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Muskox Health Ecology Symposium 2016: Gathering to Share Knowledge on *Umingmak* in a Time of Rapid Change

by Susan Kutz, Jan Rowell, Jan Adamczewski, Anne Gunn, Christine Cuyler, O. Alejandro Aleuy, Mark Austin, Joel Berger, John Blake, Kristin Bondo, Chimoné Dalton, Andy Dobson, Juliette Di Francesco, Craig Gerlach, Pratap Kafle, Fabien Mavrot, Jesper Mosbacher, Maribeth Murray, Alex Nascou, Karin Orsel, Francois Rossouw, Niels-Martin Schmidt, Mike Suitor, Matilde Tomaselli, and Bjørnar Ytrehus

BACKGROUND

The muskox, ***Ovibos moschatus***, also known as *Umingmak* 'the Bearded One,' is a taxonomically unique, cold-adapted, ice-age survivor. Originally native to Canada and Greenland, it has established a circum-Arctic distribution via introduced populations. As a key resident herbivore in northern ecosystems, the muskox has importance that should not be underestimated. Muskoxen play an important role in the cultural identity of Arctic Indigenous peoples and provide a healthy source of country food. More recently, recognition of the economic potential of the species through tourism, sport hunting, and the traditional sale of handicrafts has generated renewed interest in muskoxen and their ecology. Recent documentation of diseases, including several zoonoses, regional mortality events, and population declines have highlighted knowledge gaps in both our understanding of the drivers of muskox population fluctuations and the potential sensitivity of this species to a rapidly changing climate (Kutz et al., 2013, 2015; Handeland et al., 2014; Ytrehus et al., 2015; Tomaselli et al., 2016c; Afema et al., 2017).

From 7 to 10 November 2016, a diverse group of people from around the Arctic met at the Faculty of Veterinary Medicine, University of Calgary, Alberta, Canada, for the Muskox Health Ecology Symposium. This was the first international conference focused solely on muskoxen in almost 30 years; previous meetings had been hosted in Fairbanks, Alaska, USA, in 1983, and Saskatoon, Saskatchewan, Canada, in 1987.

The 72 delegates attending the conference came from seven countries (Canada, USA, Denmark, Norway, France, Greenland, and Russia) and a diversity of backgrounds. They included representatives from universities, co-management boards, governments, industry, conservation organizations, and consulting businesses. This diversity brought great breadth and depth to the meeting, as people from many disciplines shared their different ways of knowing about muskoxen. In particular, the participation of several Indigenous co-management partners, together with their partners in industry (outfitted hunting and *qiviut* marketing), vastly enriched the values and perspectives shared. The meeting was also linked to MoxNet, the Muskox Expert Working group of the CircumPolar Biodiversity Monitoring Program, Conservation of Arctic Fauna and Flora, Arctic Council (https://www.caff.is/terrestrial/terrestrial-expert-networks/muskox).

The overall goal was to share knowledge on muskox health, ecology, and sustainability, with a view to conserving muskoxen and the "services" they provide, now and into the future. "Health" was defined in the broadest and most holistic sense, recognizing that many determinants influence the vulnerability and resilience of populations over time (Hanisch et al., 2012; Stephen, 2014). For muskoxen, some key determinants of health include weather and climate, pathogens, predators, genetics, nutrition, habitat, anthropogenic influences, and other disturbances.

The conference opened with introductory remarks by Maribeth Murray, Executive Director of the Arctic Institute of North America at the University of Calgary, and a keynote talk by Joel Berger (2016) of the Wildlife Conservation Society and Colorado State University. Murray provided a broad overview of climate change at high latitudes and the socio-economic and biological consequences of this change. Using yaks and muskoxen as examples, Berger discussed the importance of a deeper knowledge of the biology, behaviour, and physiology of cold-adapted species to a better understanding of the interplay between weather-related variation and its consequent effects on individuals, and ultimately, on populations.

THEMED SESSIONS

The meeting was organized as a series of thematic sessions that included invited talks, contributed talks, and breakout groups. Themes were (1) identifying the value of muskoxen; (2) population status and trends; (3) case studies on declining populations; (4) advances in muskox knowledge, vulnerabilities, and resilience; and (5) tools for muskox monitoring and research.

Session 1: Value of Muskoxen

Juliette Di Francesco and Francois Rossouw chaired this session, which included four contributed talks on the value of muskoxen at local, regional, and global levels.

Using individual interviews with members of the community of Iqaluktuuttiaq, Nunavut, Matilde Tomaselli et al. (2016a) identified four primary values of muskoxen: economic, socio-cultural, environmental, and nutritional. The use of hides, horns and bones for tools, handicrafts, and art is a deeply rooted component of socio-cultural traditions, and the sale of handicrafts and guiding of sport hunts provide important income. Local people describe the muskox as an animal that has been there for thousands of years, contributing to both biodiversity and the well-being of people. Historically, muskoxen provided an important alternative food source when caribou, generally the preferred species, were scarce. The simultaneous declines of both muskoxen and caribou in this area are of concern because the reduced availability for subsistence harvest and the loss of income-generating potential are additive drivers of food insecurity in Iqaluktuuttiaq.

The Ekaluktutiak Hunters and Trappers Organization (EHTO), partnering with Canada North Outfitting, provides guided muskox and snow goose hunts and eco-tourism opportunities in the region. Shane Black of Canada North Outfitting, together with the EHTO (2016), emphasized that while these activities provide numerous economic benefits to the community, including employment of local guides, increased sales of traditional arts and handicrafts, and use of local businesses, the benefits extend well beyond the financial sphere. Black and the EHTO described guiding as a highly skilled and respected profession that encouraged the maintenance of traditional skills and culture for living and traveling on the land, harvesting and handling meat, and most importantly, respecting the Inuit traditions. Guiding also provides a unique opportunity for clients to learn about Inuit culture, values, and traditions. These experiences with the guides, perhaps more than the actual hunt or adventure, are often life-changing events that clients remember forever.

Sigrun Robertson et al. (2016) discussed the grassroots approach and economic benefits of the Oomingmak Muskox Producers Co-operative in Alaska. One source of *qiviut* (the undercoat of the muskox) is a captive muskox herd in Palmer, Alaska, where animals are combed annually to harvest the *qiviut* as it is shed. *Qiviut* is then processed and spun before the yarn is distributed to individual knitters in Alaskan villages, who knit *qiviut* garments to be sold in the retail market. Since its founding in 1968, the Co-Op has been an important source of supplementary income, and sometimes the sole source of income, for residents of these small villages.

Fernando Alvarez (2016), with Qiviuk Boutiques, a division of Jacques Cartier Clothier Inc., discussed the broader international importance of muskox byproducts, including garments made from *qiviut*. *Qiviut* is highly valued for its insulating characteristics, softness, and light weight. Its rarity and unique properties command premium prices, both at the source and as consumer luxury items, in comparison to other commercial yarns. Hides from subsistence hunters or commercially harvested muskoxen from Arctic Canada and Greenland are shaved, and the guard hairs are sorted from the soft down. *Qiviut* is then spun and woven or knit into luxury garments, which are marketed globally. In addition, muskox products like horn, leather and "rare organic meat" can also be marketed as high-end products, thereby raising global awareness of an iconic animal that some still refer to as an ice-age relic.

All speakers highlighted the valuable role that muskoxen play as a source of income and jobs, as food, and as a link to the land for practicing and preserving traditional skills and intergenerational knowledge. They are also an integral component of northern ecosystems and emblematic of the Arctic.

The invited talks were followed by breakout discussion groups, facilitated by Craig Gerlach, Maribeth Murray, and John Blake. These discussions expanded on the talks and generated additional insights (Table 1).

Session 2: Population Status and Trends

Lack of data on population status, trends, and the drivers of these trends, and the unpredictability of population trajectories were identified as key factors limiting the potential economic, cultural, and ecological value of muskoxen. In this session, chaired by Anne Gunn and Jesper Mosbacher, wildlife managers and biologists from all global jurisdictions with free-ranging populations of muskoxen presented data on the current status and trends of muskoxen across their distributional range. Muskoxen in the Northwest Territories, Nunavut, and East Greenland are the only endemic populations; all other global populations have been introduced or re-introduced (Fig. 1).

For Alaska, Patrick Jones et al. (2016) explained that muskoxen from East Greenland were introduced to Nunivak Island, Alaska, in 1935 and were subsequently translocated and established on Nelson Island and in three areas of mainland Alaska. While all introduced populations on the mainland underwent an initial growth phase, they then declined and stabilized. Muskoxen from Nelson Island have emigrated to the Yukon Kuskokwim Delta and are believed to be a small but growing population. The Nunivak and Nelson Island populations are managed through hunting to maintain population goals. The total number of muskoxen in Alaska in 2016 was estimated at 4800.

Mike Suitor et al. (2016) described how muskoxen from the Alaskan North Slope dispersed east into Yukon circa 1985–86, with a larger group colonizing the area in 1999. These muskoxen are now distributed as far east as

TABLE 1. Value of Muskoxen Breakout Session. Summary of participant responses to questions concerning the value of muskoxen and the barriers and solutions to realizing this value.

Question	Key responses
1. Identify the value of muskoxen in economic, cultural and ecosystem terms.	**Economic:** • Muskoxen provide local income through handicraft sales, guided hunts, and tourism. • These activities promote entrepreneurship, skill development, and self-sufficiency. • The development of global niche markets for *qiviut* is expanding awareness and appreciation of muskoxen beyond the Arctic. **Cultural:** • Muskoxen are a healthy source of traditional food and promote food security. • Muskoxen are a catalyst for intergenerational learning to reinforce cultural identity. • Guided hunts foster traditional skill development and broader global awareness of muskoxen, the Arctic, and Inuit culture. **Ecosystem:** • As one of two large herbivores in the Arctic, muskoxen are integral to the food web, nutrient cycling, and plant productivity.
2. What are the barriers to realizing the diverse values of muskoxen?	• Lack of data on muskox population dynamics frustrates efforts at sustainable management of wild populations. • Population fluctuations make it difficult to provide a steady supply of meat and *qiviut* to meet market demands. • National and international health and export regulations inhibit market initiatives. • Negative perceptions of muskoxen compared to caribou in some communities have limited resources available for muskox monitoring, research, and development of related economic enterprises. • The high cost of northern operations and local economic disincentives restrict local, regional, and national initiatives to develop the economic and cultural potential of muskoxen.
3. What are possible solutions to current barriers?	• Improving the public image of the muskox, which is an iconic symbol of the Arctic. • Fostering partnerships among all stakeholders in both government and private sectors. • Facilitating sharing of policy-relevant data with regulatory agencies to enable transport of muskox raw materials across national and international boundaries. • Improving frequency and consistency of population monitoring to support sustainable management practices.

the Mackenzie River delta. In 2016, the minimum muskox count in Yukon was 287, which is an increase from earlier estimates.

Jan Adamczewski et al. (2016) discussed how muskoxen on the mainland Northwest Territories have recolonized their historic range and expanded far south of the tree line following their near extirpation in the early 1900s. More recently, expansion has been followed by declines in some areas. While infrequent surveys and unsurveyed areas make an overall estimate for the mainland difficult, best estimates suggest approximately 7000 – 8000 muskoxen. On Banks Island, consistent surveys since 1982 have shown a large increase in muskoxen to almost 70 000 (1994 and 2001), then a decline to about 37 000 in 2010, and a rapid decline, associated with unusually high numbers of summer mortalities, to about 14 000 in 2014. Muskoxen on northwest Victoria Island have been stable at about 12 000 (2005 – 15). Surveys in 2012 – 15 suggest that muskox numbers on the NWT Arctic islands may total about 30 000, but fewer if the rapid decline on Banks Island has continued.

Morgan Anderson (2016) noted that infrequent surveys and inconsistencies in the extent of surveys in Nunavut have made it difficult to establish the status and trends of muskoxen across 13 management zones. The most recent estimates for all regions in Nunavut indicate that there may be up to 60 000 muskoxen. While significant declines have occurred on eastern Victoria and Prince of Wales and Somerset Islands since the early 2000s, the smaller populations in the High Arctic and eastern mainland have increased substantially. The likely drivers of population dynamics in Nunavut are stochastic weather events (High Arctic), disease (Victoria Island), and grizzly and wolf predation (mainland).

Barrie Ford (2016) described the introduction of muskoxen to northern Quebec in 1967 as part of a domestication initiative. These animals were released from captivity in 1973 and 1983 and have dispersed and increased. Numbers were very roughly estimated at 1500 in 2003, but this population has not been systematically surveyed.

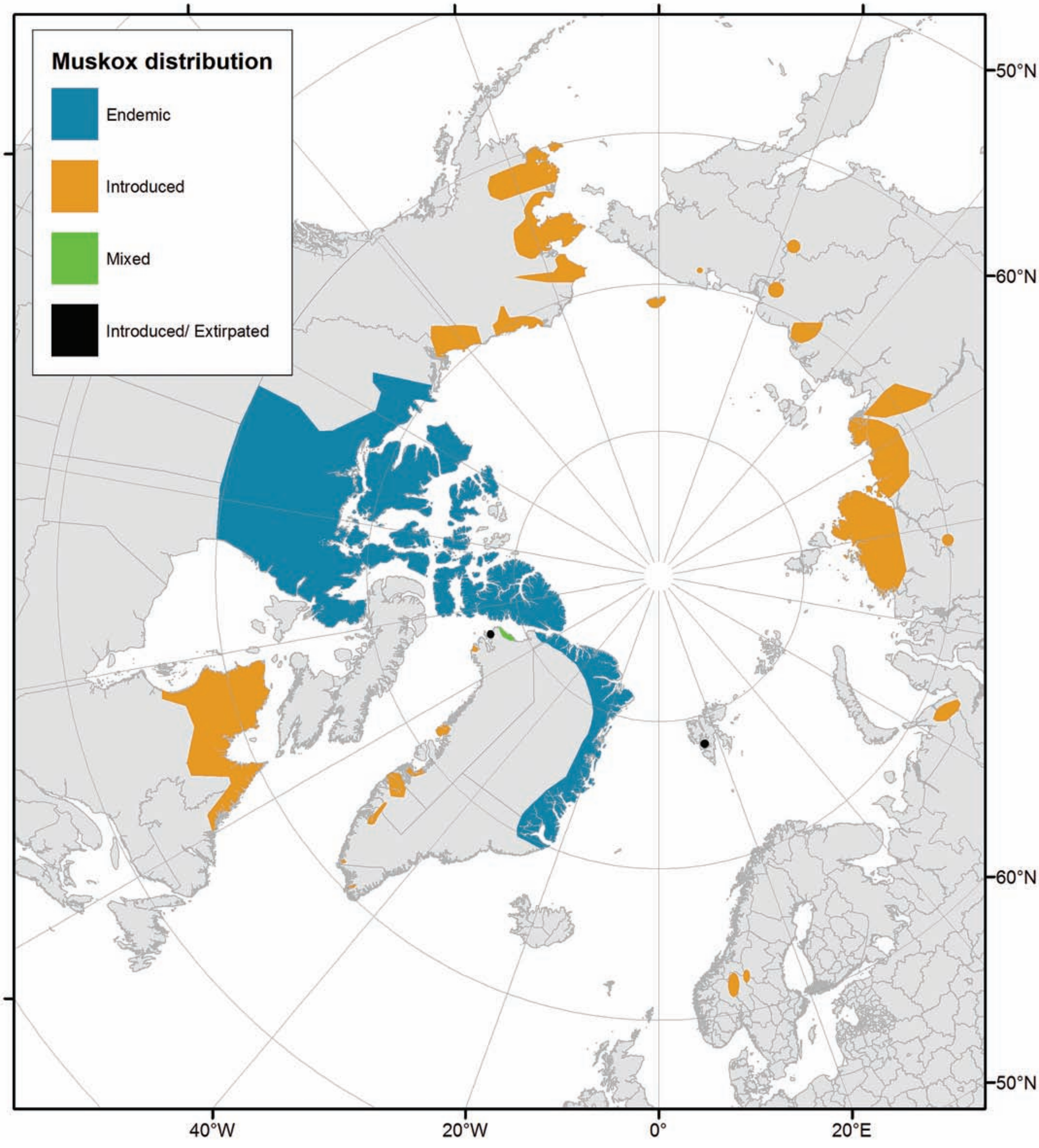

FIG. 1. Current global distribution of muskoxen. The exact distribution of muskoxen around 60˚ N in Canada is uncertain, since knowledge is limited to incidental observations, and densities in this area are very low. Ice fields on Greenland, Ellesmere and other islands are not shown due to scale of map.

Niels-Martin Schmidt (2016) reported that in 1992 the endemic muskoxen in northern and northeastern Greenland numbered 9500 – 12 500, but that the current population status and trends are unknown except in one area, Zackenberg, where muskoxen are counted annually. Here muskox abundance has rapidly declined since reaching its peak a decade ago. In contrast, Christine Cuyler (2016), presenting on the introduced West Greenland muskoxen, indicated general increases in these populations. Muskoxen introduced from East Greenland to seven areas between

1960 and 2004 now total approximately 5500 individuals (surveys from 2004 to 2015). The total number appears to be growing, largely because the population in Kangerlussuaq, with 4000–5000 animals, has been rapidly increasing.

Tord Bretten (2016) described the muskox population in Norway, which grew from a small number of animals introduced from Greenland from 1947 to 1953. This population is managed intensively, with culling of animals that disperse from the park or pose a risk to people. The population has fluctuated between 170 and 300 since 2004, and in March 2017, the minimum count was 249 animals. Major sources of mortality include disease outbreaks, train collisions, and culling of dispersing animals.

Taras Sipko and A.R. Gruzdev (2016) reported on the success of muskoxen that were initially introduced to Russia in the mid-1970s. These have since been sequentially translocated to 12 regions across the Russian Arctic mainland and Wrangel Island. Population estimates in 2016 indicated a total of around 12 400 animals, with an increasing trend in overall numbers.

On the basis of these presentations, and recognizing that infrequent surveys and variation in survey methods mean the estimates provided are in most cases approximations, the 2016 global muskox population was estimated at approximately 111 000–135 000 animals. Of those, 86 000–110 000 are found in endemic populations located in the Northwest Territories and Nunavut, Canada, and northeast Greenland. These figures indicate an estimated 10%–30% decline in total endemic muskoxen since 2005 (Gunn and Forchammer, 2008). The remaining 25 000 muskoxen were in populations that have grown from animals introduced (or re-introduced) to Alaska, USA; northern Quebec, Canada; and western Greenland, Russia, and Norway.

Speakers emphasized the need for more frequent surveys and standardized approaches to estimating muskox abundance across almost all areas of the species' distribution. The dependence on minimum counts rather than sample counts, changes in survey areas, and understanding how to define a population relative to management and survey areas, are additional challenges to both managing muskox populations and providing an accurate global estimate of their abundance. Determination of the mechanisms underlying population trends, especially why numbers in some areas are declining rapidly, was identified as a major knowledge gap. A frequently repeated concern was the divergence of views about the relationship between caribou and muskoxen; in some communities and regions, particularly where caribou have declined and muskoxen have increased, muskoxen are viewed as having a negative influence on caribou.

Breakout groups, facilitated by John Blake, Christine Cuyler, Morgan Anderson, and Anne Gunn, focused on gaps, uncertainties, solutions, and priorities with respect to understanding the status and trends of muskoxen (Table 2).

Session 3: Case Studies of Declining Populations

This session, moderated by Alejandro Aleuy and Mike Suitor, focused on four case studies of declining muskox populations in Alaska, Canada, and Norway. Infectious disease, trace mineral imbalances, ecological interactions (e.g., predator-prey), and environmental events were associated with recent and historic muskox declines.

Layne Adams (2016) noted unusually high mortality during a study comparing population dynamics of the North Seward Peninsula (NSP) and Cape Thompson (CT) muskox populations in western Alaska from 2009 to 2013. Historically, animals in the NSP population were in better body condition, and the herd had increased at a more rapid rate than the CT population. However, between 2007 and 2015, the NSP population declined by 69%. This decline was attributed to poor survival of both calves (decreased by about half to 20%) and adults (dropped from 77% to 65%) in 2011–12, as well as an unusual tidal storm surge in February 2011 that killed about 55 muskoxen (accounting for about 10% of the observed decline). Summer mortalities and exposure to the bacterium *Erysipelothrix rhusiopathiae* were also higher in NSP than in CT muskoxen during this same period. This bacterium, which has previously been associated with widespread mortality events in Canadian muskox populations, was cultured from the marrow of some of the dead NSP muskoxen, which suggests that it may have played a role in their decline.

Kimberlee Beckmen et al. (2016) reported a dramatic decline from 1999 to 2006 for the muskox population of the eastern North Slope, Alaska. Using a multifaceted approach (sampling from live captures, examination of carcasses, and serology) to investigate the muskox decline, they identified several disease syndromes that contributed to mortalities (e.g., weak calf syndrome, polyarthritis, copper deficiency, verminous pneumonia). They also found that a high proportion of animals whose deaths were initially attributed to predation had underlying disease processes, as diagnosed by post-mortem examination. Serological studies confirmed the exposure to *Brucella suis* biovar 4, *Coxiella burnetti*, and *Chlamydiophila* sp. bacteria, all of which can affect reproduction. Additional indicators of poor health status, in particular trace element imbalances such as copper deficiency, high parasite intensities, anemia, leukocytosis, and bronchopneumonia, were also associated with the declines.

Susan Kutz et al. (2016), who summarized mortality events and health status of muskox populations on Banks and Victoria Islands, NWT, and Nunavut, Canada, since the 1980s, similarly concluded that no single driver or event caused the declines. The bacterium *Yersinia pseudotuberculosis* and the lungworm *Dictyocaulus* sp. were associated with muskox mortality events in the 1980s and early 1990s. In the late 1990s and early 2000s, Banks Island muskoxen had high gastrointestinal parasite intensities. A major icing event in late fall 2003 led to a large population decline on this island the following

TABLE 2. Status and Trends of Muskoxen, Breakout Groups. Summary of participant responses to questions on substantial knowledge gaps in the basic population biology of muskoxen and the magnitude of the challenge of trying to collate and compare data on the status and trends of circumpolar muskox populations.

Question	Key responses
1. What are the gaps and uncertainties in understanding current global status?	• Knowledge gaps for almost all aspects of muskox ecology constrain our ability to understand the factors that drive muskox population dynamics. • Surveys are infrequent and methods are not standardized, making trend assessments between regions and over years difficult. • Lack of baseline data and long-term monitoring make it difficult to assess population status. • Interspecies interactions (specifically with caribou and predators), causes of mortality, and population biology are not well documented.
2. What are some solutions to addressing these gaps?	• Standardized and long-term monitoring across jurisdictions and over time are needed to understand trends and evaluate declines. • Information sharing among all stakeholders at the local, national, and international levels would aid research. • Better use could be made of community-based monitoring, including local observations and targeted sampling. • Regionally appropriate management plans need to be developed. • More funding is imperative and requires increased public awareness to help mobilize resources.
3. What are the top priorities with respect to understanding status and trends?	• Raising appreciation and perceived value of muskoxen. • Effective population monitoring (status, trends, and health) using standardized methods and tools. • Integrating information from all knowledge holders, including local and traditional knowledge. • Clarifying the causes and mechanisms of muskox population change.

year. More recently, relying on a combination of scientific investigation and traditional and local knowledge, Kutz's team identified health-related issues as playing an important role in muskox population status. Acute summer mortality events associated with *Erysipelothrix rhusiopathiae* were reported on both islands from 2010 to 2014, with a peak in the number of observations of dead muskoxen in the vicinity of Iqaluktuuttiaq in 2012. Scab lesions on the nose and mouth, consistent with a parapox virus (orf), are reported as new or increasing in frequency. On Victoria Island, broken incisors are common and severe, animals are in poorer body condition, and local knowledge (see Tomaselli et al., 2016b) indicates that muskox groups have become smaller, with greater distances between them and a smaller proportion of juveniles.

Bjørnar Ytrehus et al. (2016) summarized the pathological findings from mortality events occurring in the introduced muskox population in Dovrefjell, Norway. The first documented mass mortality event occurred in 2004, when 18 calves died and orf virus was isolated from carcasses. *Pasteurella* spp., *Mycoplasma* spp., and orf virus were associated with other mortalities. The mortality events seem to occur during population peaks. Unusually warm and humid weather in the region is suggested as the trigger for some of the disease outbreaks, with human disturbance and contact with domestic sheep (and their pathogens) as contributing factors. Ytrehus et al. emphasized the importance of better understanding the effects of stress, and in particular heat stress, on muskox behavior and physiology, and the necessity of a holistic approach, since wildlife disease is most commonly the result of multiple negative factors working simultaneously.

While all authors said that infectious agents played a role in the population declines, they emphasized that it was not clear whether these disease emergences resulted from new host-pathogen interactions or from increased muskox vulnerability due to environmental stressors, changes in ecological conditions, trace vitamin and mineral deficiencies, or poor genetic capital. Underlying aspects of their habitats also appeared to play a role in muskox population dynamics. For instance, Beckmen et al. (2016) linked poor survival of adult cows in Alaska to lameness resulting from hoof lesions, arthritis potentially driven by copper deficiencies (possibly linked to high variability in soil copper content), or both. Similarly, tooth breakage and missing teeth were features of some declining populations. Rocky, dry soils were presumed to be the cause of tooth problems in Alaska (Adams, 2016), but the causes on Victoria Island remain unknown (Kutz et al., 2016).

Speakers emphasized that no single common factor could explain the population declines. They highlighted the importance of a holistic approach that includes ongoing population monitoring, health assessments of live-captured and hunted animals (through community-based monitoring and partnerships), and thorough post-mortem investigation of mortalities.

Session 4: Advances in Knowledge, and Vulnerabilities and Resilience of Muskoxen

With recent declines and major gaps in knowledge about muskox biology, this session, chaired by Jan Adamczewski, Alex Nascou, Andy Dobson, and Kristin Bondo, aimed to improve understanding of the vulnerabilities and resilience of muskoxen. The session began with an invited talk from biologist John Nishi (2016), who proposed that effective wildlife management must be built on three essential pillars: hindsight, insight, and foresight. Hindsight refers to looking retrospectively at collected data to improve one's understanding of the mechanisms observed. Insight is the ability to interpret the current situation or events in light of the available information, which is often incomplete. Finally, foresight is the ability to draw on previous experience to anticipate future outcomes. Nishi highlighted that as the spatial or temporal scale of the system studied increases from individual, to herd, to ecosystem, so do its complexity and the uncertainty of the inferences made about it. He reminded us that management is also about people, and it is important to involve local communities in the process. Incorporating local expertise and knowledge, as well as community values and needs, is essential to manage for resilience and adaptive capacity. Nishi stressed that collaborative, strategic, and future-oriented management will lead to sustainable muskox populations globally and he urged scientists and stakeholders to be bold enough to make decisions and take action when needed.

Contributed talks covered behavioural ecology, genetics, vulnerability to climate change, and the ecology of parasites and emerging diseases. Niels-Martin Schmidt et al. (2016) discussed the seasonal movement patterns of muskoxen at Zackenberg, East Greenland. Movements are influenced by a variety of stimuli, including food availability, ambient temperature, and photoperiod. While muskoxen near Zackenberg display many different movement behaviours, they roam over only a limited area and are aptly described as "sedentary nomads." Erin Prewer et al. (2016) explored genetic structure of muskoxen and genetic diversity among muskox populations as a foundation for understanding ecological units and presented a method for detecting muskox lungworms through genetic analysis of larvae in the mucosal layer of feces. They described low genetic diversity among the sampled muskox populations; however, some differences between island and mainland muskoxen suggest that little movement occurs over the sea ice. Their current efforts aim to assemble the muskox genome in order to identify the roots of Arctic adaptations and disease susceptibility.

Anne Gunn et al. (2016a) described warming trends and more frequent severe weather in both summer and winter on Banks and Victoria Islands, Canada. Concurrent muskox declines suggest that the changing climate is likely interacting with disease to influence trends in muskox abundance and that heightened surveillance of these island muskoxen is needed. Alejandro Aleuy et al. (2016) discussed potential effects of climate change on the ecology of *Marshallagia marshalli*, an important abomasal parasite of muskoxen, wild sheep, and caribou. To address their hypothesis that parasites in higher latitudes will be locally adapted to wider variation in temperatures than their southern conspecifics, the team has collected samples from New Mexico to Yukon and is assessing differences in thermal tolerances and optima via incubation experiments. The take-home message was that equal warming will not produce equal impacts across a broad latitudinal scale: parasites at lower latitudes are likely to be more sensitive to climate change than those at higher latitudes. Pratap Kafle et al. (2016) reported on climate change and the range expansion to Victoria Island, NWT and Nunavut, of two lungworms: *Umingmakstrongylus pallikuukensis* (Up) and *Varestrongylus eleguneniensis* (Ve). The former is specific to muskoxen, whereas the latter infects both muskoxen and caribou. Examination of more than 1000 fecal samples and 40 carcasses demonstrates that Up has spread over much of Victoria Island, while Ve is still restricted to the southern part of the island. Climate modeling, together with laboratory data, suggests that this pattern may be due in part to differences in the thermal requirements of the free-living stages, as well as other species-specific life history characteristics. Both parasites are likely to expand farther as the climate warms.

Stephane Lair et al. (2016) discussed the giant liver fluke (*Fascioloides magna*) in the introduced muskox population of northern Quebec. The parasite burdens are high in these animals and cause substantial liver pathology. While the impacts are not known, the decline in mean worm burdens in older age classes may suggest a detrimental effect of this parasite, in that heavily infected animals tend to have high mortality rates.

Fabien Mavrot et al. (2016) presented results from serological surveys for the bacterium *E. rhusiopathiae* in muskoxen from Greenland to Alaska. The bacterium was detected for the first time as contributing to a series of acute die-offs on Banks and Victoria Islands, Canada, between 2009 and 2012. Serological results from more than 600 muskoxen sampled between 1976 and 2015 suggest that the bacterium has been present in Alaska since at least 1976 and was present on Banks Island at least as early as the 1990s.

The breakout groups, facilitated by Bjørnar Ytrehus and Joel Berger, discussed three main themes: climate change, diseases, and interspecies interactions. For each theme, the participants were asked to identify the characteristics of muskoxen that make them vulnerable, those that make them resilient, and our current knowledge gaps (Table 3). Delegates agreed that the cumulative effects of multiple factors and interactions among them need to be considered when assessing muskox vulnerabilities. Similarly, concurrent population and demographic monitoring are essential to identify critical determinants of individual and population health status, and integrative and comparative studies are needed to provide insights

TABLE 3. Muskox Vulnerability and Resilience Breakout Groups. Delegates were asked to discuss conditions that make muskoxen either vulnerable or resilient to climate change, infectious diseases and parasites, and interspecific interactions, and to identify and prioritize the knowledge gaps in understanding their resilience and vulnerabilities.

Questions	Key responses
1. What makes muskoxen vulnerable to:	
a) Climate change	• Small, isolated populations that are not highly mobile and have a tendency to remain "in islands of suitable habitat." • Cold-adapted animals have limited ability to respond to stochastic weather events, especially heat extremes. • Low genetic diversity may limit adaptability to rapid ecosystem changes and emerging pathogens.
b) Infectious diseases and parasites	• Apparently poor immune response increases susceptibility to new pathogens. • Herd behavior may facilitate spread of pathogens, especially during stressful events (increased animal contact and stress-mediated immunosuppression). • Heat stress may increase susceptibility.
c) Interspecies interactions	• Decline of alternative food sources (caribou/seal) may increase harvest pressure on muskoxen. • Encroachment of other herbivores or livestock may increase food competition, predator levels, and diversity and abundance of pathogens.
2. What makes muskoxen resilient to:	
a) Climate change	• They are survivors, having survived climate changes from the Pleistocene through the Holocene. • They are generalist foragers with the ability to adapt to new kinds of food and feeding behavior. • They are "desert animals" with low metabolism and large fat stores that allow them to survive temporary food crises.
b) Infectious diseases and parasites	• Small, isolated populations may act as a barrier to disease transmission. • Historical evidence suggests they have survived similar events in the past.
c) Interspecies interactions	• Small, isolated populations and wide distribution (circum-Arctic) offer broad-scale protection. • They are good at defense against traditional predators and able to modify behavior in response to other species.
3. What are the important knowledge gaps:	
a) Climate change	• What are the tolerance limits and capacities to adapt to changes in vegetation, phenology, and climate? • What drivers govern biological responses like reproduction and immune function? • What are the physiological and behavioural limits to heat tolerance?
b) Infectious diseases and parasites	• What is the physiology of disease and immunity in muskox populations? • What are the pathogen diversity and impact for individuals/populations? • What behavioral responses occur among diseased populations? • What is the historical, traditional, and local knowledge of muskox health and disease? How can it be better used to inform management? • What is the genetic capacity of muskoxen to adapt to disease threats?
c) Interspecies interactions	• What are the limits to muskox behavioral adaptation in response to predation and competition? • At what level(s) do muskoxen and caribou compete (or do they compete)? • How important is grizzly bear and wolf predation in limiting muskox populations?

into the adaptation potential and threats for muskoxen. Finally, our understanding of the physiology and genetics of muskoxen is limited by significant knowledge gaps. Further investigation is required to improve our understanding of both vulnerability and resilience in this species.

Session 5: Tools for Muskox Monitoring and Management

This last session of the conference was important for developing a framework to carry forward. Moderated by Pratap Kafle and Mark Austin, the talks ranged from developing techniques for incorporating local and traditional knowledge into a scientific framework, to options for improving international communication and collaborations, to developing non-invasive technologies and assays through which to infer physiological states.

Matilde Tomaselli et al. (2016b) worked with the community of Iqaluktuuttiaq, Nunavut, to develop a participatory muskox health surveillance system. Local and traditional knowledge gathered through individual and group interviews was used to understand trends and status of local muskox populations. Using this method, they reported epidemiological observations, population trends, and spatio-temporal patterns of mortality and associated these observations with the available scientific data. They concluded that community-based health monitoring enhances muskox health research while strengthening and facilitating the co-management process.

Jesper Mosbacher et al. (2016) reconstructed a 2.5-year dietary history for muskoxen from northeast Greenland, using sequential data on stable nitrogen isotopes in the rump guard hairs. High intra- and inter-annual seasonality in rump hair isotopes was significantly linked to changes in temperature and snow depth. The isotopic signature indicated that in snow-rich years, the animals relied more heavily on their body stores, presumably because access to forage was limited. This association provides an indirect measure of muskox health status, and considering the close link between body stores and calf production, dietary signals from the guard hairs have potential for population-level monitoring in remote areas.

Anne Gunn et al. (2016b) suggested that the complex causes of recent declines in muskox abundance raise the question of muskox vulnerability to a warmer climate. At a time when increased circum-Arctic monitoring on muskox exposure, sensitivity, and adaptability is needed to interpret vulnerability, the data are spatially and temporally fragmented. Setting up a species-monitoring network such as MOXNET is one way to address this challenge. They concluded that meetings like the present one are an opportunity to collaborate and coordinate muskox surveillance efforts.

Peter Flood (2016) provided an overview of the anatomical basis of the odour of rutting muskoxen and presented work on the use of fecal androgens as a non-invasive indicator of serum testosterone concentration. Fecal androgens were correlated to the annual seasonal cycle and male dominance. In addition, there was evidence that muskoxen losing a fight incurred a sharp decline in testosterone concentration. The feces of castrated male muskoxen contained compounds that reacted with the testosterone antibody used in the assay. These compounds were present in significant amounts and were shown to be of adrenal origin. It is likely that cortical activity could be measured using a suitable fecal assay. The challenges and limitations of using blood or feces-based assays were also discussed.

Juliette Di Francesco et al. (2016) measured cortisol levels in *qiviut* as a tool to interpret stress levels in different muskox populations. *Qiviut* cortisol concentrations were significantly higher in males than in females and followed a right-skewed distribution. They proposed that this method may prove useful as both a retrospective and a prospective indicator of individual and population-level muskox health.

Chimoné Dalton et al. (2016) used molecular approaches to explore the diversity of parapox and herpes viruses in muskoxen. Canadian Arctic muskoxen from Victoria Island, Nunavut, are infected with an apparently previously undescribed strain of parapox virus that does not match any available DNA sequences in GenBank. As expected, these muskoxen are also infected with a previously described enzootic gammaherpes virus. Phylogenetic analysis of virus strains is a useful tool for enhancing understanding of viral diversity and identifying viral reservoirs in order to manage the spread of infection.

The final breakout session, facilitated by Neils Martin-Schmidt and Jan Rowell, dealt with the theme of producing and prioritizing a list of recommendations on tools and research to help address gaps in knowledge about muskox vulnerability and sustainability.

Four common themes emerged: coordination and communication, community-based science, research directions, and remote sensing and technology for tomorrow (Table 4).

CONCLUDING REMARKS

Overall the meeting was a tremendous success. Scientific, local, and traditional management and industry knowledge and perspectives were shared among delegates, leading to very rich discussions and many new collaborations. Throughout the meeting, it was clear that the muskox is a highly valued species for a multitude of reasons, yet in many jurisdictions it remains the "poor cousin" to caribou and reindeer, with a rather quiet public profile that attracts little research and management funding. The potential vulnerability of this species was emphasized in the presentations on the recent population declines in some regions, the very low genetic diversity, and the apparently high susceptibility to disease. Increasing pressures include climate change (and the associated conditions such as warming, increased stochastic weather events, changes

TABLE 4. Tools for Muskox Monitoring and Research Breakout Session. In the final session, participants were asked to produce and prioritize a list of recommendations on tools and research to help address the knowledge gaps previously articulated. Discussions focused on tools and technologies, new or old, needed for muskox management and research. The following four themes emerged.

Theme	Key responses
1. Coordination and communication	• Create open databases allowing circumpolar data sharing. Allow open access to resources—regionally, nationally, and internationally. • Improve international communication through forums such as MOXNET. • Coordinate monitoring approaches, census methodologies, and data collections.
2. Community-based science	• Adapt web-based programs (e.g., cell phone apps) for collecting local observations. Arctic BioMap (http://arctic.ucalgary.ca/biomap-alaska) and LEO Network (https://www.leonetwork.org) could be customized for specific muskox observations. • Engage social scientists to facilitate the systematic collection, exchange, and inclusion of local and traditional knowledge. • Develop field guides to facilitate reporting of muskox information.
3. Research directions	• Expand computer modeling (i.e., individual-based models (IBMs) that integrate all current knowledge to allow for population-level predictions in space and time). • Pursue more model-guided fieldwork that focuses on key information gaps. • Increase the knowledge-base on muskox physiology, health, and ecology through collaboration, combining both field and captive-based muskox resources. • Use captive muskoxen for validating and developing new field techniques. • Establish and maintain a tissue bank repository.
4. Remote sensing, data acquisition, and technology for tomorrow	• Investigate and develop better, non-invasive methods for monitoring muskoxen and muskox populations; e.g., satellite imagery, drones, improved telemetry equipment; ground-based camera set-ups, and use of fecal and hair samples for hormone evaluation, DNA collection, and stable isotope and trace mineral analyses.

in snow and vegetation, temperature extremes, shifting species interactions, insect and pathogen pressures), and anthropogenic landscape change and disturbance (through tourism, exploration, and development of non-renewable resources). Potential conservation concerns for this species led to discussions on whether the conservation status of muskoxen needs to be assessed. Considering the many knowledge gaps identified here, and the fact that there are likely more muskoxen in the Arctic today than 50 years ago, some delegates raised concerns about the wisdom of giving the species "Special Concern" or higher risk status at this time: such a listing, depending on its level, could have consequences for harvesting, intergenerational learning, and local economies in northern communities. Nonetheless, all delegates shared a common concern for the future of the species and a commitment to its conservation. These important discussions focus attention on the issues faced by muskoxen and those concerned about them, and create priorities and momentum to move forward to better understand the biology, ecology, health, resilience, and sustainability of this important species.

The muskox is a taxonomically and biologically unique species and a precious global resource that is currently trying to persist in the earth's most rapidly changing ecosystem. We hope that the many friendships, connections, and collaborations that were initiated during this meeting continue to grow and work towards ensuring sustainable and healthy muskox populations for generations to come.

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Susan Kutz, Alejandro Aleuy, Kristin Bondo, Chimoné Dalton, Juliette De Francesco, Pratap Kafle, Fabien Mavrot, Karin Orsel, and Matilde Tomaselli are in the Faculty of Veterinary Medicine, University of Calgary; Jan Rowell is with the School of Natural Resources and Extension, University of Alaska Fairbanks; Jan Adamczewski is with the Department of Environment and Natural Resources, Government of Northwest Territories, Yellowknife; Anne Gunn is affiliated with CARMA and lives on Salt Spring Island, British Columbia; Mark Austin is with the Musk Ox Development Corporation in Palmer, Alaska; Joel Berger is at the Department of Fish, Wildlife and Conservation Biology, Colorado State University, Fort Collins; John Blake is with the Department of Animal Resources Center, University of Alaska Fairbanks; Christine Cuyler is with the Department of Birds and Mammals, Greenland Institute of Natural Resources in Nuuk; Andy Dobson is at the Department of Ecology and Evolutionary Biology, Princeton Environmental Institute, Princeton University in Princeton, New Jersey; Craig Gerlach is at the Department of Anthropology and Archaeology, University of Calgary; Jesper Mosbacher and Niels-Martin Schmidt are at the Department of Bioscience, Aarhus University, Roskilde, Denmark; Maribeth Murray is at the Arctic Institute of North America, University of Calgary; Alex Nascou is with the Department of Ecology and Evolutionary Biology, University of Toronto at Scarborough, Toronto, Ontario; Francois Rossouw is with the Department of Industry, Tourism and Investment, Government of Northwest Territories, Yellowknife; Mike Suitor is with the North Yukon Region Fish and Wildlife, Department of Environment, Government of Yukon, Dawson City; and Bjørnar Ytrehus is affiliated with the Norwegian Institute for Nature Research, Trondheim, Norway.

Susan Kutz is the corresponding author: skutz@ucalgary.ca