 – 2020

Data from ground-based minimum counts, using skidoo and ATV. Data from 2000-2010 period is pre-harvest, while that from 2014-2020 is post-harvest.

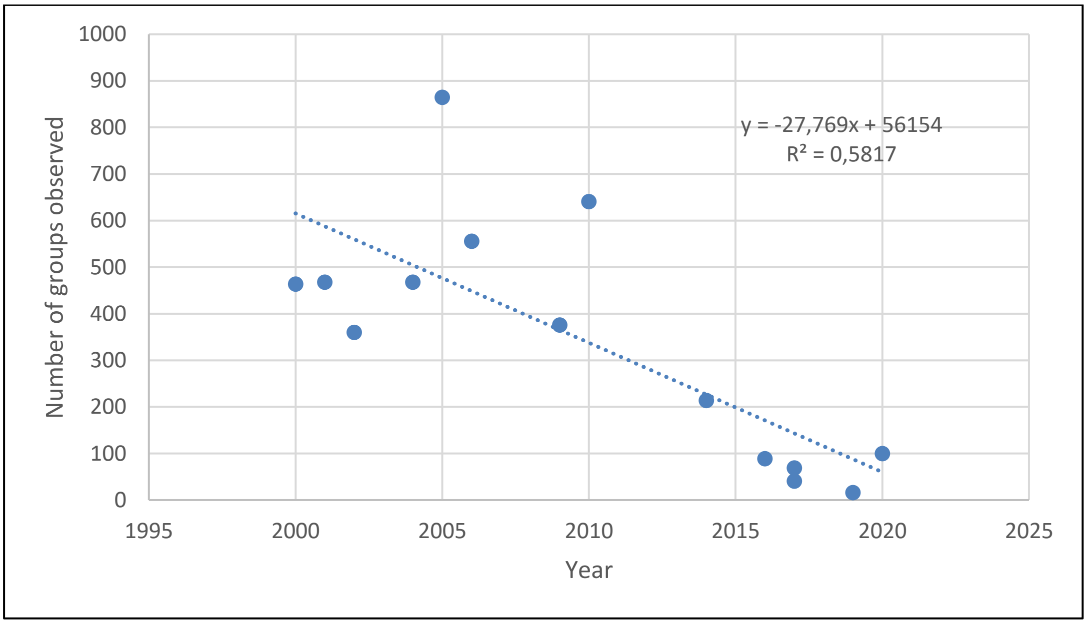

Figure 9. Number of groups of Maniitsoq muskoxen observed during minimum counts in the period 2000-2020.

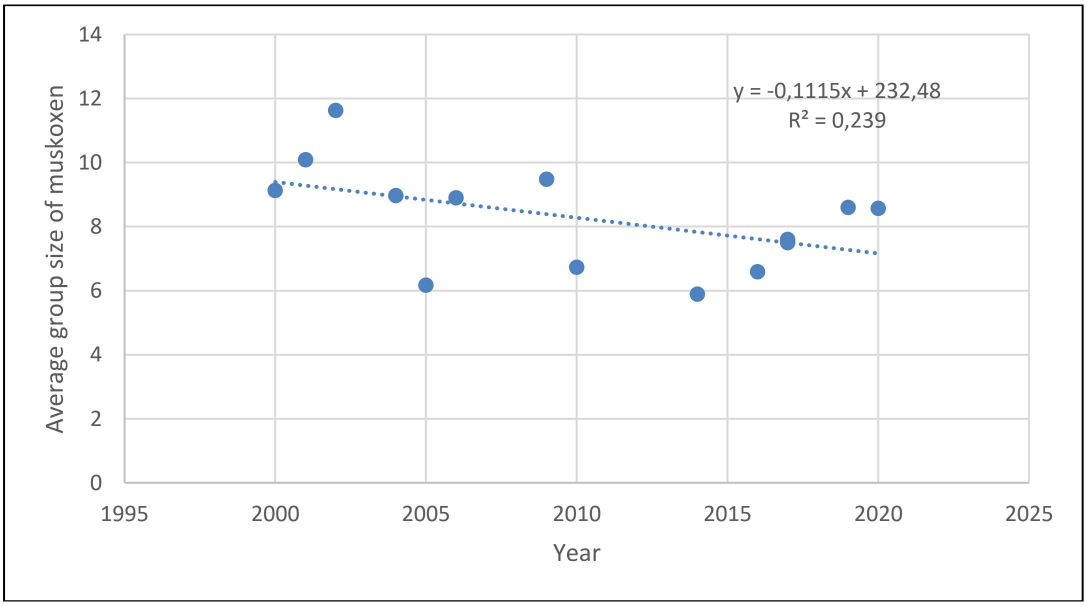

Figure 10. Number of groups of Maniitsoq muskoxen observed during minimum counts in the period 2000-2020.

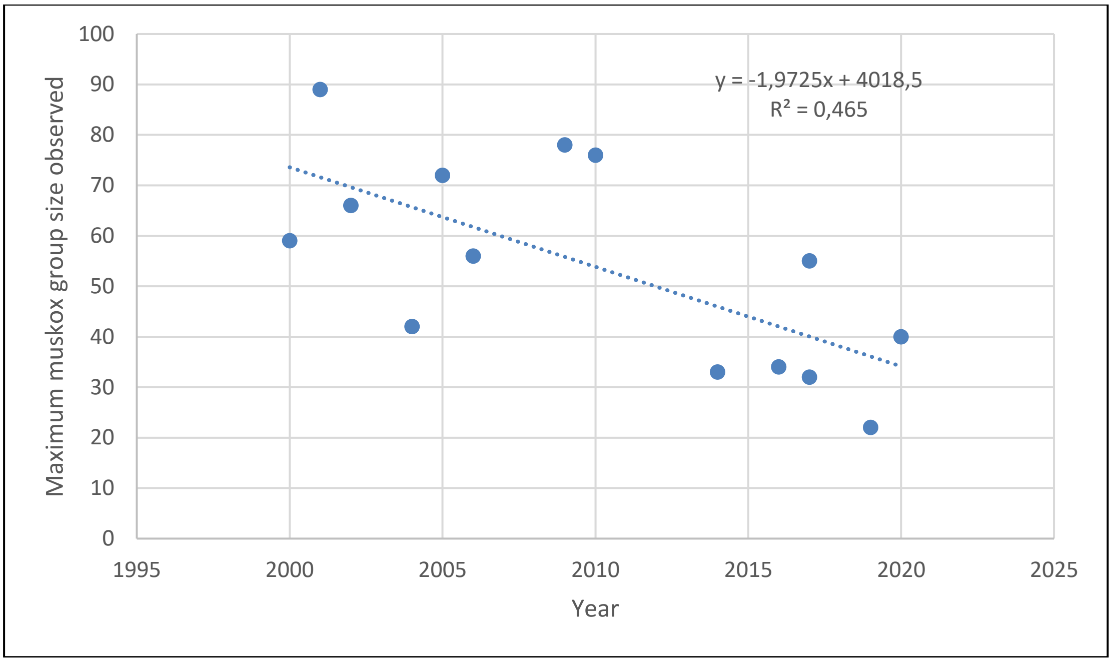

Figure 11. Maximum Maniitsoq muskox group size observed during minimum counts in the period 2000-2020.

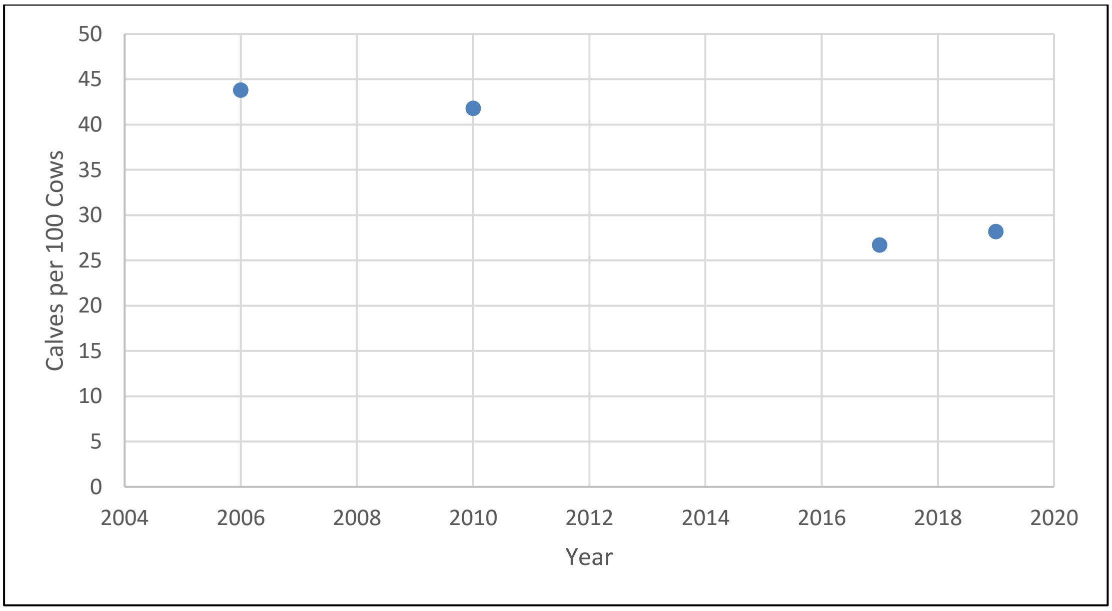

Figure 12. Winter calf recruitment as represented by calves (age ca. 10 months) per 100 cows, observed during four demographic counts completed in the period 2006-2020 for Maniitsoq muskoxen.

The recruitment values in 2017 and 2019 are lower than those obtained in 2006 and 2010 (Figure 11). Given the former are post-harvest values, although relatively low, these are probably artificially high since cows are commonly harvested but calves are not. Actual calf recruitment in 2017 and 2019 was likely lower than shown.

Supplementary Materials Cuyler (2020: Appendix 3)

Maniitsoq muskox population, Hunting Area 2

Population trends for APNN Hunting area 2, 2000 – 2020

Data from ground-based minimum counts, using skidoo and ATV. Rather than consider all four hunting management areas for Maniitsoq muskoxen (Figure 4), an examination of minimum count data from only hunting area 2 provides readily comparable results. In contrast to other hunting areas, the area 2 received relatively similar monitoring effort and coverage in the 2000-2020 period, although 2000-2010 results were pre-harvest and 2014-2020 were post-harvest. Much of hunting area 2 is preferred lowland habitat for muskoxen (Olsen 1983, Cuyler & Witting 2004). Trends observed here are expected to indicate trends for the Maniitsoq muskox population.

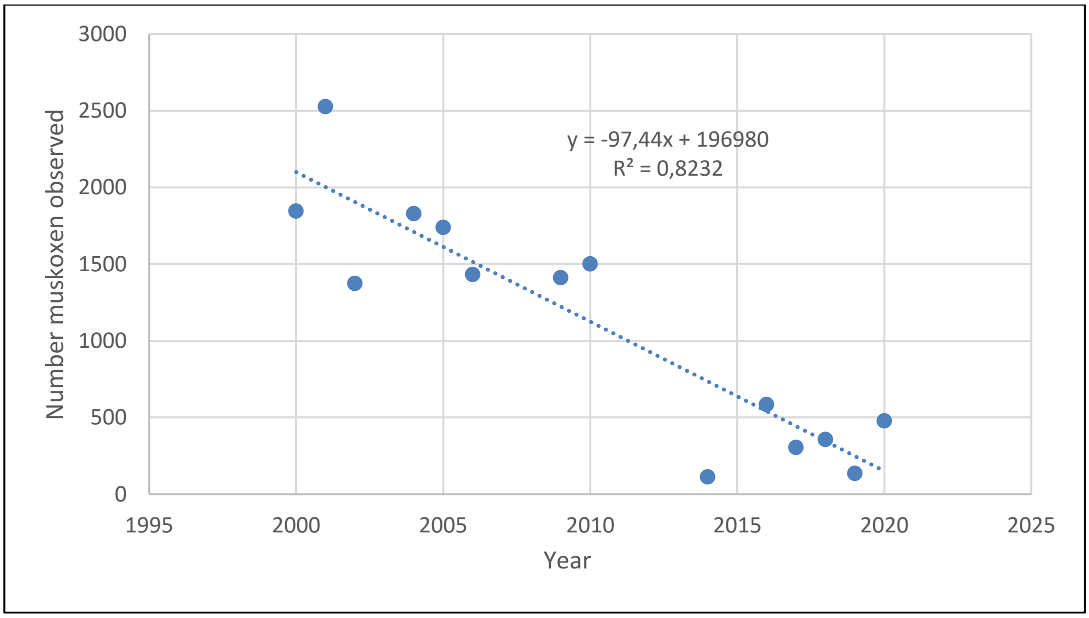

Figure 13. Hunting area 2: Maniitsoq muskox minimum ground count results in 2000-2020 period. The 2000-2010 counts occurred before the winter harvest, while 2014-2020 occurred after. All counts occurred pre-calving.

In hunting area 2 there has been a steady decline in the number of muskoxen observed. The regression's high R^2 value indicates that the line provides a reliable trend (Figure 13). Since 2014 muskox abundance appears relatively stable at low numbers. There is the possibility that numbers might have been higher if these counts had occurred pre-harvest. Regardless, already in the 2000-2010 period (when counts occurred pre-harvest), there was a marked decline in observed muskoxen.

In hunting area 2, the 2000-2010 calf percentage declined steeply to ca. 1/3 of its original value (Figure 14). Again, the regression line's high R^2 value is evidence of reliability. The post-harvest 2015-2020 calf percentages might suggest partial recovery of calf production from the low in 2010, however, these are derived post-harvest, which may have artificially boosted calf percentages (i.e., harvest biased to removal of juveniles and adults) and percentages appear to be dropping over that period. Thus, current calf percentages remain poor, specifically since calf percentages were normally ca. 25% in the 1980's and 1990's.

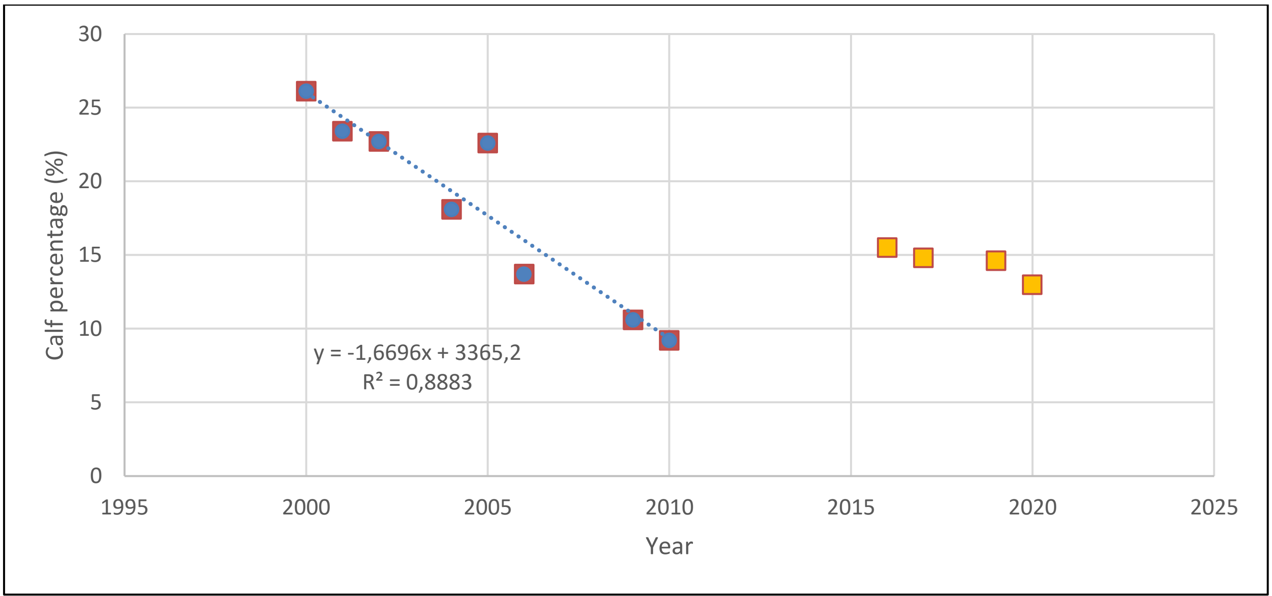

Figure 14. Maniitsoq muskoxen, hunting area 2: Calf production (percentage of the total number observed) in 2000-2020 period from muskox minimum ground counts. The 2000-2010 results are pre-harvest while 2016-2020 post-harvest. Linear regression illustrates the highly predictive declining trend for calf percentage in 2000-2010 period.

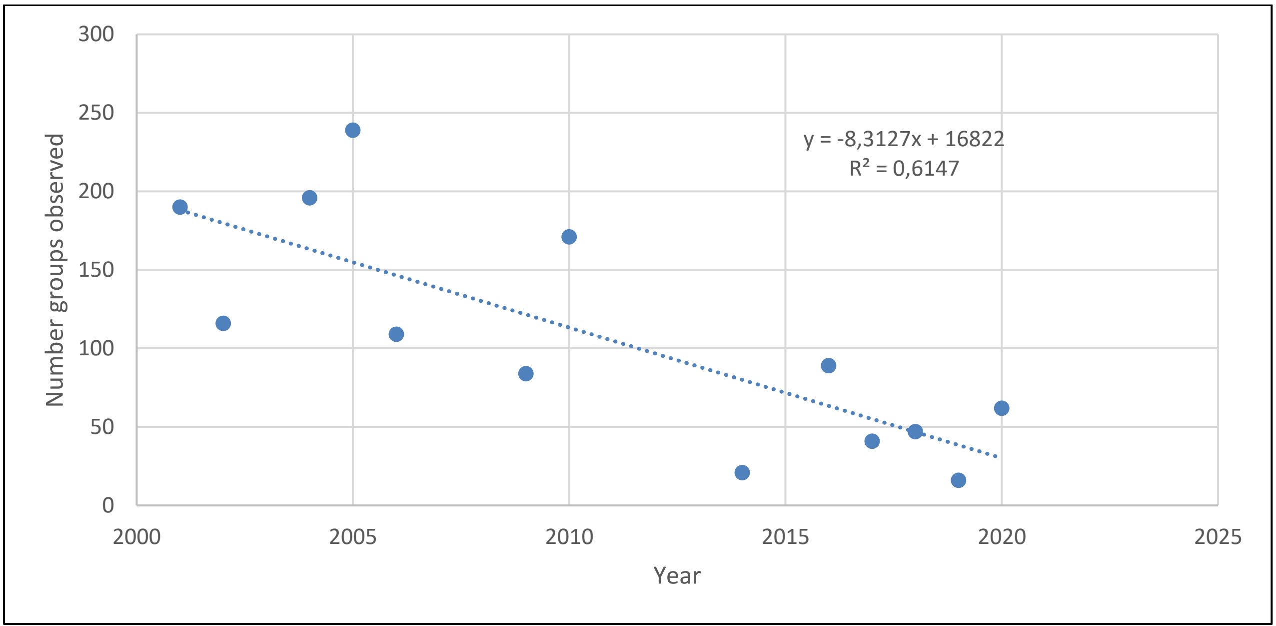

Figure 15. Maniitsoq muskoxen, hunting area 2: Number of muskox groups observed on counts during the 2000-2020 period. The 2000-2010 counts occurred before the winter harvest, while 2014-2020 counts were after.

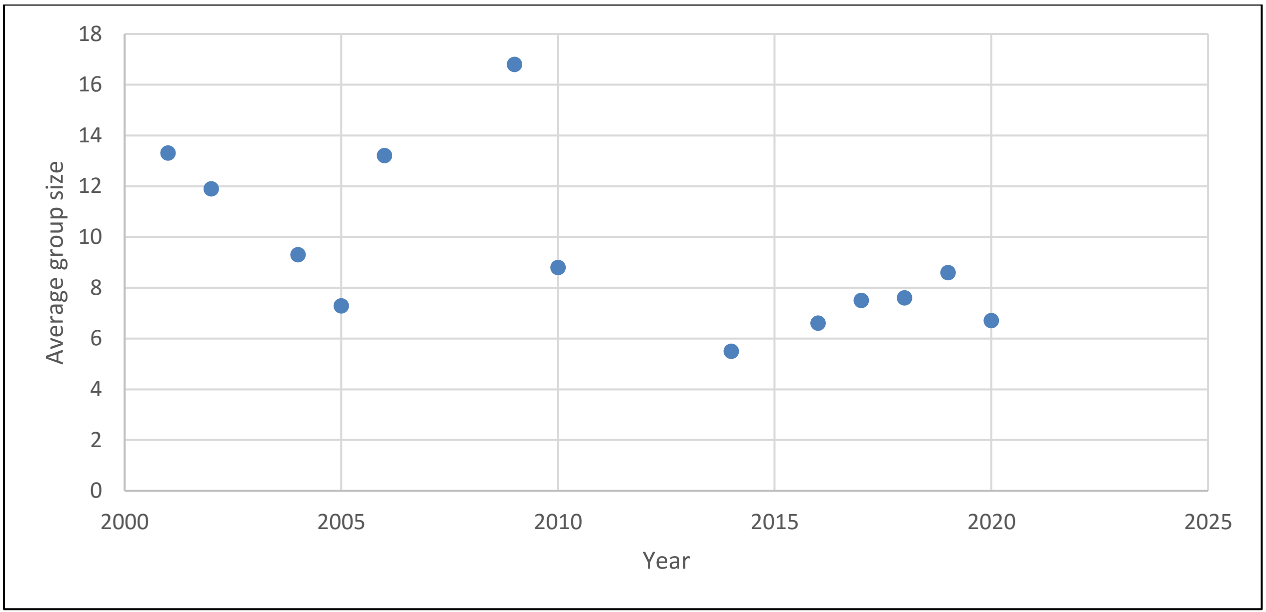

Figure 16. Maniitsoq muskoxen, hunting area 2: Average group size observed on counts during the 2000-2020 period. The 2000-2010 counts occurred before the winter harvest, while 2014-2020 counts were after.

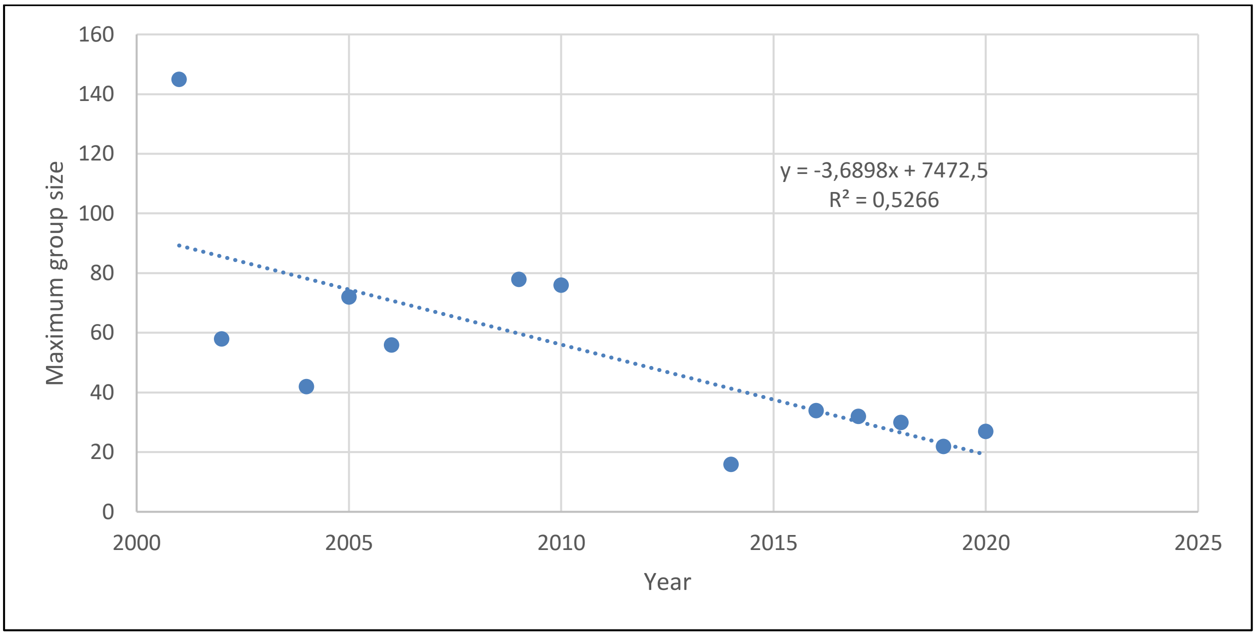

Figure 17. Maniitsoq muskoxen, hunting area 2: Maximum group size observed on counts during the 2000-2020 period. The 2000-2010 counts occurred before the winter harvest, while 2014-2020 counts were after.

In conclusion, for two decades observations from hunting area 2 illustrate that the number of muskoxen observed, calf percentage, number of groups, as well as average and maximum group sizes, have all declined. The declining trends from hunting area 2 support an overall declining trend for Maniitsoq muskox abundance and calf production (Figures 5 and 6).

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Appendix 10

Recommendations for improving future surveys for muskoxen.

Aerial survey methods & design: The approximately 11% survey coverage in 2018 promotes accuracy of abundance estimates and should be continued in future to facilitate population trend. Given muskoxen are stationary and the winter hunting season appears to disturb their distribution, in future the best option may be helicopter surveys specific for muskoxen and flown before the winter hunting season begins. This is because hunting seems to disturb normal distribution, which resulted in 'hot-spots' of high concentrations of muskoxen that made for high variance among line transects. To obtain greater accuracy and precision for estimates of muskox abundance and density, then the problem of uneven distribution and lack of presence in lowlands must be rectified. Alternatives might include a later survey period than currently used e.g., late March or early April. Albeit, all winter surveys should end before the onset of calving, which for muskoxen can begin by mid-April. Another alternative would be to prohibit hunting and motor vehicle activity before (>2 weeks) and during the survey period. A one-month period, or more, without hunting or other human disturbance may be necessary before muskox vigilance relaxes, as exhibited by foraging in the preferred lowland elevations and moving into known core winter range in hunting areas 1 and 2.

Muskox Demographics: Obtaining accurate demographics was not possible during the Distance Sampling survey. Even at the slow helicopter speed flown while flying line transects, when a group of muskoxen was detected, there was usually only sufficient time to obtain total group size, distance from the 0-line and sometimes the group's behavioral reaction to the fly-by. Accurate identification of the relatively small-bodied calves (age 9-10 months) was difficult, owing to animals often milling about and calves typically remaining hidden among or behind larger members of the group regardless of their distance from the track line. Muskox herd structure data must be collected in a specific effort separate from flying the line transects for Distance Sampling data. Future budgets must permit a minimum 3 to 6 hours helicopter time devoted exclusively to muskox demographic data collection. Alternately, a separate ground effort using aerial drones could obtain accurate demographics if used prior to hunting season(s) and on core range.

Helicopter Logistics: Always check whether other helicopter options are available. To date, the smallest helicopter available is the AS350 and only from Air Charter (Air Greenland). The AS350 permits limited vision for rear observers, owing to the small window size containing several bar/struts, and which under cold ambient temperatures always fog with ice-frost. These factors reduce visibility of terrain.

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