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Bachelor Thesis

Should nutrition plans for muskoxen (*Ovibos moschatus*) in captivity be optimized?

By: Line Enemark (sqx854)
Supervisor: Mette Olaf Nielsen
Faculty of Health and Medical Science, Department of Veterinary and Animal Sciences

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Preface

This project is the final paper on my bachelor in animal science at the University of Copenhagen.

The project deals with the difficulties of estimating nutrient requirements for animals as the muskoxen where there is limited information available. It shows how sometimes when in need of further information, we must draw related domestic animals into consideration. Working on this paper built on a lot of assumptions because of the lack of information, has taught me a lot about how to work with what is available, and the need to expand the horizon to other more known animals.

I would like to thank my supervisor Mette Olaf Nielsen from the Department of Veterinary and Animal Sciences, Section of Production, Nutrition and Health at University of Copenhagen, who has helped me with great advice, constructive critic, and reading of sections in the paper.

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Front page image: (Archer, 2016)

Abstract

A study has been made on how mineral levels are linked to the health of a herd of wild muskoxen in Northeast Greenland. This study showed a linkage between low copper and selenium hair levels and low calf recruitment together with high adult mortality. This shows that mineral deficiencies could cause health issues in captive muskoxen. But this could also be caused by other nutritional factors, and the aim of the present study was to find out which nutrient requirements the muskoxen had, and how the requirements were met in Copenhagen Zoo through the nutrition plan made for them. A quick review of the natural habitat of the muskoxen, and what it forages on, was made to help estimate the nutrient requirements. Dentition and digestive system are described to see to which domestic animals it could be compared. There was lack of information about natural forage and nutrient content. This meant that nutrient requirements were estimated, with help from a simulation and known requirements of sheep and cattle. The DM and ME for maintenance for muskoxen were found to be around 32 g/kg $BW^{0.75}$ and 0.245 MJ/kg $BW^{0.75}$. The protein, mineral and vitamin requirements were assumed to be the same as found in sheep and cattle because these are the domestic species with known requirements most similar to the muskoxen. The estimates for copper, phosphorus, iron, Vitamin A and Vitamin E differed between sheep and cattle, and symptoms of deficiency and toxicity were listed for both sheep and cattle. A nutrition plan for captive muskoxen during winter and summer was analyzed and compared with the estimates. The requirements for digestible crude protein, copper, iron, zinc and Vitamin A were exceeded in both the winter and summer diet from the nutrition plan, but maximum tolerance was not exceeded. ME for maintenance was exceeded significantly, and could lead to weight gain causing body temperature to increase, and lower the reproduction rates. If other European zoos feed with a similar diet as the one analyzed, the excess energy could be the cause of low reproduction rates in captive muskoxen. The heath increment could possibly be prevented by keeping an eye on the weight of the muskoxen, cutting down on high-quality hay, providing watering facilities or maybe transportation of ice during summer time. Further studies as nutrient content of the plants included in the natural forage of the muskoxen, urine and faeces samples to provide information about protein digestion and more wool samples is needed to estimate more exact nutrient requirement.

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1. Introduction

Trying to find a well-balanced nutrition plan and palatability for animals kept in captivity can be a struggle, especially when it comes to exotic animals, which we on some points lack knowledge about (Cheeran, 2004). This is because these animals have not been domesticated before, and in the wild live in areas that are not easy to get access to. When looking at production animals as cows, pigs, and poultry, we can easily grow and harvest their food, as hay and corn products that they consume. We even know what their optimal requirements for different nutrients are, to prevent health issues. When it comes to exotic animals it is more difficult to get their food, especially because they are adapted to all different types of feed. Free ranging herbivores, as the muskox, change their feeding habits based on what is available and phenology. The nutrient contents of the plants also change depending on, season, types of fodder, and stage of growth (Cheeran, 2004). Therefore, it is difficult to harvest and estimate exactly how much the muskox forages on which plants at different times of the year, and because of this the nutrition requirements can be difficult to estimate. Because of the small amount of knowledge about the nutrient requirements for muskoxen, it can be necessary to look at species, related to the muskox, for which we know the nutrient requirements (Cheeran, 2004).

The uncertainty about the exact nutrient requirements can lead to either oversupplying or undersupplying some nutrients. Deficiencies in essential trace minerals as Cu, Se, Mo, Mn, Zn, Co, Na, Fe and Cr are more likely to affect the animal negatively because they are tightly linked to the animals' health, survival and pregnancy rate (Underwood, 2012). Mosbacher *et al* (2016b, submitted, not published) show that years where the calf recruitment for the muskox in the wild was low, and the adult mortality was high, the concentration of the minerals Cu, Se, Mo and Co were also low. Similarly, their study showed that in years with high calf recruitment and low adult mortality the hair mineral concentrations were high.

This shows that mineral deficiencies could cause health issues in captive muskoxen. But this could also be caused by other nutritional factors. Although there have not been observed any clear signs of symptoms or health issues to support this (Stelvig 2018, personal communication), it is still an option because sometimes deficiencies do not show clear clinical signs (Underwood, 2012).

Detecting mineral levels or other nutrient concentrations in captive animals can be a challenge because sometimes it is necessary to immobilize the animals. Furthermore, in zoos the immobilization should only be short termed to avoid stress, hypothermia and hyperventilation, especially in the summer time sedation should be avoided (Eriksen, 2005; Richardson & Stelvig, 2014). Therefore, it can be useful to find non-invasive methods, maybe by analyzing wool (Mosbacher et al, 2016a) or looking at the weight condition, to help get information about the health status of animals.

This paper will discuss whether the nutrition plans for captive muskoxen (*Ovibos moschatus*) should be optimized to avoid possible health issues, due to the lack of knowledge about the exact requirements. An insight will be given on where the muskox lives and how the natural habitat and the flora look. Exploring which plants are available on specific times of the year, and how their nutrient content varies, can give a clue about what the nutrient requirements of the muskox might be. A brief explanation of how the digestive system of the muskox works, and how the dentition looks like, is necessary to understand which plants it can digest, and which nutrients it can obtain. Based on that information it is possible to select which domesticated animals, with known nutrient requirements, can be linked to the muskox.

The focus point of the paper will be to estimate nutrient requirements based on what the muskox feeds on in nature, and which nutrients it is assumed that the muskox will require from the feed. There will be a comparison with related domesticated species to gain more knowledge on what the nutrient requirement might be. From this different health issues linked to deficiencies or toxicity will be discussed and which non-invasive methods could be used to detect them.

It will through nutrition plans analyze how the muskoxen in zoos are fed and which nutrients are acquired from the feed. Then looking at the assumed requirements estimated for the muskoxen it will be discussed whether these get fulfilled by the nutrition plan, and if not, which health issues they might encounter.

Finally, based on the knowledge gained, an assessment will be made, of whether the nutrition plans for captive muskoxen should be optimized.

2. Muskoxen in the wild

The aim of this section is to give an insight into where the habitat of muskoxen is, and how the flora is. It will look at how the muskoxen are adapted, physically and physiologically, to the forage that is available and to which kind of animals the muskoxen are similar in order to provide information for later comparisons. This section will also look through what information there is about the summer and winter diet composition for the muskox, and which types of forage it feeds of.

2.1 The habitat

The muskoxen are mostly found in open and cold regions with low precipitation and low snow depth (Lent, 1988; Nellemann, 1998). Areas as these where the muskox lives are Greenland and Canada, and some muskoxen have been reintroduced in areas such as Alaska (the herd no longer exists), Russia and Norway (Eriksen, 2005; Nellemann & Reynolds, 1997; Richardson & Stelvig, 2014). The muskoxen in North and Northeast Greenland are native and from there some have been relocated to West Greenland (Richardson & Stelvig, 2014). These areas are classified as artic, or high artic areas (Nellemann, 1998), and experience hard weather conditions, such as long, cold winters, short summers with low temperatures, and nutrient limitations. In vast areas, the constant negative temperature causes the subsoil to remain permanently frozen, and acts like a barrier for biological activity and water drainage (Mosbacher, 2017). In the wintertime muskoxen prefer areas with shallow or no snow cover, and during the summer the muskoxen stay close to wet areas such as river valleys, or lakeshores (Richardson & Stelvig, 2014). The nitrogen levels are limited by the effect of low temperature on mineralization and decomposition rates. This makes these artic areas some of the least productive ecosystems on the planet. Despite the low productivity in the ecosystem, it still manages to provide feed resources and habitat to iconic animals, as the muskox (Mosbacher, 2017). In the lack of experimentally founded knowledge on nutrient requirements of muskoxen, attempts to optimize their nutrition in captivity should take their natural feeding habits into consideration.

2.2 The muskox

The muskox represents a mix between a sheep and an ox, and it has been greatly discussed, which of the two animals the muskox is most related to. Characteristics such as a short neck, bowed down horns, a hairy muzzle, shot tail, asymmetric hoofs, and the shape of the skull suggest that muskoxen are closely related to sheep. The size, gestations period and the number of teats, show connection with the ox. Characteristics from both animals found in the muskox are countless, and the connection between them is reflected in the name *Ovibos*, which translates to sheep-ox (Eriksen, 2005). It is one out of only two large ruminants in the high arctic areas, besides caribou/reindeer (*Rangifer trandus*). The muskox's feed consists to a large extent of different grasses, and it is what is called a grazer (Staaland & Thing, 1991).

2.2.1 Dentition and digestive system

With the lack of knowledge about the exact nutrition requirements of muskoxen, it can be useful to look at other domesticated animals that physiologically and physically are similar to the muskoxen, and of which we know the nutrient requirements. To do that it is important to know how the muskox is adapted to a low-quality diet by examining dentition and digestive system.

2.2.1.1 Dentition

Grazers include a large proportion of fibrous plants in their diet, and feed relatively non-selectively, meaning that they generally will have broad muzzles, relatively similar sized incisors, more flattened less protruding incisor arcades, and high crowned molariform teeth (Mathiesen et al., 2000).

The Mathiesen et al (2000) study showed that the muskox has a narrow muzzle, muzzle width ratio (MWR) around 1.6 cm. Comparison to the moose, which is a concentrated selector of similar body mass, with an MWR around 1.4 cm suggests that the muskox has a narrow muzzle. The study also showed relatively low crowned molariform teeth in muskox. The narrow muzzle and low crowned molariform teeth are expected in selective feeders.

Though the muskox has a narrow muzzle and low crowned molariform teeth, suggesting it is as a selective feeder, the muskox also has a small incisor width ratio (IWR) (around 1.1 cm approaching 1.0 cm) which is characteristic of grazers. The muskox also has intermediate curved incisor arcades and flat shovel-like incisors, which indicates an animal adapted to feeding on graminoids, just like a bulk feeding grazer like the bison (Mathiesen et al., 2000). The dentition of the sheep is similar to what is found in cattle, but the sheep has longer and more curved incisors, just like the muskoxen (Berg & Hansen, 2005).

Despite the narrow muzzle the muskox is unable to avoid ingesting a certain amount of low-quality forage in the winter, but a well-adapted digestive system, including microbial adaption in the rumen, distal fermentation and reduced retention time in the rumen, makes it possible for the muskoxen to cope with the winter conditions.

2.2.1.2 Digestive system

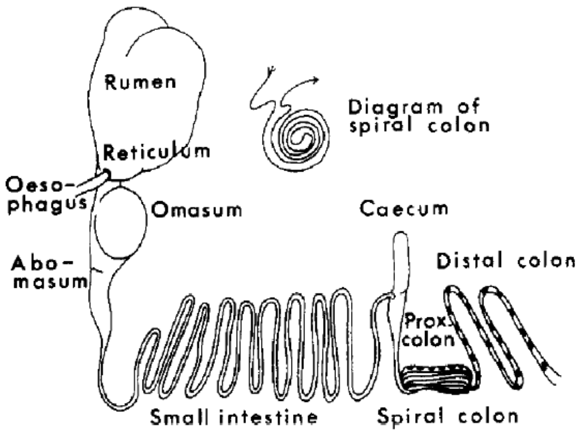

Figure 2.1 Schematic drawing of the alementary tract of the muskoxen (Staaland & Thing, 1991)

The muskoxen are well-adapted to the winter conditions in the arctic, where the access to forage is often limited by snow (Adamczewski et al., 1994). The alimentary tract of the muskox is specialized in utilizing the graminoid flora in the arctic at all seasons which is typical of a grazer or mixed feeders (Staaland & Thing, 1991). Muskoxen share several digestive features with sheep, which can also subsist on low-protein, high-fiber diets. The similarities are, a large rumen, and slow rumen passage rate, when eating high roughage diets and low intake (Adamczewski et al., 1994).
The Adamczewski *et al* (1994) study shows that the apparent digestibility of dry matter (DM) was higher in muskoxen than in cattle (52.5% vs. 45.0%) when fed on the same low-protein, high-fiber diet. Because the digestibility of high roughage diets depends on rumen fermentation, the higher digestibility of DM suggests a slower rumen passage rate in muskoxen than cattle. This digestive adaptation is possibly what makes the muskoxen able to extract more energy out of the forage. Besides the slow rumen passage rate, the study also showed that the muskoxen had a much lower intake of metabolized energy (ME) than cattle (15.9MJ vs 86.6MJ), and the low intake of ME was consistent with the relatively low fasting metabolic rate (FMR) 0.205MJ / kg$^{0.75}$. The low FMR is obtainable for the muskoxen due to low intake of DM and ME for winter maintenance, and Adamczewski *et al* (1994) DM and ME intakes for maintenance were 32g / kg$^{0.75}$ and 0.245MJ / kg$^{0.75}$. The muskox's DM and ME for maintenance are very low compared to the cattle in the

study (96g / kg$^{0.75}$ and 0.636MJ / kg$^{0.75}$), suggesting that cattle must have a higher FMR than muskoxen.
The specialized alimentary tract and relatively low metabolic requirements enable the muskox to maintain substantial body fat throughout the winter (Thing et al., 1987).

2.2.2 Vegetation

In artic areas the vegetation mainly consists of low-growing shrubs, grasses, sedges, forbs, lichens, and mosses (Mosbacher, 2017) the flora is typically what is called "open" flora, meaning that individually plants grow with some distance apart, and inbetween them there is uncovered soil (Wiley, 1902).
The vegetation composition and quantitative availability vary between geographical locations and very much also during the seasons of the year, which in turn determined which species are dominating in the diet of the muskoxen (Klein & Bay, 1990).
During winter, the forage quality is at its lowest and because of summer cropping, the quantity available to forage on is reduced (Nagy & Larter, 2001). Hence, Scheafer & Messier (1995) observed that fecal nitrogen from muskoxen rises in the summertime, which suggest that the forage quality is higher during summer than winter. Low quality forage is defined by high fiber content and low crude protein content, and high-quality forage is the opposite (Thing et al., 1987). The muskox is specialized both behaviorally and physiologically to these changes in diet quality of grasses and sedges (Staaland & Thing, 1991), and when foraging the muskox seems to maximize biomass intake, by selecting the most dominant vascular plants present. The biomass of graminoids is high, but the quality is low (Klein & Bay, 1990).

2.2.3 Forage selection and diet composition

Table 1 - Summer diet composition, with in vitro dry-matter digestibility (IVDMD) and estimates for Ca, K and P content.

Summer diet composition				
Species	% IVDMD[5]	% Ca[6]	% K[6]	% P[6]
Sedges	54	0.3-0.5		
Carex stans[1]		0.4-0.5	1-1.6	0.2-0.3
Eriophorum triste[2]		0.3-0.4	1.5-1.8	0.2-0.3
Carex rupestris[2]		0.3-0.5	1-1.6	0.2-0.3
Deschampsia brevifolia[3]				

Shrub/willow	42	1-1.5		
Salix Arctica[1]		1-1.5	1,3-1.4	0.2-0.3
Dryas integrifolia[2]				
Grasses	54	0.3-0.5	1.6-2.3	0.2-0.4
Arctophila fulva[3]				
Festuca sp.[2]				
Puccinellia angustata[2]				
Pleuropogon Sabinei[1]				
Forbs	46			
Pedicularis sp.[1]				

[1](Parker, 1978; Wilkinson et al., 1976)
[2](Parker, 1978)
[3](Wilkinson et al., 1976)
[4]CP = Crude protein
[5](Ihl & Klein, 2001)
[6](Thing et al., 1987)

Table 2 - Winter diet composition, with in vitro dry-matter digestibility (IVDMD) and estimates for Ca, K and P content.

Winter diet composition				
Species	% IVDMD[5]	% Ca[6]	% K[6]	% P[6]
Sedges	54	0.3-0.5		
Carex stans[1]		0.4-0.5	0.5-0.8	0.1
Eriophorum triste[2]		0.4	0.5	0.1
Eriophorum angustifolium[3]		0.4	0.5	0.1
Carex rupestris[1]		0.4-0.5	0.5-0.8	0.1
Carex nardina[2]				
Shrub/willow	42	0.6		
Salix Arctica[2]		0.6	0.4	0.1
Dryas integrifolia[2]				
Grasses	54	0.3-0.5	0.5-1.1	0.1
Arctogrostis latifolia[2]				
Festuca sp.[2]				
Puccinellia sp.[2]				
Forbs	46			
Oxyria digyna[2]				
Saxifraga sp.[2]				

[1](Parker, 1978; Schaefer & Messier, 1995)
[2](Parker, 1978)
[3](Schaefer & Messier, 1995)

[4]CP = Crude protein
[5](Ihl & Klein, 2001)
[6](Thing et al., 1987)

2.2.3.1 Summer diet

In the summertime the muskox's diet is dominated by graminoids as *Arctophila fulva* and especially sedges as *Carex stans* and *Deschampsia brevifolia* which are located in wet areas. Foraging on willows as *Salix artica* is of secondary importance, but still a major compartment of the summer diet. The forb *Pedicularis* sp. has also been listed as preferred feed in the summer. (Klein & Bay, 1990; Lent, 1988; Thing et al., 1987; Wilkinson et al., 1976). Studies show that when examining rumen content of muskoxen, it is mostly dominated by sedges, again as *Carex stans*, but also *Pleuropogon sabinei* (Wilkinson et al., 1976) This is probably due to the fact that muskoxen spend most of the summertime in wet areas.
According to Wilkinson *et al*. (1976) food is not a limiting factor in the summertime, because muskoxen tend to feed on only the leaves of grasses and sedges. This I supported by the fact that ungulates are known to select for the most digestible part of the forage, unless compelled to do otherwise by hunger (Wilkinson et al., 1976).
The Thing *et al* (1987) study showed that digestibility, for graminoids and willow, increased from winter, on average by a factor 4, and peaked in the late growing season (late June – early August). Meaning that there are higher levels of protein in the forage in summertime, and this is probably why the muskoxen can select only the most digestible part of the plant. It also showed that the protein/fiber levels were on average 24% higher in willows, than graminoids, this supports the fact that we find more willows in the summer diet than in the winter diet.

2.2.3.2 Winter diet

It is observed that during winter, where the nutrient quality is low, the muskox is known to select for low snow depth, softer and thinner snow, and greater food abundance (Schaefer & Messier, 1995). This is probably also because vegetation often is limited by snow (Nagy & Larter, 2001). Therefore, muskoxen forage on windblown buffs, river terraces or hilltops where snow is shallow (Nellemann & Reynolds, 1997). The diet consists of 50-80% graminoids, mostly of the sedges *Carex aquatilis* and *Eriophorum angustifolium,* and the rest consists mostly of foraging on willow slopes of *Salix arctica* (Klein & Bay, 1990; Schaefer & Messier, 1995). Thing *et al*, (1987) found that the protein/fiber levels of arctic willows were almost 42% lower than graminoids during winter, and this is probably why the muskoxen consume more graminoids during winter.

3. Nutrient requirements

Due to the lack of information on what the exact diet composition and nutrient contents are for the natural forage of muskoxen, it is needed to draw some parallels from known domestic animals to the muskoxen.
The aim of this section is to estimate what the energy requirements and DM intake for maintenance might be, by looking at other domestic animals similar to the muskoxen. The aim is also to establish what the mineral and vitamin requirements might be for muskoxen, because deficiencies or toxicities from these are often those who lead to health issues. This is also done by looking at domestic animals, similar to the muskoxen, and their known requirements

3.1 Energy and dry matter intake

During the winter, forage availability for wild muskoxen is limited, and dietary quality must be presumed to be lower than during the summer time, when vegetation is fresh and growing. A study by Thing *et al* (1987) showed that during winter (mid-September – late April) the carcass weight of adult male muskoxen decreases by around 33%, and pregnant and nonpregnant adult female muskoxen carcass weight decreases by around 26%. But even after 9 months on a graminoid-dominated diet, the fat reserves of muskoxen are not fully depleted. Suggesting that muskoxen might have a better adaption to the arctic environment, by digesting a low-protein diet more completely, than other grazers, and by maintaining body mass even at low intakes. However, estimating the nutrient requirements and the DM intake needed by muskoxen to be able to maintain their body mass throughout the winter on a low-protein diet can be difficult. This is due to the lack of knowledge about nutrient content of their natural forage, as sedges and willows, as well as lack of information about the nutrient requirements of these animals.

Adamczewski *et al* (1994) compared digestion and utilization of the same low-protein grass hay by muskoxen compared to cattle. The fiber and protein composition of the grass hay used in the experiment was similar to that of the sedges and grasses often found in the winter diets of free-ranging muskoxen. Even though this study was conducted on a herd of muskoxen from Canada, they must be expected to have similar origin and biology as the free-ranging muskoxen, which are found mostly in North/Northeast Greenland. Therefore, due to the lack of information on Greenland muskoxen, it is assumed that the results from the study by Adamczewski et al. (1994) also apply to the free ranging muskoxen in Greenland.

Table 3 - Composition of feed (% of dry matter) offered to muskoxen during digestibility trials, and mean apparent digestibility measured by using chromic oxide (Cr_2O_3) and daily intake of hay by muskoxen by offering enough long hay in the morning so each animal left 1-2kg daily (Adamczewski et al., 1994)

Diet composition		
Composition*	Hay	Apparent digestibility (%)[c]
DM	87.2[a]	52.5
OM	89.6[b]	57.8
CP	6.1[b]	43.2
NDF	73.2[b]	56.7
ADF	44.3[b]	48.9
Lignin	4.1[b]	-
Hemicellulose	28.9[b]	68.6
Cellulose	40.2[b]	59.5
GE (MJ/kg)	17.6[b]	-
Daily intake (DM)		
	Muskoxen	Cattle
Hay (kg)	1.76	12.18
DM (kg)[f]	2.04	12.05
DM (g/kg$^{0.75}$)	31.5	95.5
DE (MJ)[d]	19.3	105.7
ME (MJ)[e]	15.9	86.6
ME (MJ/kg$^{0.75}$)	0.245	0.636

[a] Ovendried hay samples to constant mass at 60 C to determine DM (Adamczewski et al., 1994)
[b] Calculated by using standard methods (Adamczewski et al., 1994)
[c] Calculated from concentrations of Cr_2O_3 in feed and feces (Adamczewski et al., 1994)
[d] Computed from digestivility of gross energy and feed consumotion (Adamczewski et al., 1994)
[e] Estimated as 82% of DE (Adamczewski et al., 1994)
[f] Is higher compared to daily intake of hay, because, the muskoxen also were fed pellets, but the amount consumed is so small, it is not in the table.
* *DM = dry matter, OM = organic matter, CP = crude protein, NDF = neutral detergent fiber, ADF = acid detergent fiber, GE = gross energy, ME = metabolic energy, DE = digestible energy*

The Adamczewski *et al* (1994) study showed that both muskoxen and cattle managed to maintain bodymass on the low-protein diet. The differences between them though were remarkable. The results showed that muskoxen DM intake for maintenance was around 32g / kg$^{0.75}$ and ME for maintenance was 0.245MJ / kg$^{0.75}$, whereas the estimates for cattle were much higher (96g / kg$^{0.75}$ and 0.636MJ / kg$^{0.75}$, respectively). The daily intake of hay was higher than for muskoxen, showing that cattle needed to eat much more of the diet to maintain their body mass, compared to the muskoxen.

The estimates for muskoxen are much lower than cattle, and other ruminants as sheep, and goats (Huston et al., 2007), meaning that their energy turnover must be really low which suggests an extreme adaption by muskoxen (Adamczewski et al., 1994).

The herd of muskoxen that was used in the study was a mix of castrated males, hysterectomized females, pregnant and nonpregnant intact females. The cattle used were 3 mature nonpregnant, nonlactating cows. The different muskoxen might have some influence on the results, but the marked difference between muskoxen and cattle in the study, still suggests that muskoxen have adapted during evolution to the harsh arctic climate so that they are able to maintain their body mass on a low-quality forage, and much lower DM and ME intakes than cattle.

When comparing DM and ME for maintenance for muskoxen with the other animal species most similar to them, namely the sheep, the DM and ME for maintenance of a 75kg ewe fed on a low-protein diet have been found to be 35.9g / kg$^{0.75}$ and 0.438MJ / kg$^{0.75}$, respectively (Nielsen et al., 2014). The sheep lost weight during the experiment, and this DM intake is therefore underestimating the needed DM intake on maintenance level for the sheep on a low-protein diet. The digestibility of the DM in sheep of the low-protein diet was quite similar (50%) to what was observed in the muskoxen, and is consistent with the fact that both animals have similar digestive features, such as low passage rate through the rumen, making them able to digest low-quality forages.

The estimates for DM and ME in sheep are higher than those observed for muskoxen, and the estimates for muskoxen are more than half the estimates found in the cattle, showing a really low DM and ME for maintenance.

However, it is relevant to evaluate whether such low estimates for ME requirements as found by Adamczewski *et al* (1994) may in fact reflect reality.

Looking at another relatively large ruminant in the same arctic environment as the muskoxen, we find the caribou (*Rangifer tarandus pearyi*). Fancy (1986) conducted simulations found that the typical diet ingested by a caribou has a DM digestibility of around 73%, and during winter the DM and ME requirements for maintenance for caribou

were around 75.9g / kg$^{0.75}$ and 0.836MJ / kg$^{0.75}$, respectively. Even though the caribou in the study by Fancy (1985) study, weight 100 kg, i.e. only half the weight of muskoxen in Adamczewski *et al* (1994) study, the caribou had a DM intake of 2.4 kg. It is odd that the DM and ME requirements for the caribou are that much higher than the observed values for muskoxen, in fact DM intake of caribou exceeded that of muskoxen by 400 g. But looking closer into the morphology and behavior of the muskoxen and caribou, they have adapted to this arctic environment in different ways. The higher DM digestibility in caribou can be explained by the fact that the caribou is an intermediate feeder (Mathiesen et al., 2000), so it is more selective in what it forages on. The main component of the caribou diet is lichens and leaves of sedges, which have a higher digestibility than graminoids, which explains why DM digestibility and DM intake are higher for caribou. Also, because the caribou is more selective, it needs to move around more than muskoxen, so the energy budget for the caribou is higher, and this may also be a reason why ME for maintenance is high. The caribou also has a smaller rumen scaled to body size than the muskoxen, meaning that the passage rate is faster, and therefore during winter it may need to consume more DM to fulfill their maintenance requirements (Klein, 1991).
Looking at another ruminating foregut fermenting animal, adapted to an extreme environment, there is the llama. Llamas are adapted to the seasonally low temperature and intense solar radiation in the Altiplano. The precipitation is limited, and during dry season there is only a little chance for forage growth. Here bunchgrasses are the dominant plant species. The llama is a so-called pseudo-ruminant with an expanded foregut consisting of 3 compartments, instead of 4 as in true ruminants (Martin & Bryant, 1989). In the study by Nielsen *et al,* (2014) sheep were compared to llamas, and llamas fed on the low-protein diet and found their digestibility of DM to be 51.7%, and DM and ME for maintenance are 25g / kg$^{0.75}$ and 0.328MJ / kg$^{0.75}$. The digestibility and estimated ME intake for maintenance in llamas of the low-protein diet were much closer to what was observed in muskoxen, and higher than the one in the sheep, showing that the llama is better at utilizing the DM in the low-protein diet than sheep. Even though the ME needed for maintenance is higher in llamas than for muskoxen, they consume less DM. This shows that it is possible to maintain body mass even on low intakes. The Nielsen *et al,* (2014) study also showed, that even when the llama was offered a high-protein diet, it still consumed less ME/kg$^{0.75}$ than sheep, and the ME for maintenance for llamas was the lowest of sheep and goats. This suggests that it may indeed be possible that the

muskoxen during evolution have attained an extraordinary low energy turnover to adapt to the extreme arctic environment and low feed availability during the long arctic winter. A lower mean body temperature in muskoxen of around 37^{o}C (Solomonov et al., 2011), compared to around 38.5^{o}C in cattle (Sjaastad et al., 2016) may be part of this adaption. The muskoxen also have a dense and thick underwool and long guard hairs, which provides maximum isolation (Klein, 1991), which is also a factor enabling the animal to maintain body temperature at a low energy turnover.

3.2 Protein, minerals and vitamins

It has not been possible to find any studies addressing protein, mineral or vitamin requirements for muskoxen. So due to the lack of information it is assumed that the requirements would be similar to what is observed in sheep and cattle, because those are the domestic animals most closely related to muskoxen.

Table 4 – Mineral and vitamin requirements for maintenance in sheep and cattle with their whole body weight (BW) and daily DM intake, and FU intake

	Sheep (BW = 100kg, 1.54 kg DM/d)[a]	Cattle (BW = 500kg[b], 4 FU/d[c])
Protein[i]	50 g/ kg DM[h] 78 g/d[a] 0.78 g/kg BW/d[e]	87,5 g/FU[h] 350 g/d[c] 0.7 g/kg BW/d[e]
Minerals		
Ca	1.95 g/kg DM[h] 3.0 g/d[a] 0.03 g/kg BW/d[e]	3.75 g/FU[h] 15 g/d[g] 0.03 g/kg BW/d[e]
P	1.8 g/kg DM[h] 2.7 g/d[a] 0.027 g/kg BW/d[e]	3.75 g/FU[h] 12 g/d[g] 0.024 g/kg BW/d[e]
Co	0.097 mg/kg DM[a] 0.15 mg/d[d] 0.0015 mg/kg BW/d[e]	0.1 mg/FU[b] 0.4 mg/d[d] 0.0008 mg/kg BW/d[e]
Cu	4.4 mg/kg DM[a] 6.7 mg/d[d] 0.067 mg/kg BW/d[e]	10 mg/FU[b] 40 mg/d[d] 0.08 mg/kg BW/d[e]

I	0.52 mg/kg DM[a] 0.8 mg/d[d] 0.008 mg/kg BW/d[e]	0.8-1 mg/FU[b] 3.2-4 mg/d[d] 0.0064 mg/kg BW/d[e]
Fe	9.1 mg/kg DM[a] 14 mg/d[d] 0.14 mg /kg BW/d[e]	100 mg/FU[b] 400 mg/d[d] 0.8 mg/kg BW/d[e]
Mg	1.16 g/kg DM[a] 1.8 g/d[d] 0.018 g/kg BW/d[e]	1.5-2 g/FU[b] 6-8 g/d[d] 0.012-0.016 g/kg BW/d[e]
Se	0.05 mg/kg DM[a] 0.08 mg/d[d] 0.0008 mg/kg BW/d[e]	0.1 mg/FU[b] 0.4 mg/d[d] 0.0008 mg/kg BW/d[e]
Zn	33.1 mg/kg DM[a] 51 mg/d[d] 0.51 mg/kg BW/d[e]	50 mg/FU[b] 200 mg/d[d] 0.4 mg/kg BW/d[e]
Vitamins		
A	6.8 IU/kg DM[a] 10.472 IU/d[d] 0.1047 IU/kg BW/d[e]	5000-10000 UI/FU[f] 20000-40000 IU/d[b] 40-80 IU/kg BW/d[e]
E	229 mg/kg DM[a] 353 mg/d[d] 3.5 mg/kg BW/d[e]	18.75-37.5 mg/FU[f] 75-150 mg/d[b] 0.15-0.3 mg/kg BW/d[e]

[a] *Protein, mineral and vitamin requirements + weight and DM intake, for sheep were found in* (Huston et al., 2007)

[b] *Mineral and vitamin requirements + weight, for cattle were found in* (Chawlibog, 2006)

[c] *Calculated: FU maintenance = LW/200+1.5, g digestible crude protein for maintenance = 0.7*LW kg* (Chawlibog, 2006),

[d] *Calculated: mg/FU or g/FU * FE/d, mg/kg DM or g/kg DM * kg DM/d, IU/kg DM * kg DM/d*

[e] *Calculated: mg/d or g/d / BW, IU/d / BW*

[f] *Calculated: IU/d / FE/d*

[g] *Found in* (Buchanan-Smith et al., 1996)

[h] *g/d / FU/d, g/d /kg DM/d*

[i] *g digestible crude protein*

BW = Body weight, IU = International Unit, LW = Living weight, FU = Feed unit

3.2.1 Protein

No studies have ever been conducted about the protein requirements for the muskoxen, and therefore, it is assumed that their protein requirements can be fulfilled if they are fed the recommended amounts as suggested for both sheep and cattle, which are very similar. Feeding after those requirements will most likely lead to oversupplying protein, considering the low-protein winter forage they are adapted to. But this will hardly be a problem because, of the liver's sufficient ability to convert the surplus of protein into urea (Sjaastad et al., 2016).

3.2.2 Minerals

Ca, P and some trace minerals are listed in Table 4, because they are the essential minerals with tight linkage to animal health, survival and reproduction rates (Underwood, 2012).

Differences in requirements for calcium, phosphorus, cobalt, iodine, magnesium, selenium, and zinc between sheep and cattle are insignificant, and in the absence of more specific information, it can be assumed that the requirements for muskoxen will be of the same magnitude as those for sheep and cattle.

Only for two of the trace minerals are there significant species differences with respect to requirements between sheep and cattle, and this is for copper and iron. Because of these differences for requirements between sheep and cattle, it is more uncertain to suggest requirements for the muskoxen. Therefore, it is needed to know, which symptoms to look for, if there are deficiencies in the trace mineral supply, or if they are oversupplied.

If there are deficiencies of copper some symptoms might include reduced growth or weight loss, and unthriftiness. With severe deficiencies there can be symptoms like: severe diarrhea, rapid weight loss, cessation of growth, rough hair coat and depigmentation of the hair and skin, swelling at the end of the leg bones, depressed or delayed estrus, and reduced reproduction. It can also lead to osteoporosis and occasional bone fracture in grazing animals (Hemken et al., 1988; Huston et al., 2007). The availability of copper can be reduced by the presence of abundant amounts of molybdenum, sulfur and iron. Especially molybdenum concentrations should be considered in sheep, a Cu:Mo ratio as 4:1, is considered safe and will avoid deficiencies, but not more or less, because sheep are sensitive to large amounts of copper (Huston et al., 2007).

In large amounts copper can be toxic, and this has frequently been observed in sheep,

which are sensitive to high levels of copper (Huston et al., 2007), and the copper poisoning is characterized by two phases: 1. Prehaemolytic, when copper accumulates in the liver, and 2. Haemolytic crises, when copper is released from the liver and the blood copper value rises, which is followed by hemoglobinuria (hemoglobin in urine), hemoglobinaemia (excess hemoglobin in blood plasma) and jaundice (discoloring of the skin). Copper toxicity can in worst cases result in death (Hemken et al., 1988; Huston et al., 2007).
When it comes to iron, deficiencies are rare in full grown cattle, but are often seen in young calves, because cow's milk is low in iron. They can develop iron deficiency anemia, and the growth and feed conversion can be affected (Hemken et al., 1988). In sheep iron deficiencies can lead to following symptoms: loss of appetite, poor growth, lethargy, increased respiration and high mortality. The storages of iron in liver, kidney, and spleen are exhausted and the animal develops hypochromic microcytic anemia (small pale red blood cells) (Huston et al., 2007).
Large amounts of iron can cause iron toxicity, which in sheep can cause peroxidative damage to lipid membranes, especially in the liver (Huston et al., 2007). Iron toxicity in cattle is often characterized by diarrhea, hyperthermia, metabolic acidosis, and reduced feed intake, and therefore maybe weight loss (Hemken et al., 1988). The extent of the toxicity depends on the Vitamin E status in the animal. Small amounts of Vitamin E increase the susceptibility to iron toxicity (Huston et al., 2007).

3.2.3 Vitamins

Only the fat-soluble vitamins are listed in Table 4, because ruminants are normally supplied with water-soluble vitamins, from microbial synthesis in the forestomachs, in amounts sufficient to satisfy the requirements (Sjaastad et al., 2016) . Furthermore, only Vitamins A and E are listed because ruminants can synthesize Vitamin D from ultraviolet radiation on the skin, so it is assumed that if muskoxen can do this from the arctic light, it is not a problem for them at our degree of latitude. Vitamin K is supplied from endogenous bacteria of the digestive tract (Hemken et al., 1988; Huston et al., 2007).
In both Vitamin A and Vitamin E there were large differences in what was required for sheep and cattle.
For small fully-grown ruminants deficiency of Vitamin A is not very common, and has been observed only in sheep, which for a long period of time has consumed grain-based concentrates poor in Vitamin A and the precursor beta-carotene (Huston et al., 2007).
Symptoms of deficiencies in Vitamin A can be split into the early stages and the late

stages. In the early stages there can be degeneration of the mucosa of the respiratory tract, mouth, salivary gland, eyes, causing night blindness but it might be hard to detect in captive muskoxen, tear gland, intestinal tract, urethra, kidneys and vagina. This makes the animal more vulnerable to infection and colds. Also, often the symptoms are diarrhea, loss of appetite, and therefore emaciation. In the late stages, as an effect of the deficiency or infection, it can cause damage to the eye, and in worse cases cause blindness (Hemken et al., 1988; Huston et al., 2007). In severe deficiencies animals can experience convulsive seizures as a result of elevated cerebrospinal fluid pressure (Hemken et al., 1988).
Generally, Vitamin A toxicity is not considered as a problem, unless the vitamin is fed in unreasonably high levels for more than 4 weeks. If it is fed for more than 4 weeks in unreasonably high amounts, there will be a decrease in feed intake (Huston et al., 2007). In cattle it is not considered a problem, because the maximum limit is so high (66.000 IU/kg diet), and the diets fed to captive muskoxen are most likely to contain the precursor beta-carotene than Vitamin A, except when fed as a supplement. 1 mg beta-carotene has been considered equivalent to 400 IU of Vitamin A. They convert beta-carotene to Vitamin A, and this process is presumably regulated depending on requirement just like in other ruminants (Hemken et al., 1988).
Deficiencies in Vitamin E are often seen only in calves, and can lead to muscle degeneration (Hemken et al., 1988; Huston et al., 2007). First there is a weakening of the leg musculature, and then the musculature of the tongue is affected, keeping them from sucking. In severe cases, the calf can be unable to stand and hold the head up. Vitamin E and selenium play a synergistic role, deficiency in one of them is often a sign of deficiency in the other (Hemken et al., 1988). Vitamin E toxicity has never been considered as a problem.

Considering the previous observation about a close relation between sheep and muskoxen, copper and iron toxicity may be a problem when feeding captive muskoxen. If the nutrient requirements of the muskoxen are closer to cattle, iron and copper toxicity can be a problem, but the tolerated amount is higher than for sheep.
Deficiencies do not often occur in captive animals because they are often fed mineral and vitamin supplements, so mostly toxicity symptoms need to be supervised. It is assumed that Vitamin A toxicity will not be a problem because of the beta-carotene regulation, and neither will Vitamin E toxicity, because it has never been considered a problem.

4. Detecting the health status in muskoxen

Sometimes mild deficiencies and toxicities can be difficult to diagnose, especially in trace minerals, because the effects on the animal often look like those arising from dietary energy deficit. The mild deficiencies are seldom accompanied by specific clinical signs (Underwood, 2012). Therefore, it is much needed to keep track of the health status of the animals to prevent the mild deficiencies or toxicities to be fatal.
The purpose of this section is to enlighten which problems there are when it comes to detecting the health status of animals, and which restrictions there might be. This section will determine which methods that cause the least problems and still are useful for detecting the health status of the animal.

4.1 Handling wild animals, risk and restrictions

Muskoxen in zoos are often kept in herds (Richardson & Stelvig, 2014), and health status, especially detecting mineral levels, is often done by a serum or liver samples. Both methods are rather invasive and require handling of the animals, which can be stressful for them (Mosbacher et al., 2016b, submitted but not published). Trying to get the samples from muskoxen that live in a herd can be difficult. It is possible to separate calves from the herd, but adults need to be immobilized (Richardson & Stelvig, 2014). One of the first problems when putting large animals under anesthesia, is trying to obtain the accurate weight so the correct dose of anesthetic is given. This is difficult but can be done with industrial weight bars under a platform, placed somewhere the animal needs to pass through (Hosey et al., 2013). When the muskox is sedated it risks hypothermia, hyperventilation (Richardson & Stelvig, 2014) and as all other ruminants, it should never be rolled on its back when sedated, because it is prone to regurgitation (Hosey et al., 2013; Richardson & Stelvig, 2014). Sedation must be avoided during hot summer days to prevent hyperventilation (Richardson & Stelvig, 2014).
To avoid these health risks and handling problems it is needed to find alternative non-invasive methods to help providing information about the herd's health status

4.2 Non-invasive methods

There are some non-invasive methods that might be useful for providing information about the health status of muskoxen.
One of them is the weight. (Mosbacher et al., 2016b, submitted but not published), study

shows that minerals are important to the health and reproduction of the muskoxen. Years with low hair mineral concentrations of Cu, Se and Mo, were related to low calf recruitment and high adult mortality. Wereas years with high hair mineral concentrations were related to high calf recruitment and low adult mortality.

The lack of minerals in some years can be connected to low forage availability and quality. During winter the forage availability can be limited by snow. If there is too much snow, or too hard snow surfaces, the vegetation can be difficult to get to, and the quality of the forage is low (Nagy & Larter, 2001; Schaefer & Messier, 1995). This explains why the weights of the muskoxen decrease over winter, and in some winters more than others (Thing et al., 1987), depending on the factors mentioned before. Therefore, the weight loss in muskoxen can be linked to deficiencies in minerals or other nutrients, and might be a sign that there is something wrong with the diet composition. Though it is normal for captive muskoxen to vary 8-10% in weight (Richardson & Stelvig, 2014), if it is more or rapid weight change it might be advisable to look at the diet.

Another non-invasive method is the one from (Mosbacher et al., 2016a) which showed that by analyzing the guard hair of muskoxen they could find out how the mineral and nutritional status was over an extended period of time.

Hair is metabolic inactive upon formation and contains stable isotopes, which then can function as a chemically stable archive of mineral and nutritional status. Though this only provides the baseline of the nutritional status over an extended period of time (Mosbacher et al., 2016a), it is an effective non-invasive method for tracking if the diet given to the muskoxen is providing the needed nutrition.

Mosbacher *et al,* (2016b, submitted, but not published) also used the underwool hair to detect the mineral status over a period of time, for a muskoxen population in Northeast Greenland. The underwool hair from muskoxen grows every winter, and is shed in synchronizing molt during the spring (Flood et al., 1989), and therefore, might provide a more recent inactive archive of the integrated mineral and nutritional status.

5. Muskoxen in captivity

To see if the way muskoxen are fed in zoos, matches the assumed nutrient requirements they have, an analyze of a possible nutrition plan is needed. This section focusses on analyzing a nutrition plan and determine whether it differs in any way from the nutrient requirements that might lead to health issues.

5.1 Nutrition plans

The given nutrition plan works for both young animals, cows, and bulls, the amount of feed differs. It has been chosen to look at the amount for a muskox cow because this is most similar to the ones in the Adamczewski et al. (1994) study (see appendix).

Table 5 – Content of a nutrition plan for a muskoxen cow.

Type of feed	High quality hay and alfalfa[a]	Grass (summer)[a]	Sliced raw carrots (winter)[a]	Sliced beetroots (winter)[a,f]	Rolled oats[a,d,o]	Zoopellets[i,o]	Fresh brows (willow and elm)	Mineral mix
Feed number	**602**	**465**	**391**	-	-	-	-	-
Amount	3kg	3kg	1kg	250g	600g	400g	Ad libitum	Salt lick
				Composition[a]				
DM (kg)[h]	2.55	0.57	0.1	0.055	0.510	0.368[k]	49.8%[p]	-
CP	16.4	21.0	10.5	5.9	10.2	13.0	8.9[l]	-
CF	2.9	3.9	-	0.3	5.3	8.0	-	-
DCP	12.3	16.5	6.8	2.5	6.5	-	-	-
CHO	72.2	65,7	81.2	85.8	81.9	22.0	-	-
NDF	-	41.0	-	13.0	28.0	38.0	50.1[m]	-
DE (MJ)[g]	29,37	7.98	14	0.76	7.8	13.65	-	-
Minerals[b]								
Ca (g)	42.84	3.14	0.44	0.099	0.41	4.05[j]	-	-
P (g)	6.89	1.94	0.3	0.94	1.84	1.84[j]	-	-
Mg (g)	5.87	1.03	0.19	0.08	0.6	1.3[j]	-	-
Fe (mg)	484.5	125,4	6	15.4	33.6	150	-	-
Mn (mg)	125	39.9	2.3	1.65	21.93	58.9	-	-
Zn (mg)	140.25	22.8	3.3	3.96	15.81	51.5	-	-
Cu (mg)	20.4	3.9	0.6	0.22	1.53	8.8	-	-

Co (mg)	0.255	0.228	0.016	-	0.005	0.52	-	-
Se (mg)	0.08	0.029	0.003	0.001	0.015	0.17	-	-
Vitamins[c]								
Vit A (I.U)	-	57000	27000	-	-	3184	-	-
Beta-caroten (mg)	-	142.5	67	-	-		-	-
Vit E (mg)	-	85.5	6	-	10.2	214	-	-

[a]*Feed stuff found in* (Møller et al., 2005)
[b] *Components stated as % of dry matter.*
[c] *(Amount of mineral / 1000) * (Amount of feed * (% dry matter/100))*
[d] *(Amount of vitamin / 1000) * (Amount of feed * (% dry matter/100))*
[e] *Used oats (Feed number 202* (Møller et al., 2005)*)*
[f] *Used sugarbeet (Feed number 361* (Møller et al., 2005)*)*
[g] *(Amount of energy / 1000) * (Amount of feed * (% dry matter/100))*
[h] *Amount fed * (% DM /100)*
[i] ("Mazuri ® Wild Herbivore Plus Diet Guaranteed Analysis", n.d.)
[j] *amount of DM * (% mineral / 100)*
[k] *DM content estimated from greenpellets (Feed number 707* (Møller et al., 2005)*)*
[l] *Estimate from* (Forwood & Owensby, 1985; Hjeljord et al., 1983; Soper et al., 1993)
[m] *Estimate from* (Hjeljord et al., 1983; Soper et al., 1993)
[o] *Fed two times a day*
[p] *Stated as % because the amount is not known* (Hjeljord et al., 1983)
CP = crude protein, CF = Crude fat, CHO = Crude carbs/fibers, ADF = Acid digestible fibers, NDF = neutral detergent fibers, DE= Digestible energy, DCP = digestible crude protein

5.1.1 Total winter diet

Table 6 – Total composition of the winter diet

Component	Amount fed[a]	% of DM
Whole diet (kg)	6.25	-
DM (kg)	4.46	71.4[d]
CP (g)	631.6	14.16
DCP (g)	388.3	8.7
CF (g)	187.1	4.2
CHO (kg)	2.97	66.5
NDF (g)	597.7	13.4
DE (MJ)	87.03	-
Minerals[b]		
Ca (g)	52.3	
P (g)	15.5	

Mg (g)	9.94	
Fe (mg)	873.1	
Mn (mg)	290.6	
Zn (mg)	282.13	
Cu (mg)	41.88	
Co (mg)	1.32	
Se (mg)	0.454	
Vitamins[c]		
Vit A (IU)	33368	
Beta-caroten (mg)	67	
Vit E (mg)	230.2	

*[a] amount of each DM for all time and winter * (each % of component /100) (oats and zoopellets twice)*
[b] Amount of minerals in all time type of feed and winter feed (Oats and zoopellets twice)
[c] Amount of vitamins in all time type of feed and winter feed (Oats and zoopellets twice)
[d] % DM of the whole diet

5.1.2 Total Summer diet

Table 7 – Total composition of the summer diet

Component	**Amount fed**[a]	**% of DM**
Whole diet (kg)	8	-
DM (kg)	4.88	61[d]
CP (g)	737.62	15.1
DCP (g)	474.2	9.7
CF (g)	201.5	4.1
CHO (kg)	3.212	65.8
NDF (g)	798.9	16.4
DE (MJ)	80.25	-
Minerals[b]		
Ca (g)	54.9	
P (g)	16.2	
Mg (g)	10.7	
Fe (mg)	977.1	
Mn (mg)	326.6	
Zn (mg)	297.7	

Cu (mg)	44.96	
Co (mg)	1.53	
Se (mg)	0.48	
Vitamins[c]		
Vit A (IU)	63368	
Beta-caroten (mg)	142.5	
Vit E (mg)	533.9	

*[a] amount of each DM for all time and summer * (each % of component /100) (oats and zoopellets twice)*
[b] Amount of minerals in all time type of feed and summer feed (Oats and zoopellets twice)
[c] Amount of vitamins in all time type of feed and summer feed (Oats and zoopellets twice)
[d] % DM of the whole diet

According to the study conducted by Adamczewski et al (1994), a muskox that weighs around 250 kg would have a DM and ME for maintenance around 2.1 kg DM/d and 15.4 MJ/d. Both the winter and summer diets fulfill those requirements and exceed them with more than 2 kg. The MJ in both diets also exceed the maintenance requirement significantly.

The muskox would have a protein requirement around 187-5 g digestible protein/d and also here both diets reach this requirement and exceed it significantly and more in the summer diet than the winter diet. The calcium and phosphorus requirement is fulfilled with both diets.

The other minerals also fulfill the requirements of a 250 kg muskox, but some of them exceed the requirements significantly. Copper content fed exceeded the requirements with more than 20 g and it might lead to toxicity. The zinc content exceeds the requirements with around 150 g, whereas the iron requirements are exceeded with around 700 g and even more if the muskoxen are more similar to the requirements of a sheep, in both summer and winter diet.

If the Vitamin A requirement for the muskoxen is more similar to a sheep it is around 25 IU/d, and if the requirement is more similar to the one for cattle it is 20000 IU/d. Therefore, in both diets the requirements are fulfilled but are definitely exceeded, and even more if the requirement is similar to that of sheep. The Vitamin E requirement is fulfilled if it is similar to the requirement found in cattle, but if it is similar to the one for sheep (875 mg/d) it is not fulfilled in neither the winter nor the summer diet.

6. Discussion

Mosbacher et al. (2016b, submitted not published) found that in nature, muskoxen low calf recruitment and high adult motality, were closly linked to low concentrations of hair trace minerals as copper and selenium. There has been observations of low reproduction rates in captive muskoxen in european zoos, and it has been speculated this could be because of copper deficiency (Stelvig 2018, personal communication). This could also be caused by other nutritional factors, and the aim of this study was therefore to find out which nutrient requirements the muskoxen has, and to what extent the requirements appear to be met in Copenhagen Zoo through the feeding plan made for them. This project chose to focus on fully grown adult muskoxen, and the requirements for maintenance because there are little to no information about requirements for other manifestions of life. Estimating requirements for exotic animals is difficult, because trying to take samples from the animal often requires that they are immobilized. This could cause complications as hyperventilation and hypothermiatha (Eriksen, 2005). In general it is retricted which samples are allowed to take, and how the animals can me restrained (*EU Zoos Directive Good Practices*, 2015; Reid et al., 2008). therefore necessary to look at what information there were available about the natural forage of the muskoxen, and how nutrient requirements could be estimated from that.

Information about requirements

There is a lack of studies and information about the nutrient content, and intake of the natural forage of the muskoxen and this makes estimating requirements difficult. The studies that have been conducted about their natural forage intake have not included direct information about what the plants nutrient content are, or the amounts of different types of plants consumed by the muskoxen. It was only possible to find one study that tried to directly adress requirements for the muskoxen. In that study, conducted by Adamczewski et al. (1994), they looked at the utilization of low-protein grass hay by muskoxen and compared it with the same diet digestion in cattle. This was to simulate a natural low-protein forage of muskoxen as they would be expected to consume in the wild during winter season, and see how they ultilize it compared to cattle. Based on the study Adamczewski et al. (1994) found the DM and ME for maintenance to be 32g/kg $BW^{0.75}$ and 0.245MJ/kg $BW^{0.75}$, respectively. The herd choosen in the study were a mixed herd of castrated males, hysterectomized females, pregnant and nonpregnant intact females. This

might obviously have influenced the results, because the chosen muskoxen have different manifestations of life and therefore, different nutrient and energy turnover. The cattle chosen as the comparison, were adult nonlactating cows and hence more comparable. However, since no other useful information, are available, it must be assumed that the muskoxen in this study still were able give a fitting estimate for DM and ME for maintenance. Also, though the different types of muskoxen, there were still remarkable differences in DM and ME for maintenance, suggestion that across sex and physiological status there is a much lower energy turnover for muskoxen, than cattle.
The estimates for DM and ME for maintenance in muskoxen, 32g/kg $BW^{0.75}$ and 0.245MJ/kg $BW^{0.75}$, respectively, are lower than in sheep (35.9g / $kg^{0.75}$ and 0.438MJ / $kg^{0.75}$, respectively (Nielsen et al., 2014)) and cattle (96g / $kg^{0.75}$ and 0.636MJ / $kg^{0.75}$(Adamczewski et al., 1994), respectively). It is therefore possible that the nutrient requirements for muskoxen might also be lower. There is though some doubt about if can be true that the energy turnover for muskoxen can be that low. Here looking at other animals adapted to extreme environment, there is the llama with a DM and ME for maintenance around 25g / $kg^{0.75}$ and 0.328MJ / $kg^{0.75}$ (Nielsen et al., 2014), respectively. This is also much lower than what is found in sheep and cattle, it must therefore be possible, but more studies are needed.

It has not been possible to find any studies that provide information needed to assess mineral, vitamin or protein requirements for muskoxen. Therefore, it was decided to look at requirements for other domestic animals most similar to the muskoxen, with known requirements. Here the animal species closest to the muskoxen physically and physiologically are sheep and cattle (Eriksen, 2005) . Because of the absence of information about the protein, mineral and vitamin requirements for the muskoxen, the only option for elaboration of dietary recommendations for these nutrients are to use those elaborated for sheep and cattle. In this case there might be some species differences in some nutrient requirements and in those requirements, it is presumed that the risk of estimating the wrong requirements are higher. It has not been chosen to estimate the requirement for the water-soluble vitamins, because it is assumed that the muskoxen can synthesize them, in amounts equivalent to requirement, just like other ruminants (Hemken et al., 1988; Huston et al., 2007). The requirements for protein, calcium, phosphorus, cobalt, iod, magnesium, selenium, copper and zinc in g/kg BW/d were close or similar to each other for sheep and cattle (See table 4). Hence, it can be assumed that the maintenance requirements for those nutrients in g/kg BW/d would be the same for muskoxen as for sheep and cattle.

This comparison with cattle and sheep gives rise to concern particularly for some nutrients, where requirements between cattle and sheep differed substantially, namely for iron, vitamin A and vitamin E. It is possible that the requirements for muskoxen are nowhere similar to those in sheep and cattle. In those where the requirements for sheep and cattle, the risk for estimating the wrong requirements, are higher. It is in these requirements where the feeding plan might have a higher risk of either oversupplying the nutrients or have deficiency in them. Depending on if the requirement for the muskoxen is most similar to the one found in sheep or cattle. Therefore, an evaluation of which consequences it might have if it is estimated wrong. Because of the lack of information, this is needed to keep in mind when discussing the requirements for muskoxen and if they are fulfilled by the nutrition plan.

Sometimes there is a big difference from which requirements are recommended to feed sheep and cattle, and what the max tolerance is before risks of toxicity. Especially sheep have low copper tolerances (Huston et al., 2007)

This is important to look at, before judging if the amounts fed in the summer and winter diet are toxic.

Table 8 – Requirement and max tolerance for copper, iron, Vitamin A and Vitamin E, in sheep and cattle

	Sheep		**Cattle**	
Mineral	Requirement[a]	Max tolerance[b]	Requirement[a]	Max tolerance[c]
Copper	0.067 (mg/ kg BW)	15 mg/kg DM	0.08 (mg/ kg BW)	100 mg/kg DM
Iron	0.14 (mg/ kg BW)	500 mg/kg DM	0.8 (mg/ kg BW)	1000 mg/kg DM
Vitamin A	0.1047 (IU/ kg BW)	20000 IU/kg BW	40-80 (IU/ kg BW)	66000 IU/kg DM[d]
Vitamin E	3.5 (mg/ kg BW)	75 mg/kg BW	0.15-0.3 (mg/ kg BW)	-

[a] *From table 4*

[b] *Found in* (Huston et al., 2007)

[c] Found in (Buchanan-Smith et al., 1996)

[d] Found in (Hemken et al., 1988)

The requirements for iron, vitamin A for muskoxen is assumed to be closer to the one found in sheep. Also, the requirements for vitamin E for muskoxen is assumed to be most similar to the one found in cattle. These assumptions are based on the fact that the muskoxen usually forage on low-quality forage (Thing et al., 1987). Therefore, the requirements are assumed to be the lower ones, maybe lower considering the much lower DM and ME for maintenance in muskoxen.

Copper requirement is assumed to be closer to the one found in cattle. This is because, sheep has a low copper tolerance (table 8.) and because of the study conducted by Mosbacher et al. (2016b, submitted, not published), which found high copper levels in muskoxen linked with great reproduction.

Even though the requirements for copper, iron, vitamin A, and vitamin E from table 8. were exceeded in both the winter and summer diet, none of the maximum tolerances are exceeded. According to this, none of the minerals and vitamin A should be causing toxicity, and therefore, cause no health issues in captive muskoxen.

The requirement for digestible crude protein for a 250kg is 195 g/d (calculated from table 4.) and is also exceeded in the summer and winter diet with around 500g. But this is not considered a problem because of the liver's sufficient ability to oxidate excess amino acids (Slyke, 1942). If there are no health issues to find in the protein, mineral or vitamin amount, then there is only one thing more there did exceed the requirements.

The ME for maintenance for the 250kg muskoxen is around 15.4MJ. The energy fed within the DM for maintenance is around 32.8MJ DE and 39MJ DE. This is more than the double of what is required for the muskoxen. Because the energy stated in the summer and winter diet is in the form of DE and the maintenance requirement is ME, some of the energy from DE will be needed for urine (Chwalibog & Hvelplund, 2003). The difference between energy requirement energy fed is still significantly. The excess energy there is left might lead to weight gain in form of white fat tissue.

The excess white fat tissue, would increase the blood leptin concentration and get sent to hypothalamus. In Hypothalamus leptin stimulates the secretion of Thyrotropin-releasing hormone (TRH) which goes to pituitary gland and releases Thyroid-stimulating hormone (TSH). TSH goes to the pancreas and stimulates the secretion of the thyroid hormones triiodothyronine (T3) and thyroxine (T4) (Ahima & Flier, 2000). T3 and T4 speeds op the body metabolism which creates a increased heat production (Dillmann, 1985). The increased heath production because of the excess energy, can cause heath stress, which can reduce spermatogenic activity of males, and impact oogenesis, oocyte maturation fertilization development and implantation rates in females (Takahashi, 2012). Considering the muskoxen have a thick wool, and are also fed excess protein, can increase the heath production and reduce the reproduction rates even more, especially in the summer. If other European zoos feed their muskoxen after a similar diet as in Copenhagen Zoo, the increased heat production could be a reason why there have been observed low reproduction.

7. Conclusion

The excess amount of energy seen fed in diet for muskoxen from Copenhagen Zoo, might be causing heath problems, and decreasing the reproduction rates in the muskoxen, as seen in European Zoos. However, there were not found any sign of mineral and vitamin deficiency or excess to inflect reproduction rates. Though there is some uncertainty about if there might be lower nutrient requirements for muskoxen because, the requirements are based on little to no information about the natural forage, and from requirements found in sheep and cattle.

Detecting the deficiencies or toxicities in a non-invasive method is possible through wool samples, and creates a view on the mineral concentrations in and extended period of time Though, this method needs more research.

More directly studies about the muskoxen requirements are needed to give a more exact estimation of the nutrient requirements.

8. Future implications

To see if the excess energy might be a weight problem, there should be kept track of the weight of the muskoxen. This can be done with industrial weight bars under a platform (Hosey et al., 2013). If the weight and therefore, the increased heath production, is causing the low reproduction. The excess energy and protein, could be reduced by cutting down on the high-quality hay with alfalfa, and replacing it with low-quality hay and taking advantage of the muskoxen effective utilization.

If there is a heath increment problem, it might be needed to provide a watering facility for the muskoxen, or transportation of ice, at least during the summer, to cool them down.

A study could be trying to monitor the body temperature in muskoxen, throughout the summer time and fed on diets with different energy density. This could provide information about how much the heath increase is in muskoxen, and if it can have an effect on the reproduction rates. Although there is restrictions about experiments on zoo animals, this could maybe be conducted with the Canadian muskoxen herd from Adamczewski et al., (1994) study.
Because of the lack of information about the requirement for the muskoxen, there are some studies that could be done to provide more information.
Here I could also be interesting to collect faeces and urine because, this could provide information about how much protein in the diet, that is digested, and more information about the exact requirement. This could also maybe be conducted at the Canadian herd.

There could be conducted a study focusing on the natural forage of the muskoxen. This could consist of taking samples of the flora, in North-Northeast Greenland in different seasons and running test on what their nutrient content are. This could be useful for more information about the nutrients available for the muskoxen in the wild and which amounts of them it might be adapted to. This could lead to more exact estimates for the nutrient requirements.
Also more wool samples need to be studied to provide more information about the mineral status and levels from wild muskoxen.
Trying to recreate from Adamczewski et al., (1994) study with more similar muskoxen would be interesting to see if the results are the same or close to each other.

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Appendix

1. Nutrition plan

ZOO COPENHAGEN

DIET

Species: muskox	Antal dyr:

Time of feeding: morning and afternoon	Amount fed pr. 1 animal pr. day

Type of feed	Amount fed	Type of feed	Amount fed
High quality Hay and Alfalfa (lucern)	3 kilograms	Rolled oats	*
Grass (Summer)	3 kilograms	Zoopellets	*
Sliced Raw Carrots (vinter)	1 kilogram		
Sliced Beet Roots (vinter)	250 grams		
Fresh Browse	Ad. Lib.	Mineral mix	Salt lick
Clean water	Ad. Lib.		

Remarks:

*** High quality Oat/Zoopellet mixture: 3 parts rolled oats – 2 parts Zoopellet.**

Bulls: 1,5 kilogram mixture fed pr. animal two times a day

Cows: 1,0 kilogram mixture fed pr. animal two times a day

Young animals: 1,0 kilogram mixture pr. animal twice a day
Preferred browse: Willow and Elm.

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remember to wash all
produces