The distribution of narwhal (*Monodon monoceros*) males, females, and newborns in the Canadian Arctic Archipelago

by

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Abstract

The narwhal (*Monodon monoceros*) is a medium-sized odontocete exclusively found in Arctic waters. The remoteness of their environment in conjunction with their widespread distribution poses numerous challenges to studying this Arctic species at a population level. The narwhal is a species with knowledge gaps regarding their population structure and the distribution of different sexes and age classes. This thesis provides a detailed description of narwhal distribution in the Canadian Arctic Archipelago using the non-invasive method of aerial photography to identify and geo-locate narwhal males, females, and newborns. In August 2013, Fisheries and Oceans Canada (DFO) conducted an extensive aerial survey of narwhal summer habitat to estimate the abundance of the Baffin Bay population. I used the georeferenced photographs collected during the surveys to develop a dichotomous key to identify newborns from photographs. The key was also used to describe the distribution of narwhal males, females, and newborns. I used a Cohen's Kappa test, across four observers, to test the replicability of the key, with strong positive results. Within the 3,393 photographs analyzed I detected 6,315 different individuals. I could identify the sex of 2,804 individuals and identified 141 newborns. To analyze the distribution of narwhals, I first used the least cost path algorithm to construct a matrix of swimming distances between individuals. Then, I performed a partitioning around the medoids algorithm, a variation of the k-means algorithm, to divide my dataset into k clusters based on the swimming distances. I found five main clusters of narwhals that align closely with four narwhal management zones currently defined by DFO. These four management zones correspond to different narwhal stocks determined through local knowledge, telemetry data, and genetics. Narwhals were unevenly distributed between each cluster and I found different male:female sex ratios varying from 0.71 to 1.4, newborns represented 10% of the number of females present in each cluster. This thesis is the first to shed light on narwhal newborn-mother spatial patterns and narwhal sex distribution of the Baffin Bay population in the Canadian Arctic Archipelago.

Résumé

Le narval (*Monodon monoceros*) est un cétacé de taille moyenne vivant exclusivement dans les eaux arctiques. L'éloignement de leur environnement en conjonction avec la large diffusion de leur distribution pose de nombreux défis pour étudier cette espèce arctique au niveau de la population. Il existe peu de connaissance sur la structure de population et la distribution des différentes classes d'âge et sexes des narvals. Dans cette thèse, j'ai utilisé la photographie aérienne comme méthode non-invasive pour étudier la distribution des narvals de manière plus détaillée, en identifiant et localisant les mâles, les femelles et les nouveau-nés à travers l'archipel arctique canadien. En août 2013, Pêches et Océans Canada (MPO) a mené des survols aériens approfondie couvrant l'air de distribution connue des narvals durant l'été afin d'estimer l'abondance de la population de la baie de Baffin. J'ai utilisé les photographies géo-référencées recueillies au cours des survols à partir desquelles j'ai élaboré une clé dichotomique pour identifier les nouveau-nés. J'ai par la suite regardé la distribution des mâles, des femelles et des nouveau-nés. J'ai testé la fiabilité de la clé en effectuant un test Kappa de Cohen entre quatre observateurs. La performance globale de la clé était bonne. En 3393 photographies analysées, j'ai détecté 6315 individus différents, sexé 2804 individus et trouvé 141 nouveau-nés. Pour analyser la distribution des narvals, j'ai d'abord utilisé l'algorithme de cheminement de plus faible coût pour construire une matrice de distances de nage entre les individus. Ensuite, j'ai effectué un partitionnement autour de l'algorithme de medoids, une variante de l'algorithme k-means, pour diviser mes données en k ensembles en fonction des distances de nage. J'ai trouvé cinq groupes principaux en alignement avec les quatre zones de gestion des narvals actuellement définies par le MPO. Ces zones de gestion correspondent à différents stocks de narvals déterminés par la connaissance locale, les données de télémétrie et la génétique. Les narvals ont été répartis

inégalement entre chaque groupe et j'ai trouvé différents ratios hommes:femmes variant de 0,71 à 1,4. Les nouveau-nés correspondaient à environ 10% du nombre de femelles présentes dans chaque groupe. Cette thèse est la première à décrire le comportement spatial des dyades mères-nouveaux-nés narvals ainsi que la distribution des sexes de la population de la Baie de Baffin dans l'Archipel de l’Arctique Canadien.

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Contribution of Authors

This is a manuscript based thesis following McGill guidelines. I am the first author on both Chapters 1 and 2.

M.M. Humphries and M. Marcoux are co-authors on Chapters 1 and 2 and contributed to the overall focus, analysis, and interpretation of both chapters. Jeffrey Cardille and Xavier Giroux-Bougard are additional co-authors on Chapter 2 have contributed to the statistical analysis of data presented in that chapter.

General Introduction and Literature Review

Detailed information on population structure and distribution is important to manage and conserve wild species adequately (Halpern et al., 2004). For example, in population ecology, it is recognized that males, females, young and old individuals play different roles in the well-being of a population and can be used as indicators of population trends (Fowler, 1988; Block and Brennan, 1993). Determining the recruitment rate is an important demographic parameter for any population, however, for long-lived species that have delayed maturity and low reproductive rates, long-term recruitment and survival data is needed to determine population viability. Variation in this parameter has a strong impact on the dynamics of a population and can ultimately indicate the decline or recovery of a species (Jorgenson et al., 1997; Gaillard et al., 1998, 2000). Another important aspect of conservation ecology is to understand the animal-environment relationship in order to assess and predict the impact of disturbances on species. However, to understand this relationship, it is important to understand habitat use and species distributions. Thus, the study of population distribution can be viewed as the first step toward habitat selection, and eventually, understanding general distribution patterns across the landscape (Morris and Brown, 1992; Morris, 2003). Studying animal distribution and population structure is essential, yet it can be difficult to observe migratory animals that occur in large numbers covering vast areas (McPherson and Jetz, 2007; Singh and Milner-Gulland, 2011).

Monitoring a population is a valuable method to provide baseline data in order to track changes over time (Block et al. 2001; Sheil 2001, Nichols and Williams 2006; Lindenmayer and Likens 2010). For species with slow reproductive strategies, long-term data are essential to extend our knowledge on the life history of a population (Thomas 1996; Whitehead, Reeves, and Tyack 2000; Legg and Nagy 2006; Nichols and Williams 2006). Ultimately, the success of long-term monitoring programs depends on the reliability and repeatability of the methods (Thomas, 1996; Block et al., 2001; Sheil, 2001; Lindenmayer and Likens, 2010).

The Eastern Canadian Arctic is composed of many islands, including Baffin Island, that are part of the Arctic Archipelago forming a complex system of fjords and bays. Every summer, thousands of narwhals migrate to different parts of the Eastern Arctic Archipelago and agglomerate in different aggregations (Best and Fisher, 1974; Cosens and Dueck, 1991). Although the general summer distribution of narwhals in the archipelago has been studied (Barber, 1989; Richard, 1991; Kingsley et al., 1994; Koski and Davis, 1994), due to challenges in the field, looking at narwhal sex distribution on this large scale has not been done (Silverman, 1979; Marcoux et al., 2009).

This thesis aims to investigate the use of aerial photography, and proposes a protocol for identifying newborns, to obtain more information on narwhal summer distribution and structure in the Canadian Arctic. The following literature review is divided into three sections, the first of which provides a brief summary of the Arctic marine environment, and the second and third provide a detailed description of narwhal natural history and conservation.

Arctic environment

The Arctic Ocean covers about 14 million km^2 (Johannessen, Environmental, and Center 2002). Sea ice plays an important role in the Arctic ecosystem, driving the primary productivity through polynyas and ice edges. It is a unique habitat for many marine mammals such as polar bears, seals, and narwhals (Stirling 1997; Kovacs et al. 2011). Sea ice cover in the Arctic varies seasonally from approximately 14 to $14.8\text{x}10^6$ km^2 in March, and 6.5 to 7.8x10km^2 in September (Comiso et al. 2008).

The Arctic climate has been warming up over the past decades, changing sea ice dynamics, thickness and coverage (Serreze et al. 2000; Maslanik et al. 2007; Walsh 2008). In 2008, Moore and Huntington predicted that ice-associated species, such as narwhals, will likely change their migration pattern and distribution due to prey availability changes in the future. Those changes in behavior will likely affect narwhal hunting activities of Inuit communities. Laidre and Heide-Jørgensen (2005) predicted a higher risk of narwhal entrapment due to changing Arctic sea ice conditions.

Changes in the Arctic environment allow major industrial development to occur. As an example, located on north Baffin Island, a company named Baffinland Corp. is developing an open pit iron ore mine called the Mary River Project. The company started to ship some of the iron ore in summer 2015. To ship the ore to market, Baffinland Corp. uses a shipping route going through Milne Inlet/Eclipse Sound, a well-known region used by narwhals during the summer. The exploitation of the mine is expected to increase the shipping traffic in the region of Eclipse Sound/Milne Inlet up to 150 voyages per year (Baffinland 2014). This development raises concerns about the impacts of this, and similar projects, on marine mammals and highlights the need for better knowledge, monitoring plans and comprehensive assessment of narwhal populations in the Canadian Arctic (Richard et al. 2010).

Cetacean studies

Cetacean research is known to be difficult due to the marine environment. Additionally, many cetaceans have a wide habitat range with seasonal migration of thousands of kilometers. However, remote technology such as telemetry, acoustic monitoring, and aerial photography are commonly used in marine mammal research to overcome some of these difficulties (Heide-

Jørgensen 2004; Laidre et al. 2004; Marcoux, Auger-Méthé, and Humphries 2012; DFO 2015). The mentioned techniques offer ways to study marine mammals in their environment over long periods and great distances (Mann 2000a). The combination of aerial monitoring with aerial photography has been used for various cetaceans. In recent years, the progress of high definition cameras opens new opportunities for scientists to extract information from aerial photographs that was impossible in the past. This new knowledge makes it easier to fill gaps of understudied species such as the narwhal.

Narwhals

The narwhal (*Monodon Monoceros*) is a medium-size arctic Odontocete (Ford and Fisher 1978). It is the only species of the genus *Monodon* and one of only two members of the family *Monodontidae* with the belugas (*Delphinapterus leucas*) (Rice 1998). The narwhal is recognized to be a gregarious deep-diving cetacean, using echolocation clicks, as well as pulsed calls and whistles to forage, communicate, and maintain group cohesion (Mansfield, Smith, and Beck 1975; Møhl, Surlykke, and Miller 1990; Miller et al. 1995; Marcoux 2009). Adults possess only two pairs of teeth located in the maxilla (Nweeia et al. 2012); one pair is characterized as tusks and the other as vestigial teeth. Their length varies from 2.9m to 5.5m with a body weight of about 1600kg and have a mottled gray pigmentation. Narwhals show a sexual dimorphism. Males are bigger than females and display a tusk that erupts when they are roughly one year old (when they measure between 2.0 and 2.5 m) whereas females are generally tuskless (Mansfield, Smith, and Beck 1975; Best 1981; Roberge and Dunn 1990; Nweeia et al. 2014). Males commonly develop only one tusk that grows through the maxillary bones and skin (Best 1981). However, variation occurs and on rare occasion, we see double tusk males, males with two embedded tusks, males with no tusks, females with one erupting tusk, and females with two erupted tusks (Nweeia et al. 2012).The function of the tusk is not well understood. Silverman and Dunbar (1980) showed that males used their tusk during aggressive interactions between males. The mechanical design of the tusk morphology indicates the organ might have multiple functions such as attracting females and detecting changes in their environment (Brear et al. 1993; Nweeia et al. 2014). In a recent study, the narwhal tusk was believed to play an important role in their ability to navigate underwater covered by densely packed ice (Koblitz et al. 2016). Males reach their sexual maturity at a body length of 420 cm at about 8 years old and females attain their sexual maturity at a body length of 360cm and at 5 years old (Garde et al. 2007; Kelley et al. 2014).

Migration

Narwhals have an annual migratory cycle with distinct wintering and summering-grounds (Dietz et al. 2001; Heide-Jørgensen et al. 2003). Their winter migration pattern is closely related to the formation and movements of the pack ice (Koski and Davis 1994; Laidre and Heide-Jørgensen 2005) where both males and females travel together in herds of hundreds of individuals (Marcoux 2009). During open water season, occurring mainly during the month of August, narwhals stay close to the shore in bays and fjords of the Canadian High Arctic Archipelago and Greenland. They are usually seen in herds of hundreds of individuals containing both sexes and different age classes. Within these herds narwhals form groups of about three individuals segregated by sex (Cosens and Dueck 1991; Marcoux, Auger-Méthé, and Humphries 2009). In autumn they start their migration before the formation of the pack ice towards their wintering grounds, where they will stay from November through April (Innes et al. 2002; Heide-Jørgensen et al. 2003; Laidre et al. 2004; Richard et al. 2010). They slowly migrate back from

May through July to regain their summering-grounds (Dietz et al. 2001; Heide-Jørgensen et al. 2003).

In Canada, the Baffin Bay population uses numerous fjords and bays from northwestern Greenland to central Canadian High Arctic during the summer, whereas the Hudson Bay population uses northern Hudson Bay Fjords. These two populations differ genetically (Koski and Davis 1994; Heide-Jørgensen et al. 2003; COSEWIC 2004; Richard et al. 2010). Narwhals are believed to be philopatric, returning to the same wintering and summering-grounds year after year (Palsboell, Heide-Jørgensen, and Dietz 1997; Heide-Jørgensen et al. 2003). However, recent studies have shown that narwhals might travel between neighboring fjords during the summer and some variation can occur (Heide-Jørgensen et al. 2002; Watt, Heide-Jørgensen, and Ferguson 2013). In 2013 the Department of Fisheries and Oceans conducted an extensive aerial survey to estimate narwhal abundance in four different summering-grounds of Baffin Bay (DFO 2015).

Population and abundance estimate

Narwhals are exclusively found in Arctic waters between 70ºN and 80ºN (Reeves and Tracey 1980; Hay and Mansfield 1989). Based on summer narwhal distribution, three different populations have been recognized worldwide (COSEWIC 2004). One in East Greenland and two in Canada (Baffin Bay population and Hudson Bay population) (Richard 1991; Richard et al. 1994). The Baffin Bay and Hudson Bay populations have been estimated at about 141,909 (Coefficient of Variation, CV by stock ranged from 20 to 65%) and 12,485 narwhals (95% confidence interval 7,515 – 20,743), respectively (DFO 2012, 2015).

Reproduction

Narwhals are seasonal breeders, reproducing during the period of late March through May (Hay 1984). Narwhal gestation is about 14 months with birth occurring from the months of May to August when pregnant females are entering their summering-grounds (Best and Fisher 1974; Mansfield, Smith, and Beck 1975). Females only bear one calf at a time even though twins can happen with a birthing interval of about 3 years. At birth, newborns are about 150cm long and weight about 80kg (Mansfield, Smith, and Beck 1975; Heide-Jørgensen et al. 2001). Parturition time is estimated at 20 months (Best and Fisher 1974). Narwhals are long-lived species. Life expectancy is estimated at about 100 years old (Garde et al. 2007, 2015).

Feeding behavior

Narwhals are able to dive to depths of over 1,400 m in order to forage (Laidre et al. 2003; Laidre 2004; Watt et al. 2015). Studies based on stomach contents have shown that narwhals have a specialized diet. They mostly eat squid (*Gonatus fabricii*), Greenland halibut during the winter, and polar cod (*Arctogadus glacialis*) and arctic cod (*Boreogadus saida*) during the spring (Laidre and Heide-Jørgensen 2005; Watt, Heide-Jørgensen, and Ferguson 2013). However, a recent study conducted by Watt, Orr, and Ferguson (2016) have shown feeding activities during the summer. Very little is known on their primary prey during the summer.

Community Importance

The narwhal is a valuable food resource and has social and cultural importance for Inuit communities (Wirz-Held 2012). Narwhal hunting activity is an important part of Inuit cultural identity who believe humans and animals are connected in a cosmic cycle maintained by hunting (Laugrand and Oosten 2010). Traditionally, Inuit hunted narwhals with harpoons from kayaks made of seal skin. Nowadays, they are mostly hunted with a rifle from shore or ice floe edge, then harpooned and retrieved by motor boats.

The muqtaq (skin blubber) is an important and valued food item shared among northern community members. Narwhal meat is not eaten by humans but was traditionally used to feed sled dogs. However, it is rarely used nowadays due to snowmobiles replacing dog teams for transportation. The tusks are used to make tools or carved art that can be traded for food, money or other goods (Wirz-Held 2012).

Status and management

In Canada, narwhal hunting activities, and narwhal product trade has been regulated since 1971. A system of quotas was established first at the individual hunter level (from 1971 to 1977), then at a community level (from 1977 to 1999) under the Narwhal Protection Regulations (Reeves 1992; Richard and Pike 1993). In 1999, five Canadian Inuit communities (Arctic Bay, Qikiqtarjuaq Broughton Island, Pond Inlet, Repulse Bay, and Kugaaruk Pelly Bay) started a community-based management program developed with Nunavut Wildlife Management Board (NWMB). This program enables more flexibility with the use and repartition of the quotas inside a community (Armitage 2005).

Starting in 2004, the narwhal has been considered by both the Committee on the Status of Endangered Wildlife in Canada, and the International Union for Conservation, as Near Threatened and of Special Concern, respectively (Jefferson et al. 2009). The reasoning behind these classifications is the lack of knowledge of this species linked to the rapid changes of its habitat due to climate change and anthropogenic development (COSEWIC 2004).

In Canada, the management of narwhals has been managed by co-partners since the ratification of the Nunavut Land Claim Agreement in 1993. Management is split between the

Nunavut Wildlife Management Board (NWMB), the Department of Fisheries and Ocean (DFO), and the local and regional hunters associations (Wirz-Held 2012). The role of DFO is to provide information on narwhal population and advising the NWMB on sustainable harvest quotas (Richard and Pike 1993). The NWMB has a role of regulator, monitoring the harvest level with the help of the Hunter and Trappers Organization (HTO) of each community. Then, the NWMB reports the total number of hunted narwhals to DFO (Wirz-Held 2012).

At an international level, the narwhal is listed in Appendix II of the Convention on International Trade in Endangered Species (CITES), thus is regulated under the trade rules and conditions of CITES (Jefferson et al. 2009). To date, the narwhal is still being reviewed to be under the federal Species at Risk Act (SARA) (Government of Canada 2011).

Aerial photography

Aerial photography has been used in many fields to study habitat characterization, plant distribution, and wildlife. In population ecology, aerial photography offers a non-invasive method to collect data on the structure, distribution, abundance estimates, movements and behavior of a population (Udevitz, Burn, and Webber 2008). Until recently, the use of aerial photographs was limited due to the low number of photographs taken on a film, limiting the area covered with the photographs (Morgan, Gergel, and Coops 2010). The arrival of digital photography changed the research landscape. It offered new ways to study hard to observe species enabling scientists to take a high number of photographs over a large area to detect the presence or absence of a species (Claridge et al. 2005). However, researchers are now faced with the challenges to analyze these large number of photographs (Wulder 1998).

In cetacean research, photography has been widely used to study aspects of population structure, distribution and habitat (Cubbage and Calambokidis 1987; Best and Rüther 1992; Mills, Newton, and Graham 1996b; Heide-Jørgensen 2004; Udevitz, Burn, and Webber 2008). Specifically for narwhals, photography has been used to investigate the feasibility to photo-identify individuals (Auger-Méthé, Marcoux, and Whitehead 2010) and aerial photography has been used to calculate the estimated abundance (Richard 1991; Heide-Jørgensen 2004).

Rationale and objectives

The objectives of this thesis are to use georeferenced aerial photographs and new analytical methods to identify narwhal newborns (Chapter 1) and to describe narwhal population structure and summer distribution in the Canadian Arctic Archipelago (Chapter 2).

In Chapter 1, I present a new standardized method to identify newborns from aerial photographs. To determine if this method is effective and potentially useful for long-term studies, the results were compared between one expert observer and several inexperienced observers. I also describe the spatial position and size of newborns relative to their mothers.

In Chapter 2, I describe the spatial distribution of narwhal males, females and newborns across the Canadian Arctic Archipelago by grouping individuals into clusters based on the swimming distance separating them.

Literature cited

Armitage, D. R. 2005. Community-based narwhal management in Nunavut, Canada: change, uncertainty, and adaptation. Society and Natural Resources, 18(8):715–731.

Auger-Méthé, M., M. Marcoux, and H. Whitehead. 2010. Nicks and notches of the dorsal ridge: Promising mark types for the photo-identification of narwhals. Marine Mammal Science, 26(3):663–678, https://doi.org/10.1111/j.1748-7692.2009.00369.x.

Baffinland. 2014. Mary River Project Phase 2, Second Amendment to Project Certificate No 005. pp.

Barber, D. G. 1989. Narwhal distribution relative to thermal sea surface temperature boundaries.

Best, P. B., and H. Rüther. 1992. Aerial photogrammetry of southern right whales, Eubalaena australis. Journal of Zoology, 228(4):595–614.

Best, R. C. 1981. The tusk of the narwhal (Monodon monoceros L.): interpretation of its function (Mammalia: Cetacea). Canadian Journal of Zoology, 59(12):2386–2393.

Best, R. C., and H. D. Fisher. 1974. Seasonal breeding of the narwhal (Monodon monoceros L.). Canadian Journal of Zoology, 52(3):429–431.

Block, W. M., and L. A. Brennan. 1993. The habitat concept in ornithology; Pp. 35–91. In Current ornithology. Springer.

Block, W. M., A. B. Franklin, J. P. Ward, J. L. Ganey, and G. C. White. 2001. Design and Implementation of Monitoring Studies to Evaluate the Success of Ecological Restoration on Wildlife. Restoration Ecology, 9(3):293–303, https://doi.org/10.1046/j.1526-100x.2001.009003293.x.

Brear, K., J. D. Currey, M. C. S. Kingsley, and M. Ramsay. 1993. The mechanical design of the tusk of the narwhal (Monodon monoceros). Journal of Zoology, 230(3):411–423, https://doi.org/10.1111/j.1469-7998.1993.tb02693.x.

Claridge, A. W., G. Mifsud, J. Dawson, and M. J. Saxon. 2005. Use of infrared digital cameras to investigate the behavior of cryptic species. Wildlife Research, 31(6):645–650.

Comiso, J. C., C. L. Parkinson, R. Gersten, and L. Stock. 2008. Accelerated decline in the Arctic sea ice cover. Geophysical Research Letters, 35(1): L01703, https://doi.org/10.1029/2007GL031972.

Cosens, S. E., and L. P. Dueck. 1991. Group size and activity patterns of belugas (Delphinapterus leucas) and narwhals (Monodon monoceros) during spring migration in Lancaster Sound. Canadian Journal of Zoology, 69(6):1630–1635, https://doi.org/10.1139/z91-227.

COSEWIC. 2004. COSEWIC assessment and update status report on the narwhal Monodon monoceros in Canada. p. 50. Ottawa: Committee on the Status of Endangered Wildlife in Canada.

Cubbage, J. C., and J. Calambokidis. 1987. Size-class segregation of bowhead whales discerned through aerial stereophotogrammetry. Marine Mammal Science, 3(2):179–185.

DFO. 2012. Abundance and total allowable landed catch for the Northern Hudson Bay narwhal population. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep., (2012/028.).

DFO. 2015. Abundance estimates of narwhal stocks in the Canadian High Arctic in 2013. DFO Can. Sci. Advis. Sec. Res., (Doc. 2015/060. v):36 p.

Dietz, R., M. P. Heide-Jørgensen, P. R. Richard, and M. Acquarone. 2001. Summer and Fall Movements of Narwhals (Monodon monoceros) from Northeastern Baffin Island Towards Northern Davis Strait. Arctic, 54(3):244–261.

Ford, J. K., and H. D. Fisher. 1978. Underwater acoustic signals of the narwhal (Monodon monoceros). Canadian Journal of Zoology, 56(4):552–560.

Fowler, C. W. 1988. Population dynamics as related to rate of increase per generation. Evolutionary Ecology, 2(3):197–204, https://doi.org/10.1007/BF02214283.

Gaillard, J.-M., M. Festa-Bianchet, and N. G. Yoccoz. 1998. Population dynamics of large herbivores: variable recruitment with constant adult survival. Trends in Ecology & Evolution, 13(2):58–63, https://doi.org/10.1016/S0169-5347(97)01237-8.

Gaillard, J.-M., M. Festa-Bianchet, N. G. Yoccoz, A. Loison, and C. Toigo. 2000. Temporal variation in fitness components and population dynamics of large herbivores. Annual Review of Ecology and Systematics, 31(1):367–393.

Garde, E., M. P. Heide-Jørgensen, S. H. Hansen, G. Nachman, and M. C. Forchhammer. 2007. Age-specific growth and remarkable longevity in narwhals (Monodon monoceros) from West Greenland as estimated by aspartic acid racemization. Journal of Mammalogy, 88(1):49–58.

Garde, E., S. H. Hansen, S. Ditlevsen, K. B. Tvermosegaard, J. Hansen, K. C. Harding, and M. P. Heide-Jørgensen. 2015. Life history parameters of narwhals (Monodon monoceros) from Greenland. Journal of Mammalogy, 96(4):866–879, https://doi.org/10.1093/jmammal/gyv110.

Government of Canada, E. C. 2011. Species at Risk Public Registry - Home - SARA. Retrieved May 29, 2017. https://www.registrelep-sararegistry.gc.ca/default.asp?lang=en&n=24F7211B-1.

Halpern, B. S., S. D. Gaines, and R. R. Warner. 2004. Habitat size, recruitment, and longevity as factors limiting population size in stage-structured species. The American Naturalist, 165(1):82–94.

Hay, K. A. 1985. The life history of the narwhal, Monodon monoceros, in the eastern Canadian arctic. p.

Hay, K. A., and A. W. Mansfield. 1989. Narwhal, Monodon monoceros, Linnaeus, 1758. Handbook of Marine Mammals, 4:145–176.

Heide-Jørgensen, M., R. Dietz, K. Laidre, and P. Richard. 2002. Autumn movements, home ranges, and winter density of narwhals (Monodon monoceros) tagged in Tremblay Sound, Baffin Island. Polar Biology, 25(5):331–341.

Heide-Jørgensen, M. P. 2004. Aerial Digital Photographic Surveys of Narwhals, Monodon Monoceros, in Northwest Greenland. Marine Mammal Science, 20(2):246–261, https://doi.org/10.1111/j.1748-7692.2004.tb01154.x.

Heide-Jørgensen, M. P., N. Hammeken, R. Dietz, J. Orr, and P. R. Richard. 2001. Surfacing Times and Dive Rates for Narwhals (Monodon monoceros) and Belugas (Delphinapterus leucas). Arctic, 284–298.

Heide-Jørgensen, M. P., R. Dietz, K. L. Laidre, P. Richard, J. Orr, and H. C. Schmidt. 2003. The migratory behavior of narwhals (Monodon monoceros). Canadian Journal of Zoology, 81(8):1298–1305.

Innes, S., M. P. Heide-Jørgensen, J. L. Laake, K. L. Laidre, H. J. Cleator, P. Richard, and R. E. Stewart. 2002. Surveys of belugas and narwhals in the Canadian High Arctic in 1996. NAMMCO Scientific Publications, 4:169–190.

Jefferson, T. A., L. Karczmarski, K. Laidre, G. O'Corry-Crowe, R. R. Reeves, L. Rojas-Bracho, E. R. Secchi, E. Slooten, B. D. Smith, J. Y. Wang, and others. 2009. Monodon monoceros. 2008 IUCN Red List of Threatened Species. pp.

Johannessen, O. M., N. Environmental, and R. S. Center. 2002. Arctic Climate Change: Observed and Modeled Temperature and Sea Ice Variability. Nansen Environmental and Remote Sensing Center Bergen, pp.

Jorgenson, J. T., M. Festa-Bianchet, J.-M. Gaillard, and W. D. Wishart. 1997. Effects of age, sex, disease, and density on survival of bighorn sheep. Ecology, 78(4):1019–1032.

Kelley, T. C., R. E. A. Stewart, D. J. Yurkowski, A. Ryan, and S. H. Ferguson. 2014. Mating ecology of beluga (Delphinapterus leucas) and narwhal (Monodon monoceros) as estimated by reproductive tract metrics. Marine Mammal Science, n/a-n/a, https://doi.org/10.1111/mms.12165.

Kingsley, M. C., H. J. Cleator, and M. A. Ramsay. 1994. Summer distribution and movements of narwhals (Monodon monoceros) in Eclipse Sound and adjacent waters, North Baffin Island, NWT. Meddelelser Om Grønland. Bioscience, 39:163–174.

Koblitz, J. C., P. Stilz, M. H. Rasmussen, and K. L. Laidre. 2016. Highly Directional Sonar Beam of Narwhals (Monodon monoceros) Measured with a Vertical 16 Hydrophone Array. PLOS ONE, 11(11):e0162069, https://doi.org/10.1371/journal.pone.0162069.

Koski, W. R., and R. A. Davis. 1994a. Distribution and numbers of narwhals (Monodon. Studies of White Whales (Delphinapterus Leucas) and Narwhals (Monodon Monoceros) in Greenland and Adjacent Waters, 15.

Koski, W. R., and R. A. Davis. 1994b. Distribution and numbers of narwhals (Monodon monoceros) in Baffin Bay and Davis Strait. Meddelelser Om Grønland. Bioscience, 39:15–40.

Kovacs, K. M., C. Lydersen, J. E. Overland, and S. E. Moore. 2011. Impacts of changing sea-ice conditions on Arctic marine mammals. Marine Biodiversity, 41(1):181–194.

Laidre, K. 2004. Deep-ocean predation by a high Arctic cetacean. ICES Journal of Marine Science, 61(3):430–440, https://doi.org/10.1016/j.icesjms.2004.02.002.

Laidre, K. L., and M. P. Heide-Jørgensen. 2005. Arctic sea ice trends and narwhal vulnerability. Biological Conservation, 121(4):509–517.

Laidre, K. L., M. P. Heide-Jørgensen, R. Dietz, R. C. Hobbs, and O. A. Jørgensen. 2003. Deep-diving by narwhals Monodon monoceros: differences in foraging behavior between wintering areas? Marine Ecology-Progress Series, 261:269–281.

Laidre, K. L., M. P. Heide-Jørgensen, M. L. Logdson, R. C. Hobbs, P. Heagerty, R. Dietz, O. A. Jørgensen, and M. A. Treble. 2004. Seasonal narwhal habitat associations in the high Arctic. Marine Biology, 145(4):821–831.

Laugrand, F., and J. Oosten. 2010. The religion of nature: Evangelical perspectives on the environment. Études/Inuit/Studies, 71–90.

Legg, C. J., and L. Nagy. 2006. Why most conservation monitoring is, but need not be, a waste of time. Journal of Environmental Management, 78(2):194–199, https://doi.org/10.1016/j.jenvman.2005.04.016.

Lindenmayer, D. B., and G. E. Likens. 2010. The science and application of ecological monitoring. Biological Conservation, 143(6):1317–1328.

M McPherson, J., and W. Jetz. 2007. Effects of species' ecology on the accuracy of distribution models. Ecography, 30(1):135–151.

Mann, J. 2000. Cetacean Societies: Field Studies of Dolphins and Whales. University of Chicago Press, pp.

Mansfield, A. W., T. G. Smith, and B. Beck. 1975. The Narwhal, Monodon monoceros, in Eastern Canadian Waters. Journal of the Fisheries Research Board of Canada, 32(7):1041–1046, https://doi.org/10.1139/f75-122.

Marcoux, M. 2009. Social Behaviour, Vocalization and Conservation of Narwhals. ARCTIC, 61(4):456–460, https://doi.org/10.14430/arctic90.

Marcoux, M., M. Auger-Méthé, and M. M. Humphries. 2009. Encounter frequencies and grouping patterns of narwhals in Koluktoo Bay, Baffin Island. Polar Biology, 32(12):1705–1716.

Marcoux, M., M. Auger-Méthé, and M. M. Humphries. 2012. Variability and context specificity of narwhal (Monodon monoceros) whistles and pulsed calls. Marine Mammal Science, 28(4):649–665, https://doi.org/10.1111/j.1748-7692.2011.00514.x.

Maslanik, J. A., C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D. Yi, and W. Emery. 2007. A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss. Geophysical Research Letters, 34(24).

Miller, L. A., J. Pristed, B. Mohl, and A. Surlykke. 1995. The click-sounds o narwhals (Monodon monocerod) in Inglefield Bay, northwest Greenland. Marine Mammal Science, 11(4):491–502.

Mills, J. P., I. Newton, and R. W. Graham. 1996. Aerial Photography for Survey Purposes with a High Resolution, Small Format, Digital Camera. The Photogrammetric Record, 15(88):575–587, https://doi.org/10.1111/0031-868X.00065.

Møhl, B., A. Surlykke, and L. A. Miller. 1990. High intensity narwhal clicks; Pp. 295–303. In Sensory abilities of cetaceans. Springer.

Moore, S. E., and H. P. Huntington. 2008. Arctic marine mammals and climate change: impacts and resilience. Ecological Applications, 18(sp2): S157–S165.

Morgan, J. L., S. E. Gergel, and N. C. Coops. 2010. Aerial photography: a rapidly evolving tool for ecological management. BioScience, 60(1):47–59.

Morris, D. W. 2003. Toward an ecological synthesis: a case for habitat selection. Oecologia, 136(1):1–13.

Morris, D. W., and J. S. Brown. 1992. The role of habitat selection in landscape ecology. Evolutionary Ecology, 6(5):357–359.

Nichols, J. D., and B. K. Williams. 2006. Monitoring for conservation. Trends in Ecology & Evolution, 21(12):668–673, https://doi.org/10.1016/j.tree.2006.08.007.

Nweeia, M. T., F. C. Eichmiller, P. V. Hauschka, E. Tyler, J. G. Mead, C. W. Potter, D. P. Angnatsiak, P. R. Richard, J. R. Orr, and S. R. Black. 2012. Vestigial Tooth Anatomy and Tusk Nomenclature for Monodon monoceros. The Anatomical Record: Advances in Integrative Anatomy and Evolutionary Biology, 295(6):1006–1016, https://doi.org/10.1002/ar.22449.

Nweeia, M. T., F. C. Eichmiller, P. V. Hauschka, G. A. Donahue, J. R. Orr, S. H. Ferguson, C. A. Watt, J. G. Mead, C. W. Potter, R. Dietz, A. A. Giuseppetti, S. R. Black, A. J.

Trachtenberg, and W. P. Kuo. 2014. Sensory ability in the narwhal tooth organ system. The Anatomical Record, 297(4):599–617, https://doi.org/10.1002/ar.22886.

Palsboell, P. J., M. P. Heide-Jørgensen, and R. Dietz. 1997. Population structure and seasonal movements of narwhals, Monodon monoceros, determined from mtDNA analysis. Heredity, 78(3):284–292.

Reeves, R. R. 1992. Recent Developments in the Commerce in Narwhal Ivory from the Canadian Arctic. Arctic and Alpine Research, 24(2):179–187, https://doi.org/10.2307/1551538.

Reeves, R. R., and S. Tracey. 1980. Monodon monoceros. American Society of Mammalogists.

Rice, D. W. 1998. Marine Mammals of the World: Systematics and Distribution. Society for Marine Mammalogy, pp.

Richard, P., and P. Weaver. 1994. Distribution and numbers of Canadian High Arctic narwhals (Monodon monoceros) in August 1984. Meddelelser Om Grønland, Bioscience, 39.

Richard, P. R. 1991. Abundance and distribution of narwhals (Monodon monoceros) in northern Hudson Bay. Canadian Journal of Fisheries and Aquatic Sciences, 48(2):276–283.

Richard, P. R., and D. G. Pike. 1993. Small whale co-management in the eastern Canadian Arctic: A case history and analysis. Arctic, 138–143.

Richard, P. R., J. L. Laake, R. C. Hobbs, M. P. Heide-Jørgensen, N. C. Asselin, and H. Cleator. 2010. Baffin Bay Narwhal Population Distribution and Numbers: Aerial Surveys in the Canadian High Arctic, 2002-04. Arctic, 63(1):85–99.

Roberge, M. M., and J. B. Dunn. 1990. Assessment of the Subsistence Harvest and Biology of Narwhal Monodon Monoceros L. from Admiralty Inlet, Baffin Island, NWT, 1983 and 1986-89. Department of Fisheries and Oceans, Central and Arctic Region, pp.

Serreze, M. C., J. E. Walsh, F. S. Chapin Iii, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W. C. Oechel, J. Morison, T. Zhang, and R. G. Barry. 2000. Observational evidence of recent change in the northern high-latitude environment. Climatic Change, 46(1–2):159–207.

Sheil, D. 2001. Conservation and Biodiversity Monitoring in the Tropics: Realities, Priorities, and Distractions. Conservation Biology, 15(4):1179–1182, https://doi.org/10.1046/j.1523-1739.2001.0150041179.x.

Silverman, H. B. 1979. Social organization and behavior of the narwhal: Monodon monoceros L. in Lancaster Sound, Pond Inlet, and Tremblay Sound, Northwest Territories. p.

Silverman, H. B., and M. J. Dunbar. 1980. Aggressive tusk use by the narwhal (Monodon monoceros L.). Nature, 284(5751):57–58.

Singh, N. J., and E. J. Milner-Gulland. 2011. Conserving a moving target: planning protection for a migratory species as its distribution changes. Journal of Applied Ecology, 48(1):35–46.

Stirling, I. 1997. The importance of polynyas, ice edges, and leads to marine mammals and birds. Journal of Marine Systems, 10(1):9–21.

Thomas, L. 1996. Monitoring Long-Term Population Change: Why are there so Many Analysis Methods? Ecology, 77(1):49–58.

Udevitz, M. S., D. M. Burn, and M. A. Webber. 2008. Estimation of walrus populations on sea ice with infrared imagery and aerial photography. Marine Mammal Science, 24(1):57–70.

Walsh, J. E. 2008. Climate of the arctic marine environment. Ecological Applications, 18(sp2): S3–S22, https://doi.org/10.1890/06-0503.1.

Watt, C. A., M. P. Heide-Jørgensen, and S. H. Ferguson. 2013. How adaptable are narwhal? A comparison of foraging patterns among the world's three narwhal populations. Ecosphere, 4(6): art71,

Watt, C. A., J. R. Orr, and S. H. Ferguson. 2016. Spatial distribution of narwhal (Monodon monoceros) diving for Canadian populations helps identify important seasonal foraging areas. Canadian Journal of Zoology, 95(1):41–50, https://doi.org/10.1139/cjz-2016-0178.

Watt, C. A., J. R. Orr, M. P. Heide-Jørgensen, N. H. Nielsen, and S. H. Ferguson. 2015. Differences in dive behavior among the world's three narwhal Monodon monoceros populations correspond with dietary differences. MEPS, 525:273–285.

Weingarth, K., C. Heibl, F. Knauer, F. Zimmermann, L. Bufka, and M. Heurich. 2012. First estimation of Eurasian lynx (Lynx lynx) abundance and density using digital cameras and capture–recapture techniques in a German national park. Animal Biodiversity and Conservation, 35(2):197–207.

Whitehead, H., R. R. Reeves, and P. L. Tyack. 2000. Science and the conservation, protection, and management of wild cetaceans. Cetacean Societies: Field Studies of Dolphins and Whales, 12:308–332.

Wirz-Held, M. B. E. 2012. Narwhal co-management in Nunavut: Deepened collaboration needed to improve partnership, process and outcome. University of Dalhousie, Halifax, 100 p.

Wulder, M. 1998. Optical remote-sensing techniques for the assessment of forest inventory and biophysical parameters. Progress in Physical Geography, 22(4):449–476.

Chapter 1: Aerial photographic identification of narwhal (*Monodon monoceros*) newborns and their spatial proximity to the nearest adult female

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1.1 Abstract

Population and species management of long-lived species such as narwhal (*Monodon monoceros*) require long-term ecological monitoring programs to provide baseline information on population structure and dynamics. The success of such programs is dependent on the repeatability of the methods. Here, I propose a dichotomous key to identify narwhal newborns from aerial photography based on cetacean mother-newborn dyads behaviors and narwhal newborn physical description. The key was tested between three inexperienced observers and an expert observer. The Cohen Kappa algorithm proved that this method yields fair to good interobserver agreement, leading us to believe this method will be useful for long-term studies where observers change over time. This study gives some insight into narwhal-newborn spatial relationships, showing a predominant number of newborns located in the infant and echelon positions.

1.2 Introduction

Population monitoring is an important tool in population ecology, conservation and management (Thomas 1996; Magurran et al. 2010) because it provides valuable baseline data on populations and allows researchers to assess population responses to anthropogenic influences, management measures, and natural disturbances (Block et al. 2001; Sheil 2001, Nichols and Williams 2006; Lindenmayer and Likens 2010). For long-lived species with slow reproductive strategies, such as cetaceans, long-term population monitoring programs are essential to extend our knowledge and develop successful management and conservation plans (Thomas 1996; Whitehead et al. 2000; Legg and Nagy 2006; Nichols and Williams 2006). However, the success of a long-term monitoring plan depends on repeatable methods and comparable results throughout time (Cassey and Blackburn 2006; Legg and Nagy 2006). Research of deep diving cetaceans is known to be extremely challenging, due to their cryptic behavior (spending up to 90% of their time underwater) and their wide range of habitats (Mann 2000a). Thus, it is not surprising that gaps of knowledge exist for many cetaceans, limiting the success of conservation and management efforts (Taylor et al. 2007). Effective and replicable protocols, that are detailed enough to ensure the repeatability by a third party or inexperienced observer (Cassey and Blackburn 2006; Legg and Nagy 2006), will make long-term monitoring of these difficult to study animals easier, and provide more and better quality population and demographic data.

Aerial photography can be used to assess abundance, population viability, and age structure of cetacean populations (Thompson and Hammond 1992; Ratnaswamy and Winn 1993; Pettis et al. 2004). With improved camera technology, scientists can adapt visual aerial survey protocols to incorporate high definition cameras that can collect continuous, georeferenced photographs along survey transects (Mills and al. 1996). Photographs can then be analyzed to assess age class, group size, and group composition, yielding more detailed information on cetacean species (Cubbage and Calambokidis 1987; Rugh 1990; Best and Rüther 1992; Heide-Jørgensen 2004).

Narwhals (*Monodon monoceros*) live in Arctic waters year-round (Dietz et al. 2001), making them one of the most challenging whales to study. Their conservation status has been categorized as Near Threatened and of Special Concern by, respectively, the Committee on the Status of Endangered Wildlife in Canada, and the International Union for Conservation of Nature (COSEWIC 2004; Jefferson et al. 2009), mainly due to the lack of knowledge on this species and the difficulty of assessing the impacts of different threats on narwhal populations (COSEWIC 2004; Jefferson et al. 2009; Richard et al. 2010). Many studies on narwhals have used aerial surveys to assess their distribution and population size (Kingsley 1989; Koski and Davis 1994; Heide-Jørgensen 2004; Richard et al. 2010). Therefore, developing a repeatable method to quantify the information in aerial photographs would greatly benefit difficult to study species such as the narwhal. The ability to score, identify and classify the same individuals by different observers is an important part of long-term cetacean studies that can lead to a better understanding of these species.

Here, I propose using high definition aerial photographs paired with a dichotomous key to identify narwhal newborns. I targeted narwhal newborns in my research because newborn survival is an important parameter to assess population viability in the wild (Smith et al. 2016). Dichotomous keys are a common tool allowing inexperienced observers to identify species or individuals based on specific criteria (Walter and Winterton 2007). Whale researchers rarely assess their protocols to determine if they can be repeatable by inexperienced observers (Mann 2000b). My study presents a systematic and repeatable method to detect narwhal newborns from aerial photography, document their spatial position and grouping pattern. This method can be used by different observers over time, and facilitates studying the age structure and social spacing of narwhal populations, so that better management tools can be developed.

1.3 Method

1.3.1 Study area and data collection

In August 2013, Fisheries and Oceans Canada (DFO) conducted an extensive aerial survey known as the High Arctic Cetacean Survey (Doniol-Valcroze et al 2015). This survey aimed to estimate the abundance of narwhals in the Baffin Bay population, as well as the bowhead whale population in Eastern Canada-West Greenland covering the following Arctic regions: Eclipse Sound, Admiralty Inlet, Somerset Island, East Baffin, Jones Sound, and Smith Sound (Figure 1.1) (Doniol-Valcroze et al 2015). Survey dates were set based on Inuit traditional knowledge as well as narwhal and bowhead telemetry data (Dietz et al. 2001; Dueck et al. 2006; Dietz et al. 2008; Watt et al. 2012; Wheeler et al. 2012). The survey was designed as a double-platform using four visual observers, two at the front and two at the rear of a twin-engine Havilland Twin Otter 300 plane. The plane flew at an altitude of about 1000 feet (304.8 meters) with a speed of 100 knots (185km/h) following pre-determined transect lines. The coverage effort of the six-summer aggregation varied between 4 to 14%. Two Nikon D-800 cameras with 35mm lens were mounted on each side of the plane at an angle of 27 degrees. Cameras were set up to take photos every three seconds resulting in a 20% overlap between two consecutive photographs. Each photo taken had the long side perpendicular to the transect (orientation 'width-wise') and the width of each photo taken was 420 m (with a strip width of 840 m), and was georeferenced using a linked GPS. Narwhals were also visually detected by observers in the survey plane, allowing identification of photographs likely to include narwhals. After the survey, all photos that included narwhals were projected in ArcGIS (version 10.1). The photos should be trapezoid but for the need of this study, they were projected as rectangles. I then built a database including group size, sex and class age of narwhals, when possible, and removed any duplicates found between the overlap of two consecutive photographs. Newborn identification was performed by one expert observer using the dichotomous key developed in this study.

1.3.2 Dichotomous key

The aim of this study was to identify new individuals of the year, here referred to as newborns. Most narwhals are born between May and August of each year (mostly between mid-July and mid-August) (Cosens and Dueck 1990). The photographs were taken in August; therefore, for this study, I defined newborns as narwhals between 0-3 months of age. The use of the dichotomous key was only performed on whales at the surface, given the difficulty of assessing the full body length and color of whales underwater. The closest adult female to newborns was likely to be their mother (Cosens and Dueck 1990), but because I have no direct information about their relatedness, I refer to these whales only as the closest adult female and the pairs as newborn-female dyads.

Based on other cetacean mother-newborn dyads dominant behaviors, physical descriptions, and knowledge of belugas (narwhal's closest related species), I used the following four characteristics observable from the aerial photographs to build a dichotomous key to identify newborns: (1) the size of the newborn relative to the closest adult female, (2) the distance from this female, and (3) its position relative to this female (Figure 1.2).

(1) Newborn size: At birth, narwhal newborns measure between 140 to 170cm representing about 1/3 of the size of an adult female (Mansfield and al. 1975; Cosens and Dueck

1990). It has also been discovered that beluga newborns *(Delphinapterus leucas)* grow at a rapid pace potentially being close to half the body size of an adult female after three months (Krasnova and al. 2009). Therefore, I limited the size of a potential newborn at half the length of an adult female (Best and Fisher 1974; Mansfield and al. 1975; Hay and Mansfield 1989; Kingsley 1989).

(2) Distance from the mother: Most beluga and bottlenose dolphins (*Tursiops sp.*) calves remain very close to their mother during the first few weeks after birth (Mann 2000a). In this study, I used a distance of less than two body lengths away, or approximately 10m, as the criteria to identify newborns (Krasnova et al. 2006).

(3) Newborn/female spatial position: Newborn whale and its mother form a strong dyad with different formation locomotion (Reid et al. 1995; Gubbins et al. 1999; Mann and Smut 1999; Krasnova et al. 2006; Noren et al. 2006). Due to newborns' lack of physical and physiological maturity to support swimming and diving (Noren and Edwards 2007; Noren 2008), newborns are likely to improve their hydrodynamics by being parallel and in close proximity of their mother's flank when swimming (McBride and Kritzler 1951; Mann and Smut 1999;Noren and Edwards 2007; Noren et al. 2008; Noren and Edwards 2011). However, newborns are often positioned differently when not actively swimming, including above the mother, on top of the mother, below the mother, closer to the tail, or behind the mother (Krasnova et al. 2006). Given belugas and narwhals are congeners, I expected newborn narwhals to occupy a similar range of positions. In the dichotomous key, I described the position as at female's side, at female's tail, above the female, on top of the female, and behind the female (Figure 1.2). My exclusion of newborns not at the surface precluded classification of newborns below the mother.

1.3.3 Test of the dichotomous key

To assess the quality of the results and repeatability of the key, three inexperienced observers and one expert observer analyzed 40 photographs containing a total of 958 narwhals, taken in Admiralty Inlet and Eclipse Sound (two well-known area used by narwhals during the summer, located on north Baffin Island, Nunavut). To determinate the level of agreement among observers, I calculated Cohen's kappa coefficient for each observer pair to account for the degree of agreement due to chance (Cohen 1968; Haley and Osberg 1989; Viera and Garrett 2005). The Kappa coefficient varies between -1 and 1, with -1 representing total disagreement between observers, 0 reflecting agreement by chance and 1 representing total agreement (Cohen 1968; Sim and Wright 2005). I interpreted Kappa coefficients according to guidelines suggested by Landis and Koch 1977, with values of 0.00-0.40, 0.41-0.60, 0.61-0.80, and 0.81-1.0 considered to be, respectively, poor, fair, good, and excellent agreement.

1.3.4 Group composition

In this study, only groups with newborns were analyzed. The composition of each group was established following these assumptions:

1) All individuals within 10 adult narwhal body widths or 3 adult body lengths were part of the same group (Mann 2000; Marcoux and al. 2009).
2) A narwhal was considered an adult if not detected as a newborn.
3) An individual was recognized as female if no tusk was present (Mansfield et al. 1975; Best 1981).
4) Individuals with a tusk were considered males (Koski and Davis 1994).
5) Individuals for which the sex could not be identified were classified as unknown sex (thereafter referred as unknown).

1.3.5 Analysis

Once the key was assessed, the expert observer analyzed all the photographs. Using the non-parametric Kruskal Wallis Test, I compared group size and group composition using the statistical software R (RDevelopment 2011).

To examine a newborn's position in relation to the nearest adult female (their presumed mother), I divided the body of the female into ten equal percentiles and defined the position of the newborn in relation to the female with this scale. The head of the adult female was defined by the value zero, and -100 corresponded to the fluke of the mother. Newborns in front of the female were assigned a positive number and those positioned behind her fluke were assigned a number smaller than -100 (Figure 1.4).

1.4 Results

1.4.1 Inter-observer reliability

The three inexperienced observers achieved a high agreement percentage with the experienced observer of 85.2%, 85.2%, and 88.5% respectively; and across all three observers, Cohen's Kappa coefficients indicated fair to good agreement with the expert observer (Figure 1.3). In 17% of cases where there was disagreement with the expert observer, there were 11 false positives (whale identified as a newborn by the inexperienced observer but not experienced observed) and 17 false negatives (inexperienced observer did not identify a newborn that was observed by the experienced observer). All false negatives involved newborns close to the half size threshold. Most false positives also involved whales close to the half size threshold. However, on one occasion a false positive was due to an identification of a whale under the surface and two other false positives were attributed to whales that were diving. Finally, one false positive was attributed to a whale that was more than two body lengths away from the adult female.

1.4.2 Newborn position

A total of 3,393 photographs were processed to identify narwhal newborns. From these photographs, 6,315 narwhals were detected with 6,173 whales identified as adults and 141 as newborns. Among the 141 newborns, 10 were a third or less of the female body length and 130 were between a third and half the length of their mothers. There were 136 newborns at a distance less than one body length away from their mothers and only five were found between one and two adult body lengths away from their mothers. I found 118 newborns located at the side of the adult female, nine were located behind the adult female and 13 were located above and only one was found on top of the female.

Newborns did not exhibit strong laterality, with 70 newborns on the left side of their mothers and 58 on the right side (Figure 1.4.b). Newborns were predominantly observed at the nearest female's tail (56 %, n=79) or at her side (27%, n=39), with only a few located above the mother (10%, n=14) or behind the mother (7%, n=9) and only one was sighted on top of the female (0.7%, n=1). Typically, the head of the newborn was centered around the midpoint of the mother's body (Figure 1.4.a). The length of newborn varied between 24 and 50% of the adult body length with most newborns between 40-45% of the adult female's size (Figure 1.4.c). Almost all newborns (94%, n=132) were less than one body length away from an adult female and most (86.5% (n=122) were less than 0.25 body lengths away (Figure 1.4.d).

1.4.3 Narwhal newborn grouping size, composition and location

I identified 141 newborns in 130 groups ranging from two to 17 individuals ($\bar{x}$= 4.0, SD= 2.7). Among the 528 whales comprising these 130 groups, 3% (n=16) were adult males and 48%

(n=252) were adult females. Females were present in all 130 groups whereas males were present in only 10 of the 130 groups. Narwhals of unknown sex represented a total of 22.53% (n=119) dispersed in 46 of the 130 groups with newborns. The number of newborns found in each of the 130 groups varied from one to four ($\bar{x}$=1, SD=0.35). There were 121 groups containing one newborn in each group, eight groups with two newborns and one group with four newborns. I found 36.8% of newborns in groups of two; 38.2% were found in groups of three to five individuals and 21.3% were found in groups of six to 10 individuals. Only 3.5% were found in bigger groups of 13, 16 and 17 individuals. Overall, the mean group size with a newborn present was four individuals ($\bar{x}$=4.06, SD=2.73). Of the 141 newborns identified, 52 were found in Admiralty Inlet, 44 in Eclipse Sound, 6 in East Baffin, seven in Jones Sound, three in Smith Sound and 18 in Somerset Island.

The average group size containing newborns did vary significantly by area with bigger groups found in Eclipse Sound and smaller groups found in East Baffin (area: $\bar{x}$±SD; AI:3.78±2.77, ES:5.0±3.03, EB:2.0±0, SS:2.6±1.15, JS:4.0±1.91, SI:3.4±1.97) (Kruskal-Wallis chi-squared = 17.078, df = 5, p-value= 0.004354).

1.5 Discussion

In this study, the assessment of the dichotomous key by inexperienced observers shows a high interobserver agreement with the expert observer, with an agreement of 85% or higher with the experienced observer, which was assessed to be fair to good based on Cohen’s kappa coefficient. Therefore, in general, the dichotomous key allowed multiple observers, whether experienced or inexperienced, to identify the same whales as newborns. This leads us to believe that the key is a strong tool for long-term studies with different observers. Most disagreements between observers involved whales that were slightly larger than the ½half-the-size-of-the-nearest-adult threshold described in the key (which is more commonly observed than the 1/3 threshold, see Figure 1.4.c). Narwhal newborns have a white or slate gray skin coloration and thus differ in coloration from adults, which are in general darker and more mottled (Mansfield and al. 1975; Reeves and Tracy 1980; Koski and Davis 1994). However, I found that discrimination of color differences was compromised by variation in exposure and lighting among different photographs and thus color was not used as an identification criterion. The key does not permit identification of newborns that are alone at the surface. Beyond the 141 identified newborns, I observed six whales that appeared to be newborns, but because they were not close to a visible adult, their size relative to an adult female could not be determined. Thus, those whales were not classified as newborns according to my dichotomous key. Because I focus my key only on whales present at the surface, of course, this method will miss any submerged newborns. As far as I am aware, there are no published data on the proportion of time that newborn narwhals spend submerged.

This study also provides the first description of mother-newborn spacing patterns. I cannot know with certainty that the whale adjacent to newborns is their mother and have thus referred to this whale as the closest adult female. Narwhal newborns were generally located close to the midpoint of the nearest adult female, either at their side (echelon position) or at her tail (infant position). These are the two main positions described for other odontocetes including bottlenose dolphins, belugas and killer whales *(Orcinus Orca)* (Reid et al. 1995; Mann and Smut 1999; Krasnova, et al. 2006; Noren 2008; Karenina et al. 2013). Narwhal newborns tended to be very close to the nearest adult female, with the vast majority within ¼ body length and nearly all within one body length. In this study, I did not find a strong side preference for narwhal newborns, but I did observe slightly more newborns located on the left side than the right side of the mothers. This suggests narwhal newborns might present a similar lateralization pattern found in other cetaceans (Delfour and Marten 2006; Karenina et al. 2010; Siniscalchi et al. 2012; MacNeilage 2013; Karenina et al. 2013), as well as several terrestrial species (Karenina et al. 2017). Narwhal newborn-mother dyads were often associated with another adult female, creating a group composed of a newborn with two adult females. This is consistent with previous studies of narwhals grouping behavior showing a tendency for females with offspring to occur in small groups of a few individuals (Hay 1984; Koski and Davis 1994; Marcoux et al. 2009).

The research of Arctic cetaceans, such as belugas and narwhals, is notoriously difficult due to the remoteness of the Arctic and the cryptic behavior of these species. Sampling methods using high definition aerial photography and other remote sensing approaches offer new opportunities to study Arctic cetaceans. This study is the first to use a systematic approach to identify narwhal newborns from aerial photography, offering a standardized technique for detecting newborns across regions and years of aerial surveys that can provide important information regarding population age structure and recruitment long-term.

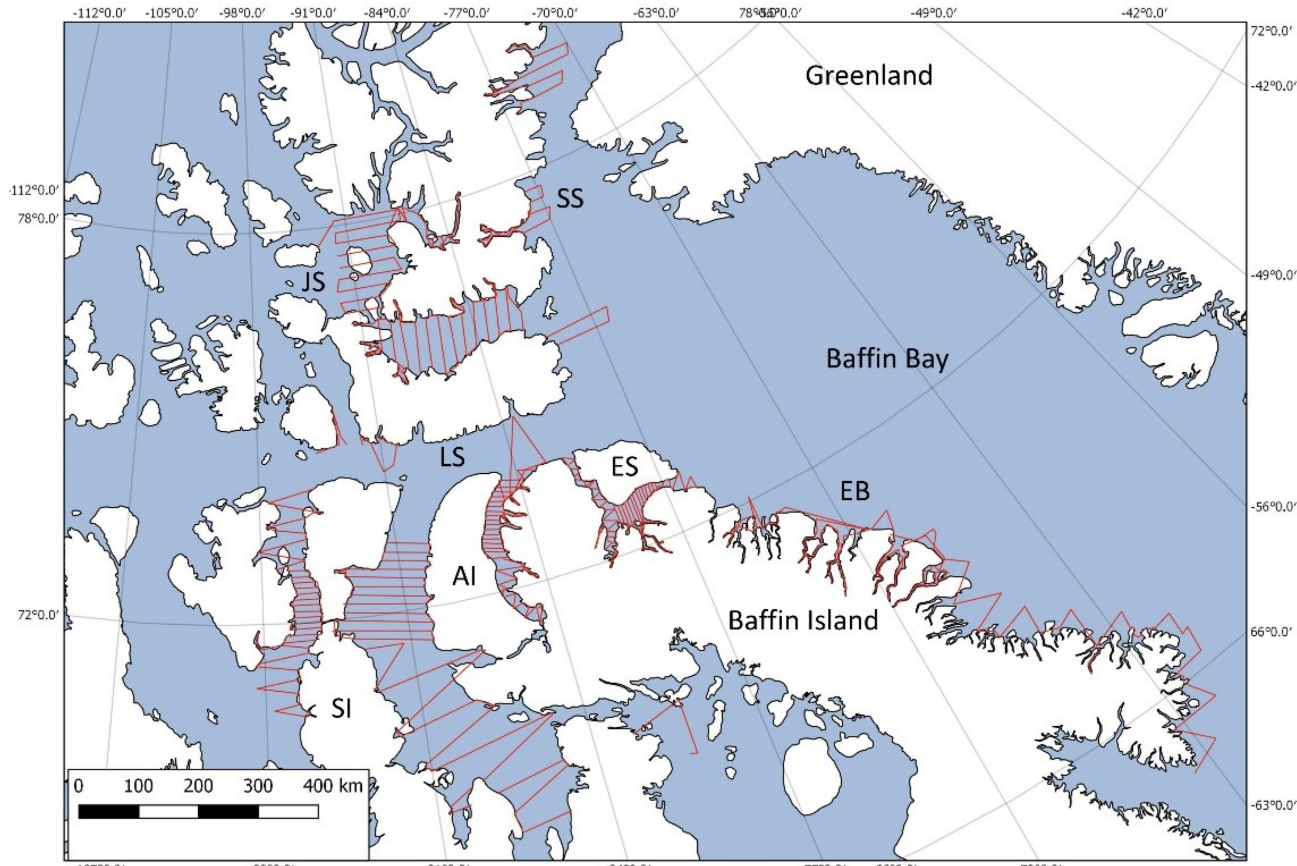


Figure 1.1 Map of the 2013 High Arctic Cetacean Survey done by the Department of Fisheries and Oceans (transect lines in red). The map identifies the geographic localities of Admiralty Inlet (AI), Eclipse Sound (ES), East Baffin (EB), Jones Sound (JS), Smith Sound (SS), Lancaster Sound (LS) and Somerset Island (SI).

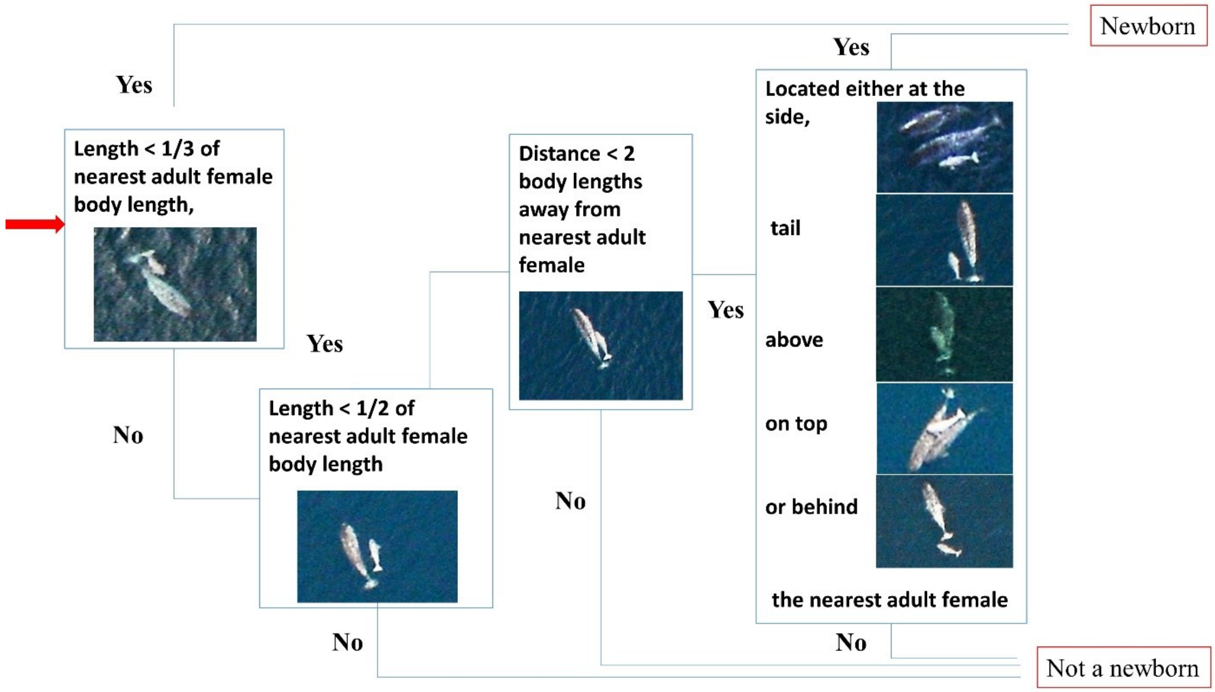


Figure 1.2 Dichotomous key developed by the authors and used in this study to detect narwhal newborns. The key reads from left to right starting at the red arrow and ending with two outcomes either as a newborn or not a newborn. Only whales at the surface were tested in this study.

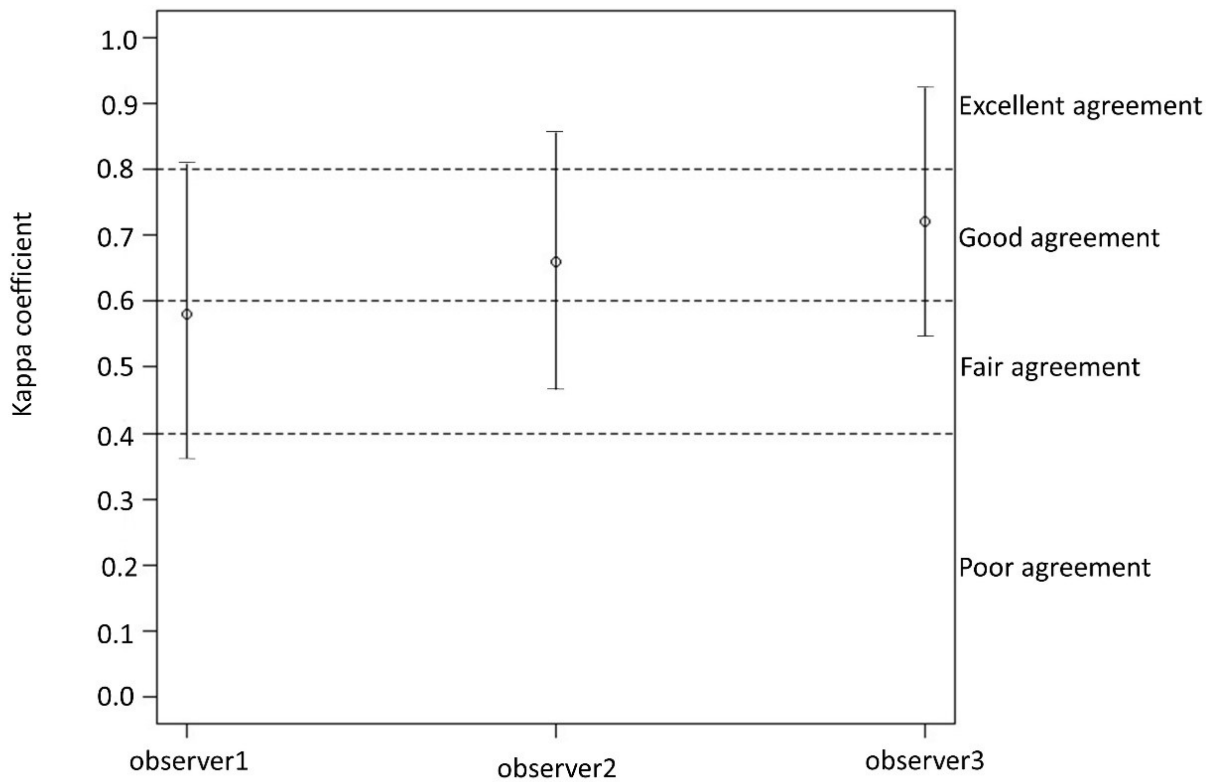


Figure 1.3 Scatter plot of Cohen's Kappa coefficient calculated between the expert observer and the inexperienced observers (observer 1: kappa coefficient= 0.57, CI: 0.34-0.81, n=61, observer 2: kappa coefficient= 0.66, CI: 0.47-0.86, n=61 observer 3: kappa coefficient= 0.72, CI: 0.54-0.92, n=61).

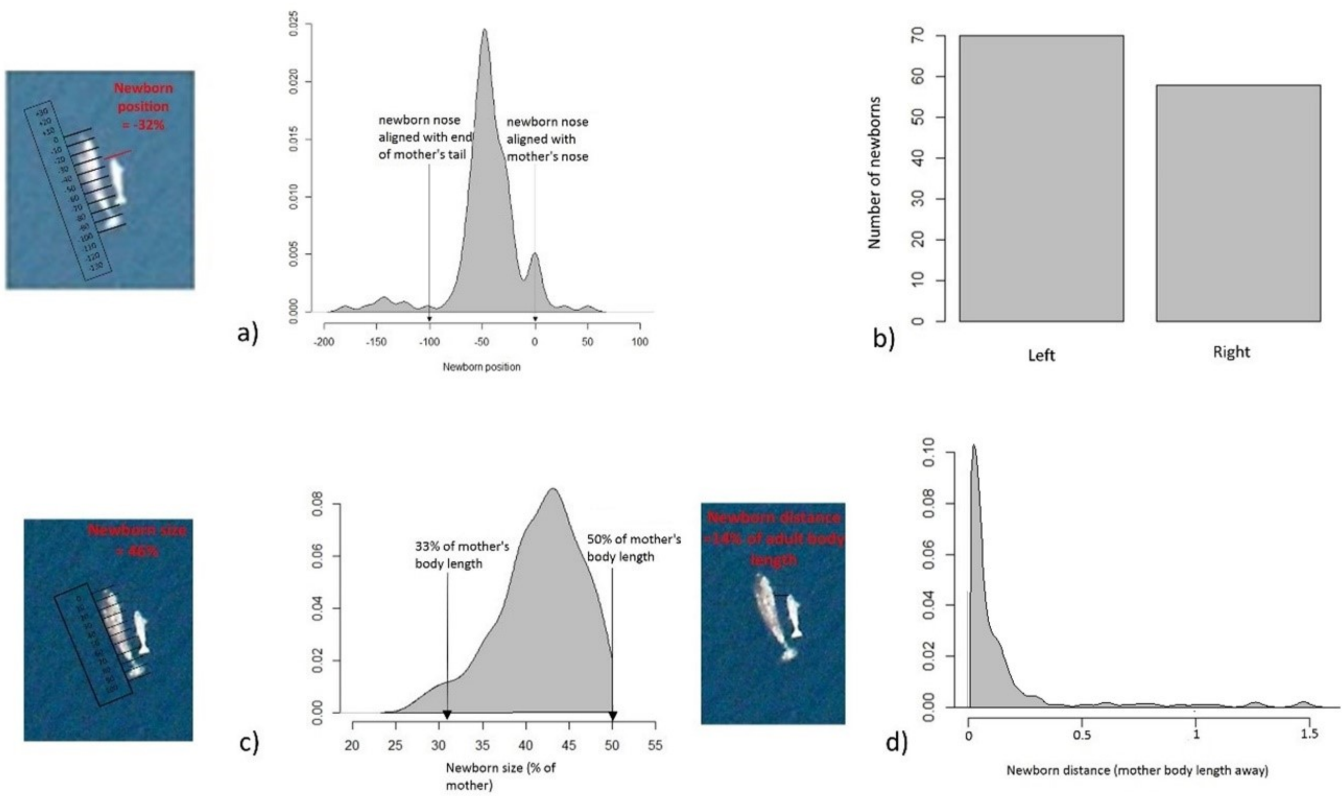


Figure 1.4 Spatial position of newborn narwhals relative to the nearest adult female. a) Position of newborns along the longitudinal axis of the nearest female represented by a Kernel density (n=141, bandwidth= 5.741); b) Number of newborns found on the left and right side of the nearest female; c) Size of newborns relative to the size of the nearest female represented by a kernel density function (n=141, bandwidth= 2.748) d) Distance of newborns from the nearest female, expressed as adult body lengths and represented by a kernel density function (n=141, bandwidth= 2.748).

1.6 Appendix

Photo Analysis protocols:

Narwhal's newborn detection

Background Information

The Narwhal (*Monodon monoceros*) has been listed as Near Threatened by the International Union for Conservation (Jefferson and al. 2008) and the Baffin Bay population as of Special Concern by COSEWIC in 2004, due to lack of knowledge. Therefore, better understanding the population dynamics of narwhals will be essential to adapt and develop better conservation and management plans. One essential parameter in assessing the health of a wild population is population growth; thus, having any insight on the number of calves born per year is be valuable information.

Narwhals are a medium size odontocete, exclusively found in Arctic waters, that have an annual migratory cycle with distinct wintering and summering-grounds (COSEWIC, 2004). In Canada, two distinct populations are recognized: The Hudson Bay population and the Baffin Bay population. The Baffin Bay population uses numerous fjords and bays from northwestern Greenland to the central Canadian High Arctic over the summer (COSEWIC, 2004; Heide-Jørgensen et al., 2003). Sexual maturity is estimated at five years with a reproductive interval of about three years (Kingsley, 1989). Most calves are born during the summer in July and August

(Mansfield and al., 1975) even though it has been reported that some calves can be born earlier (Fisher, 1978).

The goal is to validate the decision-making key for understandability and accuracy.

Getting started:

Installing GIMP software:

1 **Download free software GIMP 2.8.14 at: https://www.gimp.org/downloads/**

GIMP set up

3 **Add photos:**

On the toolbar click "file/ Open/ select photo to open such as: kbg_13Aug19_L_00344". **Load one photo at a time. All the photos are in the dropbox file that I sent you.**

4 **Add Grid layer:**

On the toolbar click on Filters/ Render/ Pattern/ Grid.

Grid set up:

	Horizontal Lines	*Vertical Lines*	*Intersection*	
Width:	1	1	0	Px
Spacing:	100	100	2	Px
Offset:	8	8	6	Px

Photo Analysis

In order to detect the calves, you might want to change the brightness of the photos.

on the toolbar click: “Colors/ Hue-saturation/lightness”. This step is optional.

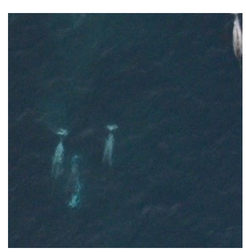
<u>Photo scanning</u>:

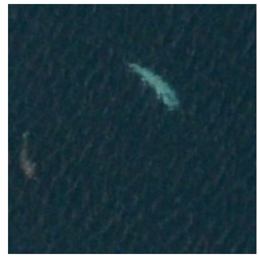
Personally, I like to scan the photo beginning from the top left corner (you can develop your own method but it is important to remember where you looked so you don’t score the same whale twice). **Since we are only interested in whales at the surface** you should be able to see the whales in the photos by setting the photo at 50%. To do that click on the bottom toolbar and select 50%.

When looking at the images you will quickly realize that determining if a whale is a surface or not is not as easy as it sounds. It will require some time working with the photos to develop your confidence. But here are some examples to guide you in the process:

Whale at the surface:

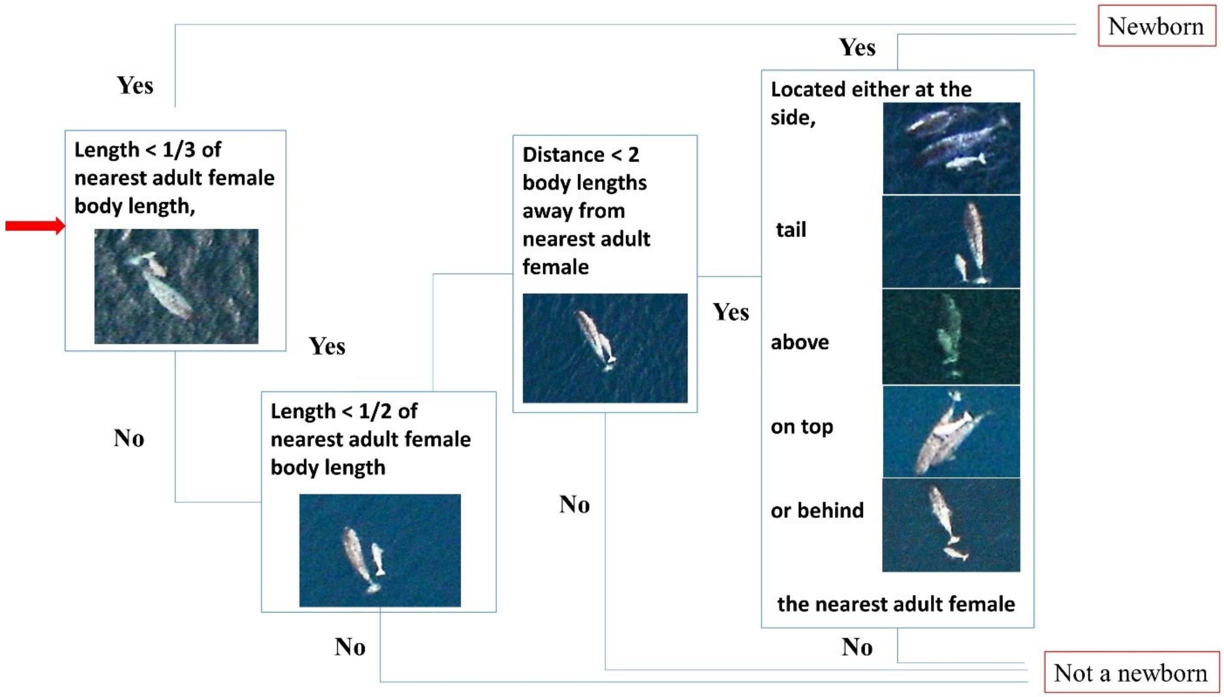
Whale not at the surface:



If the whale is just underneath the surface it is fine. Keep in mind that we are focusing on newborns, therefore if the adult female is a little bit at an angle, or underneath the surface, this does not matter as long as the newborn is less than half the size of the adult female.

Once you see a potential newborn, use the dichotomous key to make your final decision. You will see that to identify a newborn you will have to measure the whale. To measure a whale, use the measuring tool located on the toolbar click “Tools/Measure”. Zoom into the whale until you see the pixels. Take the measurement from the snout of the whale to the end of the tail between the left and right fluke. Read the measurement in pixels located on the bottom left of the Gimp window.



Dichotomous key to detect narwhal newborns. Photo examples are places next to certain cases to assist in decision making. The key reads from left to right ending with two outcomes either as a newborn or not a newborn. Only whales at the surface are used in this key.

Once you have determined a whale is a newborn, enter the information into the Excel file as follows:

	A	B	C	D	E	F
1	Photo ID	Individual:	Coordinates on the picture	length in pixels	calf position	Distance from the female
2	kbg_13Aug19_L_00335	AF	3568/3171	82.3	x	x
3	kbg_13Aug19_L_00335	C	3568/3171	40.3	S	1
4						

Insert the name of the photos

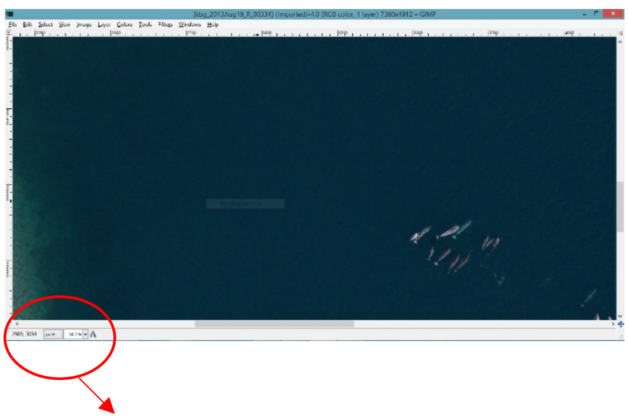
Photo ID
kbg_13Aug19_L_00335
kbg_13Aug19_L_00335

Identify Individual: Put either AF for an adult female or C for a newborn (calf)

Individual:
AF
C

Locate the individuals: Insert in this column the coordinates of the individual. Once you have placed the curser on the head of the individual you will find the coordinates on the bottom left of the Gimp window.

Coordinates on the picture	I
3568/3171	



Whale measure: To measure a whale, use the measuring tool located on the toolbar click “Tools/Measure”. Zoom into the whale until you see the pixels. Take the measurement from the snout of the whale to the end of the tail between the left and right fluke. Read the measurement in pixels located on the bottom left of the gimp window, insert this measurement into the Excel file.

length in pixels
82.3
40.3

Distance of the newborn from the closest adult female: In this column, you only need to enter it for the newborn. It can be either 1, meaning that the newborn is located at a distance less than one adult body length from the female. Or 2, meaning the newborn is more than one adult body length from the closest female

Distance from the female
x
1

1.7 Literature Cited

Best, P. B., and H. Rüther. 1992. Aerial photogrammetry of southern right whales, Eubalaena australis. Journal of Zoology, 228(4):595–614.

Best, R. C. 1981. The tusk of the narwhal (Monodon monoceros L.): interpretation of its function (Mammalia: Cetacea). Canadian Journal of Zoology, 59(12):2386–2393.

Best, R. C., and H. D. Fisher. 1974. Seasonal breeding of the narwhal (Monodon monoceros L.). Canadian Journal of Zoology, 52(3):429–431.

Block, W. M., A. B. Franklin, J. P. Ward, J. L. Ganey, and G. C. White. 2001. Design and Implementation of Monitoring Studies to Evaluate the Success of Ecological Restoration on Wildlife. Restoration Ecology, 9(3):293–303, https://doi.org/10.1046/j.1526-100x.2001.009003293.x.

Cassey, P., and T. M. Blackburn. 2006. Reproducibility and Repeatability in Ecology. BioScience, 56(12):958–959, https://doi.org/10.1641/0006-3568(2006)56[958:RARIE]2.0.CO;2.

Cohen, J. 1968. Weighted kappa: Nominal scale agreement provision for scaled disagreement or partial credit. Psychological Bulletin, 70(4):213–220, https://doi.org/10.1037/h0026256.

Cosens, S. E., and L. P. Dueck. 1990. Spring Sightings of Narwhal and Beluga Calves in Lancaster Sound, N.W.T. Arctic, 43(2):127–128.

COSEWIC. 2004. Assessment and Update Status Report on the Narwhal Monodon Monoceros in Canada. pp.

Cubbage, J. C., and J. Calambokidis. 1987. Size-class segregation of bowhead whales discerned through aerial stereophotogrammetry. Marine Mammal Science, 3(2):179–185, DFO. 2015. Abundance estimates of narwhal stocks in the Canadian High Arctic in 2013. DFO Can. Sci. Advis. Sec. Res., (Doc. 2015/060. v):36 p.

Dietz, R., M. P. Heide-Jørgensen, P. R. Richard, and M. Acquarone. 2001. Summer and Fall Movements of Narwhals (Monodon monoceros) from Northeastern Baffin Island Towards Northern Davis Strait. Arctic, 54(3):244–261.

Dietz, R., M. P. Heide-Jørgensen, P. Richard, J. Orr, K. Laidre, and H. C. Schmidt. 2008. Movements of narwhals (Monodon monoceros) from Admiralty Inlet monitored by satellite telemetry. Polar Biology, 31(11):1295–1306.

Gubbins, C., B. Mcowan, S. K. Lynn, S. Hooper, and D. Reiss. 1999. Mother-infant spatial relations in captive bottlenose dolphins, Tursiops truncatus. Marine Mammal Science, 15(3):751–765.

Haley, S. M., and J. S. Osberg. 1989. Kappa Coefficient Calculation Using Multiple Ratings Per Subject: A Special Communication. Physical Therapy, 69(11):970–974,

Hay, K. A., and A. W. Mansfield. 1989. Narwhal monodon monoceros Linnaeus, 1758. Handbook of Marine Mammals, 4:145–176.

Heide-Jørgensen, M. P. 2004. Aerial Digital Photographic Surveys of Narwhals, Monodon Monoceros, in Northwest Greenland. Marine Mammal Science, 20(2):246–261, https://doi.org/10.1111/j.1748-7692.2004.tb01154.x.

Jefferson, T. A., L. Karczmarski, K. Laidre, G. O'Corry-Crowe, R. R. Reeves, L. Rojas-Bracho, E. R. Secchi, E. Slooten, B. D. Smith, J. Y. Wang, and others. 2009. Monodon Monoceros. 2008 IUCN Red List of Threatened Species. pp.

Kingsley, M. 1989. Population dynamics of the narwhal Monodon monoceros: an initial assessment (Odontoceti: Monodontidae). Journal of Zoology, 219(2):201–208, https://doi.org/10.1111/j.1469-7998.1989.tb02576.x.

Koski, W. R., and R. A. Davis. 1994. Distribution and numbers of narwhals (Monodon. Studies of White Whales (Delphinapterus Leucas) and Narwhals (Monodon Monoceros) in Greenland and Adjacent Waters, 15.

Krasnova, V. V., V. M. Bel'kovich, and A. D. Chernetsky. 2006. Mother-infant spatial relations in wild beluga (Delphinapterus leucas) during postnatal development under natural conditions. Biology Bulletin, 33(1):53–58, https://doi.org/10.1134/S1062359006010079.

Krasnova, V. V., V. M. Bel'kovich, and A. D. Chernetskii. 2009. Formation of behavior in the White Sea beluga calf, Delphinapterus leucas, during early postnatal ontogenesis. Russian Journal of Marine Biology, 35(1):53–59.

Landis, J. R., and G. G. Koch. 1977. The Measurement of Observer Agreement for Categorical Data. Biometrics, 33(1):159–174, https://doi.org/10.2307/2529310.

Legg, C. J., and L. Nagy. 2006. Why most conservation monitoring is, but need not be, a waste of time. Journal of Environmental Management, 78(2):194–199, https://doi.org/10.1016/j.jenvman.2005.04.016.

Lindenmayer, D. B., and G. E. Likens. 2010. The science and application of ecological monitoring. Biological Conservation, 143(6):1317–1328,

Magurran, A. E., S. R. Baillie, S. T. Buckland, J. M. Dick, D. A. Elston, E. M. Scott, R. I. Smith, P. J. Somerfield, and A. D. Watt. 2010. Long-term datasets in biodiversity research and monitoring: assessing change in ecological communities through time. Trends in Ecology & Evolution, 25(10):574–582, https://doi.org/10.1016/j.tree.2010.06.016.

Mann, J. 2000a. Cetacean Societies: Field Studies of Dolphins and Whales. University of Chicago Press, pp.

Mann, J. 2000b. Unraveling the dynamics of social life. Cetacean Societies: Field Studies of Dolphins and Whales. University of Chicago Press, Chicago, Illinois, USA, 45–64.

Mann, J., and Smut. 1999. Behavioral development of wild bottlenose dolphin newborns. Behaviour, 136(5):529–566, https://doi.org/10.1163/156853999501469.

Mansfield, A. W., T. G. Smith, and B. Beck. 1975. The Narwhal, Monodon monoceros, in Eastern Canadian Waters. Journal of the Fisheries Research Board of Canada, 32(7):1041–1046, https://doi.org/10.1139/f75-122.

Marcoux, M., M. Auger-Méthé, and M. M. Humphries. 2009. Encounter frequencies and grouping patterns of narwhals in Koluktoo Bay, Baffin Island. Polar Biology, 32(12):1705–1716.

McBride, A. F., and H. Kritzler. 1951. Observations on Pregnancy, Parturition, and Postnatal Behavior in the Bottlenose Dolphin. Journal of Mammalogy, 32(3):251–266, https://doi.org/10.2307/1375657.

Mills, J. P., I. Newton, and R. W. Graham. 1996. Aerial Photography for Survey Purposes with a High Resolution, Small Format, Digital Camera. The Photogrammetric Record, 15 https://doi.org/10.1111/0031-868X.00065.

Nichols, J. D., and B. K. Williams. 2006. Monitoring for conservation. Trends in Ecology & Evolution, 21(12):668–673, https://doi.org/10.1016/j.tree.2006.08.007.

Noren, S. R. 2008. Infant carrying behavior in dolphins: costly parental care in an aquatic environment. Functional Ecology, 22(2):284–288, https://doi.org/10.1111/j.1365-2435.2007.01354.x.

Noren, S. R., and E. F. Edwards. 2007. Physiological and Behavioral Development in Delphinid Calves: Implications for Calf Separation and Mortality Due to Tuna Purse-Seine Sets. Marine Mammal Science, 23(1):15–29, https://doi.org/10.1111/j.1748-7692.2006.00083.x.

Noren, S. R., and E. F. Edwards. 2011. Infant position in mother-calf dolphin pairs: formation locomotion with hydrodynamic benefits. Marine Ecology Progress Series, 424:229–236, https://doi.org/10.3354/meps08986.

Noren, S. R., G. Biedenbach, and E. F. Edwards. 2006. Ontogeny of swim performance and mechanics in bottlenose dolphins (Tursiops truncatus). Journal of Experimental Biology, 209(23):4724–4731, https://doi.org/10.1242/jeb.02566.

Noren, S. R., G. Biedenbach, J. V. Redfern, and E. F. Edwards. 2008. Hitching a ride: the formation locomotion strategy of dolphin calves. Functional Ecology, 22(2):278–283, https://doi.org/10.1111/j.1365-2435.2007.01353.x.

Pettis, H. M., R. M. Rolland, P. K. Hamilton, S. Brault, A. R. Knowlton, and S. D. Kraus. 2004. Visual health assessment of North Atlantic right whales (Eubalaena glacialis) using photographs. Canadian Journal of Zoology, 82(1):8–19, https://doi.org/10.1139/z03-207.

Ratnaswamy, M. J., and H. E. Winn. 1993. Photogrammetric Estimates of Allometry and Calf Production in Fin Whales, Balaenoptera physalus. Journal of Mammalogy, 74(2):323–330, https://doi.org/10.2307/1382387.

RDevelopment, C. In press. TEAM 2011: R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria,

Reid, K., J. Mann, J. R. Weiner, and N. Hecker. 1995. Infant development in two aquarium bottlenose dolphins. Zoo Biology, 14(2):135–147.

Richard, P. R., J. L. Laake, R. C. Hobbs, M. P. Heide-Jørgensen, N. C. Asselin, and H. Cleator. 2010. Baffin Bay Narwhal Population Distribution and Numbers: Aerial Surveys in the Canadian High Arctic, 2002-04. Arctic, 63(1):85–99.

Rugh, D. 1990. Bowhead whales reidentified through aerial photography near Point Barrow, Alaska. Rep. Int. Whal. Commn, 289–94.

Sheil, D. 2001. Conservation and Biodiversity Monitoring in the Tropics: Realities, Priorities, and Distractions. Conservation Biology, 15(4):1179–1182, https://doi.org/10.1046/j.1523-1739.2001.0150041179.x.

Sim, J., and C. C. Wright. 2005. The Kappa Statistic in Reliability Studies: Use, Interpretation, and Sample Size Requirements. Physical Therapy, 85(3):257–268.

Smith, H., C. Frère, H. Kobryn, and L. Bejder. 2016. Dolphin sociality, distribution and calving as important behavioural patterns informing management. Animal Conservation, n/a-n/a, https://doi.org/10.1111/acv.12263.

Taylor, B. L., M. Martinez, T. Gerrodette, J. Barlow, and Y. N. Hrovat. 2007. Lessons from monitoring trends in abundance of marine mammals. Marine Mammal Science, 23(1):157–175.

Thomas, L. 1996. Monitoring Long-Term Population Change: Why are there so Many Analysis Methods? Ecology, 77(1):49–58.

Thompson, P., and P. Hammond. 1992. The Use of Photography to Monitor Dermal Disease in Wild Bottle-Nosed Dolphins (Tursiops-Truncatus). Ambio, 21(2):135–137.

Viera, A. J., J. M. Garrett. 2005. Understanding interobserver agreement: the kappa statistic. Fam Med, 37(5):360–363.

Walter, D. E., and S. Winterton. 2007. Keys and the Crisis in Taxonomy: Extinction or Reinvention? Annual Review of Entomology, 52(1):193–208, https://doi.org/10.1146/annurev.ento.51.110104.151054.

Watt, C. A., J. Orr, B. LeBlanc, P. Richard, and S. H. Ferguson. 2012. Satellite tracking of narwhals (Monodon monoceros) from Admiralty Inlet (2009) and Eclipse Sound (2010–22011). DFO Canadian Science Advisory Secretariat Research Document, 46.

Whitehead, H., R. R. Reeves, and P. L. Tyack. 2000. Science and the conservation, protection, and management of wild cetaceans. Cetacean Societies: Field Studies of Dolphins and Whales, 12:308–332,.

Linking Statement

In the previous chapter, I developed a dichotomous key to identify narwhal newborns from aerial photographs. The identification of newborns also gave some insight into narwhal mother-newborn spatial relationship. In the next chapter, I identify narwhal males and females when possible from aerial photographs. I then explored the distribution of males, females, and newborns in the Canadian Arctic Archipelago.

Chapter 2: Narwhal (*Monodon Monoceros*) sex and age distribution of the Baffin Bay population across the high Canadian Arctic Archipelago.

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2.1 Abstract

Effective wildlife management and conservation require knowledge of distribution, sex composition and age structure of a population. Here, I explored the distribution of narwhal population, looking at sex and age distribution, across the Canadian Arctic Archipelago. I calculated a matrix of swimming distances between individuals to partition my dataset using the partitioning around the medoids algorithm. The clusters obtained from my analysis supported the delimitation of narwhal management stocks currently used by the Department of Fisheries and Oceans. Interestingly, each cluster presented different sex ratios, and the proportion of newborns relative to the number of females varied between seven and 18% in all clusters. Overall, my study is a step forward the comprehension of the Baffin Bay population structure and distribution of narwhals.

2.2 Introduction

Successful wildlife population management and conservation depend on knowledge such as a population's age structure, sex composition, and distribution (Eberhardt 1977; Block and Brennan 1993; Caughley, Sinclair, et al. 1994; Krebs 2009; Garde et al. 2015). Characterizing species habitat use is a common tool to establish conservation and management policies on land and oceans (Aron 1988; Morris and Brown 1992; Caughley, Sinclair, et al. 1994; Lefebvre et al. 2000; Ceballos et al. 2005; Harris et al. 2008). An important step toward understanding a population's habitat selection is through their population distribution and assessing general patterns of habitat use across a landscape (Morris and Brown 1992; Morris 2003; Redfern et al. 2006). This is especially important, though difficult to quantify, for long-lived, migratory animals such as cetaceans. These species are often data-poor due to their wide distribution living mostly offshore, making their management potentially less successful than it could be (Evans and Raga 2001; Kaschner et al. 2006; Pompa, Ehrlich, and Ceballos 2011).

Research on Arctic cetaceans, such as the narwhal (*Monodon Monoceros* L.,1758), is known to be especially challenging due to their marine environment, low probabilities of sightings and vast distribution (Mann 1999, 2000a; Moore and Huntington 2008; Walsh 2008; Marcoux, Auger-Méthé, and Humphries 2009). Narwhal distribution follows a year-round cycle with a wintering-ground and a summering-ground (Koski and Davis 1994; Richard 1994; R. Dietz et al. 2001; Heide-Jørgensen et al. 2003; Richard et al. 2010). They are believed to have a high site fidelity of their summering-ground in the fjords and bays of the Canadian Arctic Archipelago (Dietz et al. 2001; Laidre 2003; Laidre et al. 2004; Auger-Méthé, Marcoux, and Whitehead 2010) even though, it has been shown that some degree of migration between management stocks occurs (Watt et al. 2012). This behavioral characteristic enables managers to divide the Baffin Bay population into management stocks during the summer to establish harvesting quotas for local Inuit communities.

In 2004 the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) categorized the Baffin Bay population as of Special Concern. The reasoning for this status is the lack of knowledge of narwhal ecology and uncertainties about numbers, trends, life history parameters, and levels of sustainable hunting of the Baffin Bay population (COSEWIC 2004). In 2007, the International Union for Conservation of Nature (IUCN) established the narwhal conservation status as Near Threatened (Jefferson et al. 2009). Filling these knowledge gaps is essential so narwhals can be effectively managed at both the national and international scales.

To date, narwhal distribution and structure have been studied via telemetry tags, aerial surveys, land observation, chemical dietary evidence and genetics data collected from harvested individuals (Koski and Davis 1994; Richard 1994; Palsboell, Heide-Jørgensen, and Dietz 1997; Dietz et al. 2008; Marcoux, Auger-Méthé, and Humphries 2009; Richard et al. 2010; Watt et al. 2012; Watt et al. 2012; Watt and Ferguson 2015). All these methods present limitations to either the sample size, the size of the study area or the quality of the data collected (Caughley 1974; Eberhardt, Chapman, and Gilbert 1979; Mann 1999; Hobbs, Waite, and Rugh 2000; Laidre 2003; Marcoux, Auger-Méthé, and Humphries 2009).

Aerial surveys, in conjunction with aerial photography, offers multiple advantages over other methods. Aerial surveys follow transects reducing the risk of counting same individuals twice, whereas aerial photography reduces perception bias and allows multiple observers to analyze the same photos (Dueck 1989; Heide-Jørgensen 2004). Using these two methods together, researchers can develop reproducible studies at multiple spatial and temporal scales, with high sample sizes (Morgan, Gergel, and Coops 2010). As a long-lived marine mammal with low reproductive rates, it is essential to obtain long-term ecological data on narwhals in order to observe and predict changes of the populations in response to environmental changes (Nichols and Williams 2006; Clutton-Brock and Sheldon 2010; Lindenmayer and Likens 2010).

This study aims to investigate the spatial distribution of narwhal, especially, spatial aggregation and to compare to existing management units. I examined narwhal sex and age distributions across a large spatial scale of the Canadian High Arctic Archipelago, using aerial photographs collected during narwhal aerial surveys.

2.3 Material and Methods

2.3.1 Study area and data collection

In August 2013, Fisheries and Oceans Canada (DFO) conducted an extensive aerial survey known as the High Arctic Cetacean Survey. The survey aimed to estimate abundance of narwhals in the Baffin Bay population and the Eastern Canada-West Greenland bowhead whale population covering the following Arctic regions: Eclipse Sound, Admiralty Inlet, Somerset Island, East Baffin, Jones Sound, and Smith Sound (Figure 2.1) (DFO 2015a). Survey dates were set based on traditional knowledge, previous survey results and telemetry narwhal and bowhead whale (Dietz et al. 2001; Dueck et al. 2006; Dietz et al. 2008; Watt et al. 2012; Wheeler, Gilbert, and Rowe 2012). The survey was designed as a double-platform using three teams of four visual observers, two at the front and two at the rear of each twin-engine Havilland Twin Otter 300 plane. Planes flew at an altitude of about 1000 feet (304.8m) with a speed of 100 knots (185km/h) following pre-determined transect lines avoiding any recounts of the same whales. The strip width of each transect line covered by photos represented 840m at the surface of the water. Two Nikon D-800 cameras with 35mm lens were mounted on each side of the plane at an angle of 27 degrees. Cameras were set up to take photos every 3 seconds resulting in a 20% overlap between two consecutive photographs. Each photo taken had the long side perpendicular to the transect (orientation 'width-wise') and the width of each photo taken was 420m. Images were georeferenced and saved in a laptop by connecting the cameras to a GPS unit and a laptop.

2.3.2 Photograph analysis

After the survey, all photographs were projected in ArcGIS (version 10.1). The photos should be trapezoid but for the need of this study, they were projected as rectangles. To help detect narwhals, photo-analysts only referred to photographs where observers in the field noted seeing narwhals. Each narwhal present in the photos was georeferenced using ArcMap 10.1 and saved into a Geographic Information System (GIS) data layer. Due to some overlap between two consecutive photographs, some photographs had duplicates of individuals. When an individual appeared in two photographs I kept only one sighting of these individuals removing any duplicates from the dataset in this study. One expert observer revisited all the photographs with narwhal detections to collect sex and class age data. Each whale was assigned to a sex category and age. A narwhal could be either an adult, a newborn (whale of 0 to 3 months old), or a whale of unknown age. To be consistent in my detection of a newborn a dichotomous key was used to classify newborns. Newborn whales could not be sexed. Thus, all newborn was classified as unknown sex whales. However, adult narwhals were classified as males or females when possible based on the following criteria. An adult narwhal was a female if no tusk was present (Mansfield, Smith, and Beck 1975; Hay 1985), and an adult narwhal was a male if a tusk was present (Koski and Davis 1994). Individuals that could not be identified were classified as unknown sex (Mann 2000).

2.3.3 Data analysis

Statistical analyses were performed using the statistical software R (RDevelopment 2011). Prior to partition the narwhal dataset I first calculated a matrix of swimming distance of all narwhals detected in the photographs using the R package “gdistance” (RDevelopment, 2011.; Etten 2012). To obtain a swimming distance between all individuals I first transformed the study area into a raster. Each grid cell of the raster represented a surface of $1km^2$. I assigned a value of 1 to the grid cells containing water. The grid cells containing land had no data. This insured the distances calculated between whales would correspond to a swimming distance. Then, I calculated all the distances between grid cells containing narwhals. To obtain the final distance matrix of all the individuals I assigned Euclidian distances between whales that were less than 5km apart, and when distances were greater than 5km I used the distances calculated previously between grid cells containing narwhals using the least cost path algorithm.

Once the narwhal matrix of swimming distances was obtained I then performed a partitioning around the medoids (PAM) analyses using the PAM function in the R package “cluster” (Maechler et al. 2015). The PAM algorithm divides the data by first selecting a user-defined number of medoids, actual data point, to represent the center of each cluster. Then, each cluster is constructed by minimizing the distance between data points and the medoids. (Kaufman and Rousseeuw 2009). To find the optimum number of clusters, I assessed the clustering structure using the within-cluster sum of squares and the average silhouette width (ASW) for 2 to 20 clusters. The ASW gives a measure of the homogeneity and separation of clusters. Kaufman and Rousseeuw (2009) suggested the silhouette coefficient (defined as the overall ASW for the entire data set) interpretation as follows: a value between 0.71-1 corresponds to a strong structure of the data, between 0.51-0.7 a reasonable structure, 0.26-0.50 a weak structure and below 0.25 there is no structure of the data. Based on the optimal number of clusters, I calculated the proportion of males, females, and newborns in each cluster. The percentage of newborns corresponds to the number of newborns relative to the number of females. To determine if the number males and females observed in each cluster were significant, I performed a chi-square test.

2.4 Results

I analyzed 3,393 photographs for this study that included a total of 6,315 narwhals (Figure 2.2). The photographs included 1,425 females, 1,379 males and 3,511 individuals of unknown sex. 6,033 narwhals were identified as adults, 141 were newborns, and I was unable to age 140 individuals.

The outcome of PAM for k=3 divided the data with cluster 1 containing 2,682 narwhals corresponding to the regions of Eclipse Sound and East Baffin. The second cluster had 2,966 narwhals corresponding to whales found in Admiralty Inlet, Lancaster Sound, and Somerset Island. Finally, cluster 3 had 666 whales containing individuals in Jones Sound and Smith Sound. The outcome of PAM analyses for k=5, the algorithm divided the previous cluster 1 into 2 clusters corresponding respectively to Eclipse Sound and East Baffin and divided the previous cluster 2 separating the areas of Somerset Island and Admiralty Inlet. Finally, when dividing the data into 7 clusters, the algorithm divided the region of Admiralty Inlet into two distinguishing the region of Lancaster Sound as a unique cluster. The algorithm also divided Somerset Island into two different clusters (Figure 2.4).

Using the elbow criterion method of interpretation (Madhulatha 2012) on sum of squares and ASW for k=2-20 (Figure 2.3); I identified five clusters as being the best partition outcome

(Figure 2.5). Clusters 1 and 2 contained 2,213 and 2,392 individuals containing the most males, females, and newborns. In the first cluster, 981 narwhals were sexed representing respectively 52% males (n=509), 48% females (n=472). Newborns represented 10% of the females (n=49) in cluster 1. In the second cluster, 1,132 whales were sexed. Males represented 46% (n=516), and females 54% (n=616) of the narwhals that could be sexed. The proportion of newborns was 9% (n=57). The number of males and females observed in each cluster was statistically different (χ^2=27.9, DF= 3, P=0.001) (Table 2.1). The male: female ratios for each of the final five clusters were: 1.07 (cluster 1), 0.83 (cluster 2), 1.4 (cluster 3), 1.38(cluster 4) and 0.71 (cluster 5). Overall, the male: female ratio was 0.97.

2.5 Discussion

This study offers a novel assessment of narwhal management stocks based on swimming distances. Previous studies based on telemetry data, surveys, genetics, contaminants and local knowledge distinguished four different narwhal management stocks for the Baffin Bay population known as East Baffin, Eclipse Sound, Admiralty Inlet and Prince Regent stocks (Petersen et al. 2011; Heide-Jørgensen et al. 2013; DFO 2013, 2015b). Additional two stocks – Jones Sound and Smith Sound – have been suggested based on sightings and hunting activities around Ellesmere Island and Devon Island (Heide-Jørgensen et al. 2013). In this study, I identified five different clusters similar to the narwhal stocks currently defined by DFO. Based only on swimming distances and a purely quantitative clustering approach, my findings are in broad alignment with the DFO stocks. My analysis did not provide evidence for the Jones Sound and Smith Sound hypothesized stocks, even when I divided the sighting into seven clusters (Figure 2.4).

Sexual segregation; defined as the different use of space by sexes (Conradt 1998); is found in different marine and terrestrial mammal species (Ohsumi 1966; Bleich, Bowyer, and Wehausen 1997; Kathreen E. Ruckstuhl 1998; Kathreen E. Ruckstuhl and Neuhaus 2000; Laidre et al. 2009; Fury, Ruckstuhl, and Harrison 2013). Different hypotheses attempt to explain sex segregation including the predation risk hypothesis, the forage selection hypothesis and the activity budget hypothesis (Ruckstuhl 2007). In this study, the distribution of narwhal males and females in each cluster is unequal with a male: female ratio varying from 0.71 to 1.40. In 1979 Silverman observed a high male: female sex ratio in Tremblay Sound (cluster 1) which is similar to what I observed in this study. Interestingly, the male: female sex ratio reversed in the next fjord known as Admiralty Inlet (cluster 2). The differences observed between clusters could indicate variation in site fidelity among individuals depending on sex class and age, different energetic needs, or individual behavior regarding site fidelity and range of movements (Bearzi and al., 1995; Mann, 1997). The proportion of newborns relative to the number of females ranged from 7 to 18% in all clusters, which is consistent with the predicted birth rate of 7% (Silverman 1979; Kingsley 1989) (Figure 2.4). The difference in newborn proportions between clusters could be due to differences in habitat characteristics (e.g.: water temperature, food availability, bottom depth) (Redfern et al. 2006).

Aerial digital photography combined with aerial surveys have the advantage of collecting more reliable data on sex composition and age classes than aerial surveys alone. Photographs can be analyzed multiple times by multiple observers, reducing errors (Caughley 1974; Heide-Jørgensen 2004). This study gives new insight on the distribution of Baffin Bay narwhal stocks.

Although this research contributes to our knowledge of narwhal sex and newborn distribution, I acknowledge that having only one year of data limits the ability to make greater inferences. Moreover, the differentiation between male and female narwhals was only based on the presence or absence of a tusk. In 2012 Petersen et al. estimated the proportion of females with tusk to be 6%, but no correction factors have been applied to this data to account for the proportion of females with tusks and the proportion of males without a tusk. However, this bias should be consistent between clusters.

This study is the first to look at sex distribution and narwhal newborns at a large scale across the Canadian Arctic Archipelago. The reproducibility of my study design provides an important opportunity for future research to obtain multiple years of data and compare future narwhal trends to these preliminary findings. Studying newborn, calf and juvenile behaviors via focal studies could further help identification of different class ages from aerial photographs, refining our ability to collect information about narwhal population from photographs. Building a long-term narwhal database can be a powerful tool to help decision makers and northern communities to improve the management and conservation of the Baffin Bay narwhal population in Canada.

Table 2.1 Contingency table of male and female narwhals using the optimal number of clusters (k=5). Chi-square results at the bottom of the table.

	Sex		
	Male	Female	***Total***
Cluster 1	509	472	**981**
Cluster 2	516	616	**1132**
Cluster 3	46	32	**78**
Cluster 4	185	134	**319**
Cluster 5	123	171	**294**
Total	**1379**	**1425**	**2804**

$\chi^2=27.99 \cdot df=4\ p=0.001$

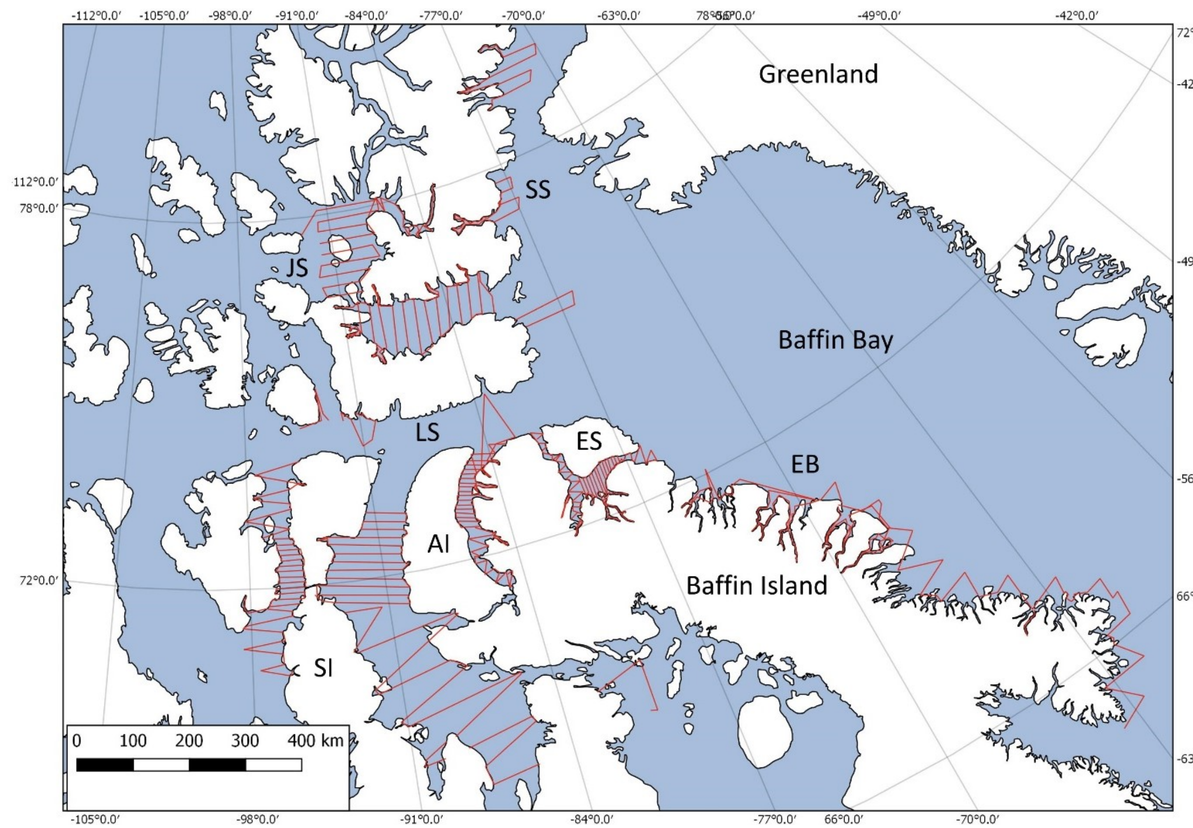

Figure 2.1 Map of the 2013 High Arctic Cetacean Survey done by the Department of Fisheries and Oceans (transect lines in red). The map identifies the geographic localities of Admiralty Inlet (AI), Eclipse Sound (ES), East Baffin (EB), Jones Sound (JS), Smith Sound (SS), Lancaster Sound (LS) and Somerset Island (SI).

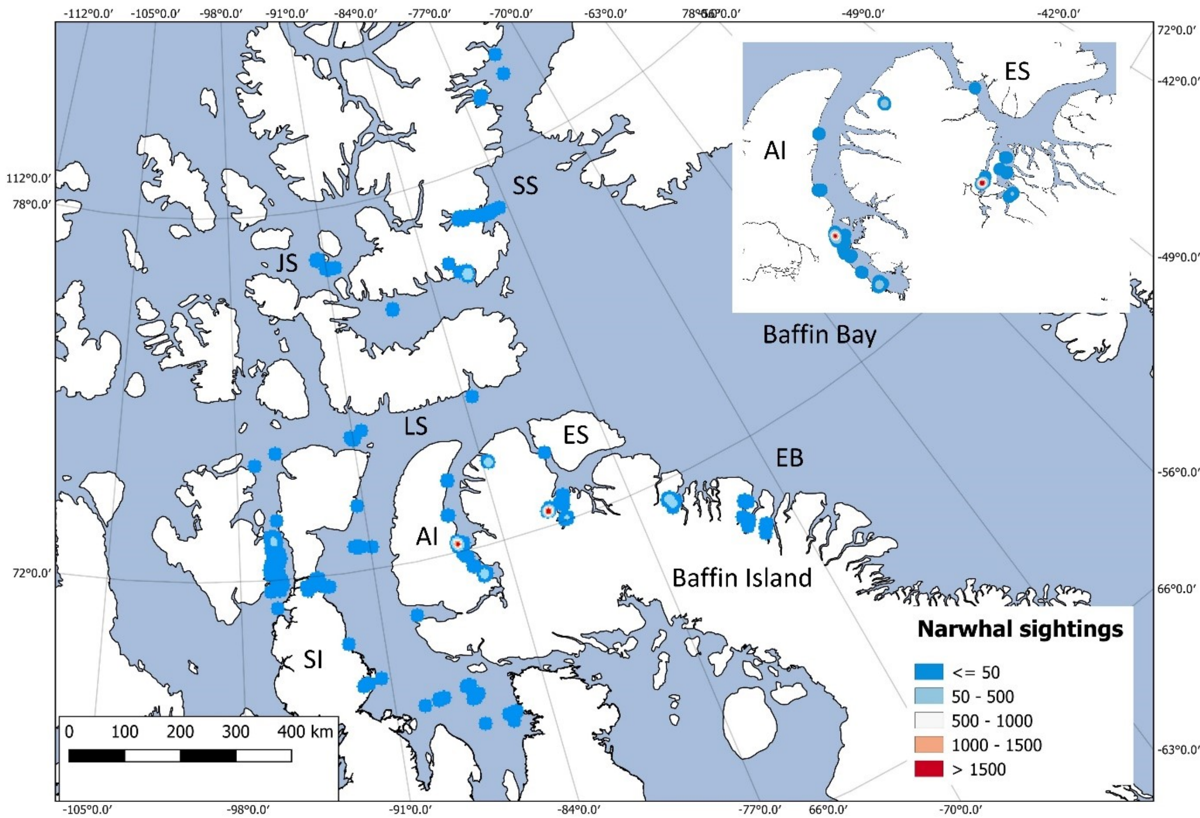

Figure 2.2 Heat map of unique narwhal sightings with a zoom on Admiralty Inlet and Eclipse Sound found in aerial photographs taken during the 2013 High Arctic Cetacean Survey. Darker reds represent higher densities of whale sightings. The map identifies the geographic localities of Admiralty Inlet (AI), Eclipse Sound (ES), East Baffin (EB), Jones Sound (JS), Smith Sound (SS), Lancaster Sound (LS) and Somerset Island (SI).

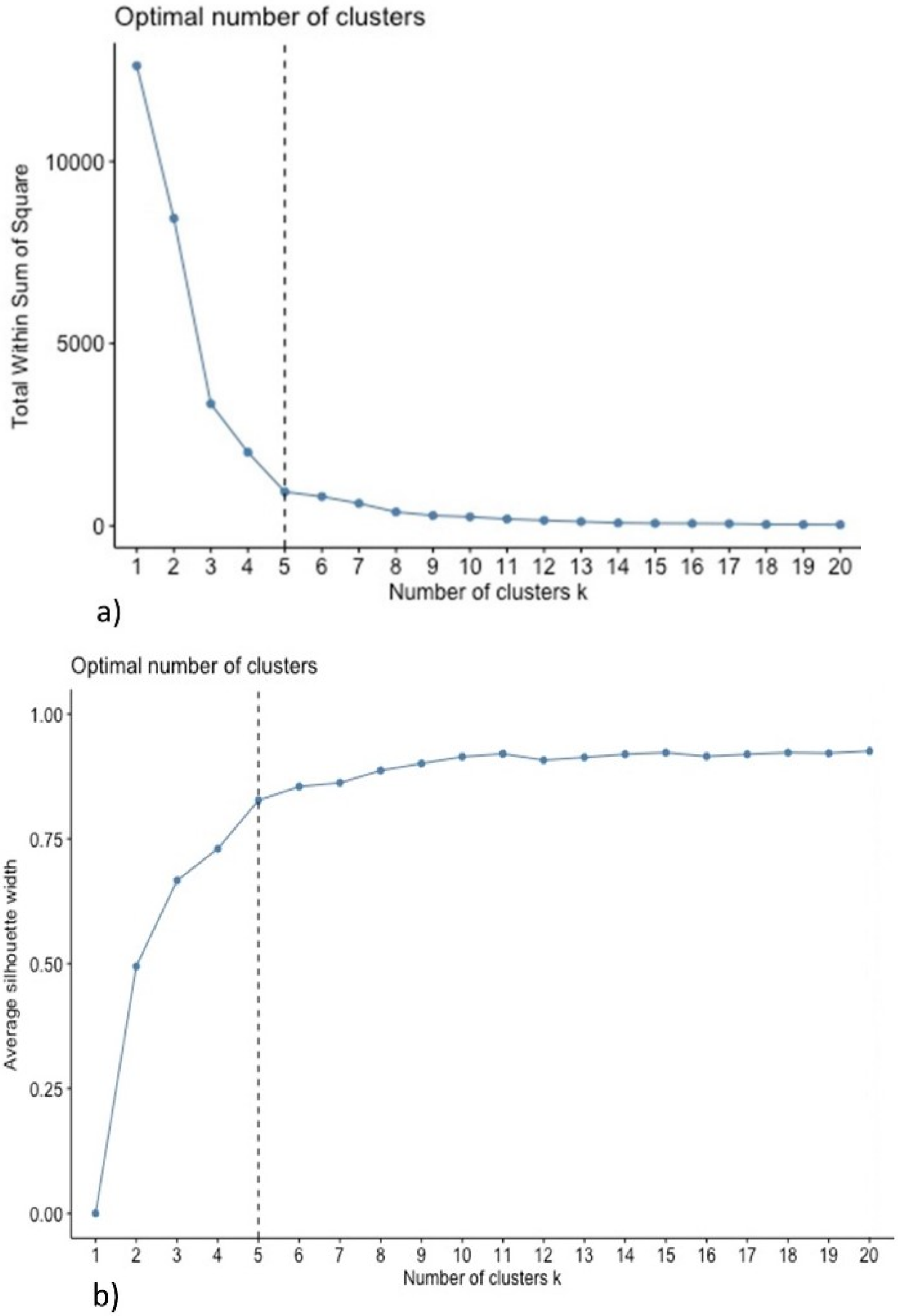

Figure 2.3 Optimal number of clusters obtained with the a) total within sum of square and b) Average silhouette width methods. The dash lines represent the optimal number of clusters.

a) b) c)

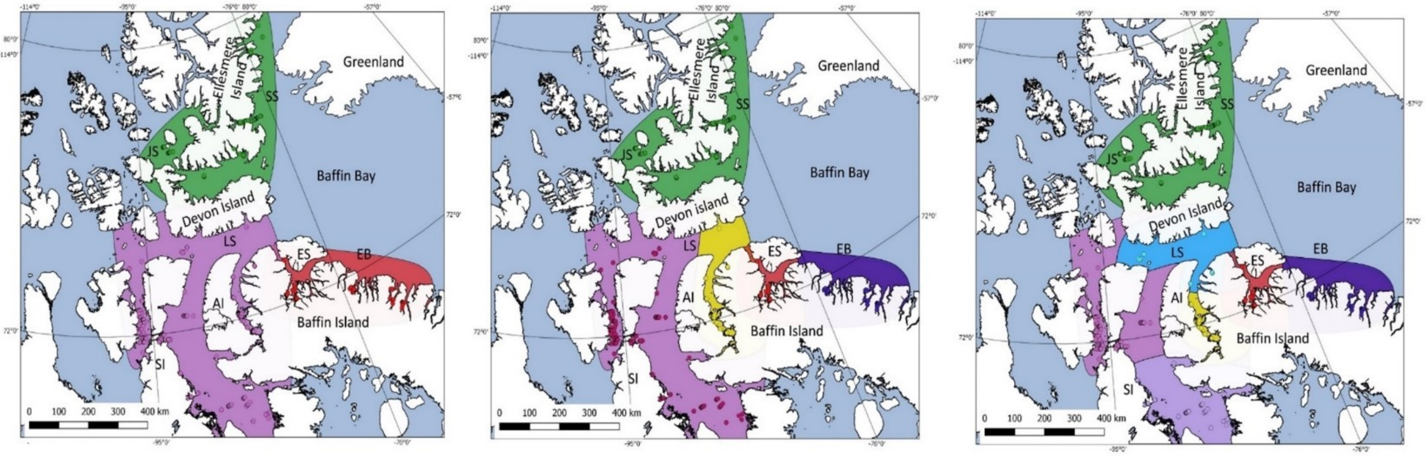

Figure 2.4 Different outcomes of cluster analysis using the partitioning around medoids (PAM). a) results of PAM to obtain three clusters (k=3), b) results of PAM to obtain five clusters (k=5), c) results of PAM to obtain seven clusters (k=7). Each cluster is represented by a different color. The map identifies the geographic localities of Admiralty Inlet (AI), Eclipse Sound (ES), East Baffin (EB), Jones Sound (JS), Smith Sound (SS), Lancaster Sound (LS) and Somerset Island (SI).

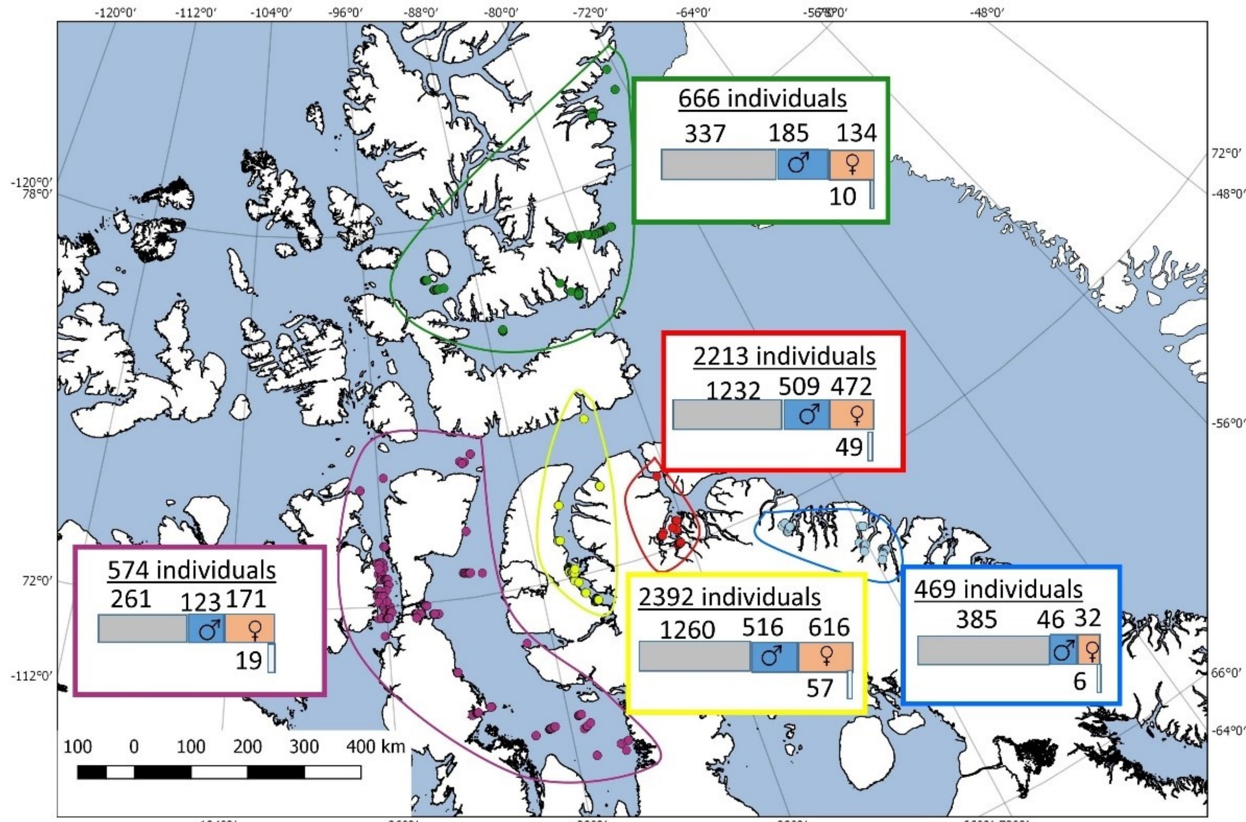

Figure 2.5 Map showing the repartition of narwhals with a detailed number of males, females, and newborns found in each of the cluster determined by the partitioning around medoids algorithm, calculated on swimming distance between individuals, to obtain five clusters (k=5). Cluster1 (red), cluster 2 (yellow), cluster 3 (blue), cluster4 (green) and cluster 5 (purple). The gray box represents the number of individuals that could not be sexed. The blue boxes represent the males; the orange boxes the females and the white boxes the newborns.

2.6 Literature Cited

Aron, William. 1988. "The Commons Revisited: Thoughts on Marine Mammal Management." *Coastal Management* 16 (2):99–110. https://doi.org/10.1080/08920758809362051.

Auger-Méthé, Marie, Marianne Marcoux, and Hal Whitehead. 2010. "Nicks and Notches of the Dorsal Ridge: Promising Mark Types for the Photo-Identification of Narwhals." *Marine Mammal Science* 26 (3):663–78. https://doi.org/10.1111/j.1748-7692.2009.00369.x.

Bleich, Vernon C., R. Terry Bowyer, and John D. Wehausen. 1997. "Sexual Segregation in Mountain Sheep: Resources or Predation?" *Wildlife Monographs*, 3–50.

Block, William M., and Leonard A. Brennan. 1993. "The Habitat Concept in Ornithology." In *Current Ornithology*, 35–91. Springer. http://link.springer.com/chapter/10.1007/978-1-4757-9912-5_2.

Bourke, Robert H., and Robert P. Garrett. 1987. "Sea Ice Thickness Distribution in the Arctic Ocean." *Cold Regions Science and Technology* 13 (3):259–280.

Caughley, Graeme. 1974. "Bias in Aerial Survey." *The Journal of Wildlife Management* 38 (4):921–33. https://doi.org/10.2307/3800067.

Caughley, Graeme, Anthony Ronald Entrican Sinclair, and others. 1994. *Wildlife Ecology and Management*. Vol. 334. JSTOR. http://www.jstor.org/stable/pdf/5904.pdf.

Ceballos, Gerardo, Paul R. Ehrlich, Jorge Soberón, Irma Salazar, and John P. Fay. 2005. "Global Mammal Conservation: What Must We Manage?" *Science* 309 (5734):603–607.

Clutton-Brock, Tim, and Ben C Sheldon. 2010. "Individuals and Populations: The Role of Long-Term, Individual-Based Studies of Animals in Ecology and Evolutionary Biology." *Trends in Ecology & Evolution*, Special Issue: Long-term ecological research, 25 (10):562–73. https://doi.org/10.1016/j.tree.2010.08.002.

Conradt, Larissa. 1998. "Measuring the Degree of Sexual Segregation in Group-Living Animals." *Journal of Animal Ecology* 67 (2):217–226.

COSEWIC. 2004. "Assessment and Update Status Report on the Narwhal Monodon Monoceros in Canada." COSEWIC.

DFO. 2013. "Evaluation of Baffin Bay Narwhal Hunt Sustainability." DFO report.

———. 2015a. "Abundance Estimates of Narwhal Stocks in the Canadian High Arctic in 2013." *DFO Can. Sci. Advis. Sec. Res.*, no. Doc. 2015/060. v:36 p.

———. 2015b. "Abundance Estimates of Narwhal Stocks in the Canadian High Arctic in 2013." Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/046. DFO.

Dietz, R., M. P. Heide-Jørgensen, P. R. Richard, and M. Acquarone. 2001. "Summer and Fall Movements of Narwhals (Monodon Monoceros) from Northeastern Baffin Island Towards Northern Davis Strait." *Arctic* 54 (3):244–61.

Dietz, Rune, Mads Peter Heide-Jørgensen, Pierre Richard, Jack Orr, Kristin Laidre, and Hans Christian Schmidt. 2008. "Movements of Narwhals (Monodon Monoceros) from Admiralty Inlet Monitored by Satellite Telemetry." *Polar Biology* 31 (11):1295–1306.

Dueck, Larry P. 1989. "The Abundance of Narwhal (Monodon Monoceros L.) in Admiralty Inlet, Northwest Territories, Canada, and Implications of Behavior for Survey Estimates." http://mspace.lib.umanitoba.ca/bitstream/handle/1993/16947/Dueck_The_abundance.pdf?sequence=1.

Eberhardt, L. Lee. 1977. "Optimal Policies for Conservation of Large Mammals, with Special Reference to Marine Ecosystems." *Environmental Conservation* 4 (03):205–212.

Eberhardt, Lester Lee, Douglas George Chapman, and James R. Gilbert. 1979. "A Review of Marine Mammal Census Methods." *Wildlife Monographs*, 3–46.

Evans, Peter G. H, and Juan Antonio Raga. 2001. *Marine Mammals: Biology and Conservation*. New York: Kluwer Academic/Plenum Publishers.

Fury, Christine Ann, Kathreen E. Ruckstuhl, and Peter L. Harrison. 2013. “Spatial and Social Sexual Segregation Patterns in Indo-Pacific Bottlenose Dolphins (Tursiops Aduncus).” *PloS One* 8 (1):e52987.

Garde, Eva, Steen H. Hansen, Susanne Ditlevsen, Ketil Biering Tvermosegaard, Johan Hansen, Karin C. Harding, and Mads Peter Heide-Jørgensen. 2015. “Life History Parameters of Narwhals (Monodon Monoceros) from Greenland.” *Journal of Mammalogy* 96 (4):866–79. https://doi.org/10.1093/jmammal/gyv110.

Harris, Grant M., Gareth J. Russell, Rudi I. van Aarde, and Stuart L. Pimm. 2008. “Rules of Habitat Use by Elephants Loxodonta Africana in Southern Africa: Insights for Regional Management.” *Oryx* 42 (1):66–75. https://doi.org/10.1017/S0030605308000483.

Hay, Keith Alexander. 1985. “The Life History of the Narwhal, Monodon Monoceros, in the Eastern Canadian Arctic.”

Heide-Jørgensen, M. P., P. R. Richard, R. Dietz, and K. L. Laidre. 2013. “A Metapopulation Model for Canadian and West Greenland Narwhals.” *Animal Conservation* 16 (3):331–43. https://doi.org/10.1111/acv.12000.

Heide-Jørgensen, Mads Peter. 2004. “Aerial Digital Photographic Surveys of Narwhals, Monodon Monoceros, in Northwest Greenland.” *Marine Mammal Science* 20 (2):246–61. https://doi.org/10.1111/j.1748-7692.2004.tb01154.x.

Heide-Jørgensen, Mads Peter, Rune Dietz, Kristin L. Laidre, Pierre Richard, Jack Orr, and Hans Christian Schmidt. 2003. "The Migratory Behaviour of Narwhals (Monodon Monoceros)." *Canadian Journal of Zoology* 81 (8):1298–1305.

Jefferson, T. A., L. Karczmarski, K. Laidre, G. O'Corry-Crowe, R. R. Reeves, L. Rojas-Bracho, E. R. Secchi, et al. 2009. *Monodon Monoceros. 2008 IUCN Red List of Threatened Species*.

Kaschner, K., R_ Watson, A. W. Trites, and D. Pauly. 2006. "Mapping World-Wide Distributions of Marine Mammal Species Using a Relative Environmental Suitability (RES) Model." *Marine Ecology Progress Series* 316:285–310.

Kaufman, Leonard, and Peter J. Rousseeuw. 2009. *Finding Groups in Data: An Introduction to Cluster Analysis*. Vol. 344. John Wiley & Sons. https://books.google.ca/books?hl=en&lr=&id=YeFQHiikNo0C&oi=fnd&pg=PR11&dq=kaufman+rousseeuw+finding+groups+in+data&ots=5zwhG7NGvD&sig=mk-5C0EfkdjRUFb0q1Npbr0gzKo.

Kingsley, Michael. 1989. "Population Dynamics of the Narwhal Monodon Monoceros: An Initial Assessment (Odontoceti: Monodontidae)." *Journal of Zoology* 219 (2):201–8. https://doi.org/10.1111/j.1469-7998.1989.tb02576.x.

Koski, William R., and Rolph A. Davis. 1994a. "Distribution and Numbers of Narwhals (Monodon." *Studies of White Whales (Delphinapterus Leucas) and Narwhals (Monodon Monoceros) in Greenland and Adjacent Waters*, 15.

———. 1994b. "Distribution and Numbers of Narwhals (Monodon Monoceros) in Baffin Bay and Davis Strait." *Meddelelser Om Grønland. Bioscience* 39:15–40.

Krebs, Charles J. 2009. “Population Dynamics of Large and Small Mammals: Graeme Caughley’s Grand Vision.” *Wildlife Research* 36 (1):1–7.

Laidre, Kristin L. 2003. “Space Use Patterns of Narwhals (Monodon Monoceros) in the High Arctic.” University of Washington. http://faculty.washington.edu/klaidre/docs/Laidre_dissertation.pdf.

Laidre, Kristin L., Patrick J. Heagerty, Mads Peter Heide-Jørgensen, Lars Witting, and Malene Simon. 2009. “Sexual Segregation of Common Minke Whales (Balaenoptera Acutorostrata) in Greenland, and the Influence of Sea Temperature on the Sex Ratio of Catches.” *ICES Journal of Marine Science* 66 (10):2253–2266.

Laidre, Kristin L., Mads P. Heide-Jørgensen, Miles L. Logsdon, Roderick C. Hobbs, Rune Dietz, and Glenn R. VanBlaricom. 2004. “Fractal Analysis of Narwhal Space Use Patterns.” *Zoology* 107 (1):3–11.

Lefebvre, Lynn W., James P. Reid, W. Judson Kenworthy, and James A. Powell. 2000. “Characterizing Manatee Habitat Use and Seagrass Grazing in Florida and Puerto Rico: Implications for Conservation and Management.” *Pacific Conservation Biology; Clayton* 5 (4):289–98.

Lindenmayer, David B., and Gene E. Likens. 2010. “The Science and Application of Ecological Monitoring.” *Biological Conservation* 143 (6):1317–1328.

Madhulatha, T. Soni. 2012. “An Overview on Clustering Methods.” *arXiv:1205.1117 [Cs]*, May. http://arxiv.org/abs/1205.1117.

Maechler, M., P. Rousseeuw, A. Struyf, A. Hubert, and K. Hornick. 2015. “Cluster: Cluster Analysis Basics and Extensions, R Package Version 2.0.3.”

Mann, Janet. 1999. “Behavioral Sampling Methods for Cetaceans: A Review and Critique.” *Marine Mammal Science* 15 (1):102–122.

———. 2000. *Cetacean Societies: Field Studies of Dolphins and Whales*. University of Chicago Press. https://books.google.ca/books?hl=en&lr=&id=W-UQNoxMONwC&oi=fnd&pg=PR9&dq=cetacean+societies+connor&ots=WSrTUQufsh&sig=TmASSVABKqxpxB21gvE3m_2J2C8.

Mansfield, A. W., T. G. Smith, and B. Beck. 1975. “The Narwhal, Monodon Monoceros, in Eastern Canadian Waters.” *Journal of the Fisheries Research Board of Canada* 32 (7):1041–46. https://doi.org/10.1139/f75-122.

Marcoux, Marianne, Marie Auger-Méthé, and Murray M. Humphries. 2009. “Encounter Frequencies and Grouping Patterns of Narwhals in Koluktoo Bay, Baffin Island.” *Polar Biology* 32 (12):1705–1716.

Moore, Sue E., and Henry P. Huntington. 2008. “Arctic Marine Mammals and Climate Change: Impacts and Resilience.” *Ecological Applications* 18 (sp2): S157–S165.

Morgan, Jessica L., Sarah E. Gergel, and Nicholas C. Coops. 2010. “Aerial Photography: A Rapidly Evolving Tool for Ecological Management.” *BioScience* 60 (1):47–59.

Morris, Douglas W. 2003. “Toward an Ecological Synthesis: A Case for Habitat Selection.” *Oecologia* 136 (1):1–13.

Morris, Douglas W., and Joel S. Brown. 1992. “The Role of Habitat Selection in Landscape Ecology.” *Evolutionary Ecology* 6 (5):357–359.

Nature, International Union for Conservation of, Natural Resources, and IUCN Species Survival Commission. 2001. *IUCN Red List Categories and Criteria*. IUCN. https://books.google.ca/books?hl=en&lr=&id=RUJui5ubKFoC&oi=fnd&pg=PP3&dq=+I

UCN+Red+List+of+Threatened+Species.+Gland:+International+Union+for+Co&ots=WXUfp5AsWo&sig=MQPmb1pwgvij9hYvOret8f03aMI.

Nichols, James D., and Byron K. Williams. 2006. "Monitoring for Conservation." *Trends in Ecology & Evolution* 21 (12):668–73. https://doi.org/10.1016/j.tree.2006.08.007.

Ohsumi, Seiji. 1966. "Sexual Segregation of the Sperm Whale in the North Pacific." *Scientific Reports of the Whales Research Institute, Tokyo* 20:1–16.

Petersen, S.D., D. Tenkula, and S.H. Ferguson. 2011. "Population Genetic Structure of Narwhal (Monodon Monoceros). DFO Can. Sci. Advis. Sec. Res. Doc. 2011/021. vi + 20 P."

Petersen, S.D., D. Tenkula, S.H. Ferguson, T. Kelley, and D.J. Yurkowski. 2012. "Sex Determination of Belugas and Narwhals: Understanding Implications of Harvest Sex Ratio." *DFO Can. Sci. Advis. Sec. Res. Doc.*, no. 2012/019. iii:+ 9 p.

Pompa, Sandra, Paul R. Ehrlich, and Gerardo Ceballos. 2011. "Global Distribution and Conservation of Marine Mammals." *Proceedings of the National Academy of Sciences* 108 (33):13600–605. https://doi.org/10.1073/pnas.1101525108.

RDevelopment, CORE. n.d. "TEAM 2011: R: A Language and Environment for Statistical Computing." *R Foundation for Statistical Computing, Vienna, Austria*.

Redfern, J. V., M. C. Ferguson, E. A. Becker, K. D. Hyrenbach, Caroline P. Good, J. Barlow, K. Kaschner, et al. 2006. "Techniques for Cetacean–habitat Modeling." http://darchive.mblwhoilibrary.org/handle/1912/4510.

Richard, P. R., J. L. Laake, R. C. Hobbs, M. P. Heide-Jørgensen, N. C. Asselin, and H. Cleator. 2010. "Baffin Bay Narwhal Population Distribution and Numbers: Aerial Surveys in the Canadian High Arctic, 2002-04." *Arctic* 63 (1):85–99.

Richard, Pierre, and Patt Weaver. 1994. “Distribution and Numbers of Canadian High Arctic Narwhals (Monodon Monoceros) in August 1984.” *Meddelelser Om Grønland, Bioscience* 39.

Ruckstuhl, K. E. 2007. “Sexual Segregation in Vertebrates: Proximate and Ultimate Causes.” *Integrative and Comparative Biology* 47 (2):245–57. https://doi.org/10.1093/icb/icm030.

Ruckstuhl, Kathreen E. 1998. “Foraging Behaviour and Sexual Segregation in Bighorn Sheep.” *Animal Behaviour* 56 (1):99–106.

Ruckstuhl, Kathreen E., and Peter Neuhaus. 2000. “Sexual Segregation in Ungulates: A New Approach.” *Behaviour* 137 (3):361–377.

Silverman, Helen B. 1979. “Social Organization and Behaviour of the Narwhal: Monodon Monoceros L. in Lancaster Sound, Pond Inlet, and Tremblay Sound, Northwest Territories.”

Van Etten, Jacob. 2012. “Gdistance: Distances and Routes on Geographical Grids. R Package Version 1.1-4.” *Available a T CRAN. R-Project. Org/Package= Gdistance*.

Walsh, John E. 2008. “Climate of the Arctic Marine Environment.” *Ecological Applications* 18 (sp2): S3–22. https://doi.org/10.1890/06-0503.1.

Watt, C. A., J. Orr, B. LeBlanc, P. Richard, and S. H. Ferguson. 2012. “Satellite Tracking of Narwhals (Monodon Monoceros) from Admiralty Inlet (2009) and Eclipse Sound (2010–22011).” *DFO Canadian Science Advisory Secretariat Research Document* 46.

Watt, Cortney A., and Steven H. Ferguson. 2015. “Fatty Acids and Stable Isotopes (δ13C and δ15N) Reveal Temporal Changes in Narwhal (Monodon Monoceros) Diet Linked to Migration Patterns.” *Marine Mammal Science* 31 (1):21–44. https://doi.org/10.1111/mms.12131.

Watt, Cortney A., Steven H. Ferguson, Aaron Fisk, and Mads Peter Heide-Joergensen. 2012. "Using Stable Isotope Analysis as a Tool for Narwhal (Monodon Monoceros) Stock Delineation. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/057. Iv + 29 P." *DFO Can. Sci. Advis. Sec. Res. Doc. 2012/057. Iv + 29 P.*

Summary and final conclusions

In this thesis, I explored the use of aerial photography to study narwhal population structure and distribution. I first assessed the ability to recognize narwhal newborns by developing a dichotomous key. This also provided some information on narwhal newborn-mother relationships (Chapter 1). I then looked at the sex distribution and aggregations of narwhals in their summering-grounds (Chapter 2).

Identification of narwhal newborns

Understanding the dynamics and structure of a population is important knowledge to manage and conserve wild species adequately (Whitehead, Reeves, and Tyack 2000). In long-lived species such as narwhals, newborns are an important age class used as one indicator of population health and viability (Fowler 1988). IUCN and COSEWIC mention lack of knowledge on this species as a reason for their "Species of Concern" and "Near Threatened" status; it is, therefore, important to obtain demographic and spatial information on narwhal population. I created a dichotomous key to differentiate newborn narwhals from other whales based on physical characteristics of narwhal newborns and also based on typical mother-newborn spacing patterns described in previous cetacean research. The dichotomous key provided a replicable method to detect newborns from aerial photographs by different observers.

Narwhal mother-newborn spatial relation

Narwhal mother-newborn interactions have never been studied in detail. The results of my first chapter give some insight into the spatial relationship between narwhal mother-newborn dyads. In other odontocetes such as bottlenose dolphins (*Tursiup truncatus*) and beluga whales (Delphinapterus *leucas*) newborns in the few weeks after their birth spend a large amount of their time in close proximity to their mother. They are either slightly underneath their mother's fluke (infant position) or at their mother's mid-lateral flank (echelon position) due to their limited swimming capabilities (Mann and Smut 1999; Gubbins et al. 1999; Mann 2000; Krasnova, Bel'kovich, and Chernetsky 2006; Krasnova, Bel'kovich, and Chernetskii 2009). I found narwhal newborns exhibited similar position preferences. Most newborns-mother dyads were associated with another adult female forming groups of three individuals. This is also consistent with previous observations done on narwhals (Hay 1985; Koski and Davis 1994; Marcoux, Auger-Méthé, and Humphries 2009).

Narwhal aggregation

Narwhals are known to be unevenly distributed across the Canadian Arctic during the summer, forming different aggregations with large numbers, concentrated in relatively few fjords (Koski and Davis 1994; Richard and Weaver 1994). For management purposes, such as determining hunting quotas for northern communities, DFO has identified six management zones which are intended to reflect major narwhal aggregations in the region (Richard 2010; DFO 2013, 2015) based on general knowledge of narwhals in the region derived from telemetry tags, aerial surveys, land observations, genotyping of harvested individuals, and traditional knowledge (Koski and Davis 1994; Richard 1994; Palsboell Heide-Jørgensen, and Dietz 1997; Dietz et al. 2008; Marcoux, Auger-Méthé, and Humphries 2009; Richard et al. 2010; Watt et al. 2012; DFO 2015). In this study, I looked at narwhal distribution using only on swimming distances and a purely quantitative clustering approach, my findings are in broad alignment with the DFO zones, re-enforcing the management unit defined by DFO.

Sex and newborn distribution

Little is known about the sex distribution of narwhals in the Canadian Arctic and only a few studies looked at sex distribution in some part of the Eastern Canadian Arctic (Mansfield, Smith, and Beck 1975; Silverman 1979). The analysis of Chapter 2 gave more information of the sex distribution of narwhals across the Canadian Arctic Archipelago. Narwhals presented different male: female sex ratio in each of the different cluster varying from 0.71 to 1.40. An interesting observation was the high male:female sex ratio observed in the region of Eclipse Sound in this study correspond to the male:female sex ratio biased found by Silverman in 1979. This suggests a real trend of the sex ratio biased towards the males in this region.

Newborns were also distributed across the Canadian Arctic Archipelago. I found more newborns in the regions were more narwhals were sighted. And the proportion of newborns relative to the number of adult females sighted varied between 7 to 18% depending on the region. This finding is in accordance with a 10% proposed by Mansfield, Smith, and Beck in 1975 and Kingsley in 1989.

Future directions

As a non-invasive remote sensing method, aerial photography offers many opportunities to gain new knowledge of narwhal population dynamics and habitat selection. Developing a long-term monitoring of narwhal populations will be essential in the near future to manage and conserve this species living in an environment changing rapidly. The use of aerial photography can help get valuable information about population structure and habitat use over a large spatial scale. However, to extract the best information offered by photographs it is essential to conduct more in situ research. Nowadays narwhal research requires a limited amount of time spent in the field reducing the opportunity for the researcher to observe them in nature (Mann 2000). The high cost and environmental challenges of fieldwork in the Arctic limit time spent on the field. However, new technology such as unmanned aircraft systems (UAS) could be a good alternative to increase our time to observe narwhals in their environment (Fiori et al. 2017). Researchers could use UAS to design and conduct focal sampling by recording a large number of videos that could be analyzed later in the laboratory.

As the next step to my thesis, it would be interesting to conduct a focal sampling study following narwhal mother-newborn dyads to improve our knowledge of their behaviors and interactions. This knowledge will help to improve our detection of newborns from photographs and establish a correction factor to account for newborns under the surface when calculating abundance estimates. This type of study would also help to establish a baseline of undisturbed behavior of newborns prior to new disturbances.

Literature Cited

DFO. 2013. Evaluation of Baffin Bay Narwhal Hunt Sustainability. DFO Can. Sci. Advis. Sec.Sci. Advis. Rep. 2012/038.

DFO. 2015. Abundance Estimates of Narwhal Stocks in the Canadian High Arctic in 2013. DFO, pp.

Fiori, L., A. Doshi, E. Martinez, M. B. Orams, and B. Bollard-Breen. 2017. The Use of Unmanned Aerial Systems in Marine Mammal Research. Remote Sensing, 9(6):543, https://doi.org/10.3390/rs9060543.

Fowler, C. W. 1988. Population dynamics as related to rate of increase per generation. Evolutionary Ecology, 2(3):197–204, https://doi.org/10.1007/BF02214283.

Gubbins, C., B. Mcowan, S. K. Lynn, S. Hooper, and D. Reiss. 1999. Mother-infant spatial relations in captive bottlenose dolphins, Tursiops truncatus. Marine Mammal Science, 15(3):751–765.

Hay, K. A. 1985. The life history of the narwhal, Monodon monoceros, in the eastern Canadian arctic. p.

Kingsley, M. 1989. Population dynamics of the narwhal Monodon monoceros: an initial assessment (Odontoceti: Monodontidae). Journal of Zoology, 219(2):201–208, https://doi.org/10.1111/j.1469-7998.1989.tb02576.x.

Koski, W. R., and R. A. Davis. 1994. Distribution and numbers of narwhals (Monodon. Studies of White Whales (Delphinapterus Leucas) and Narwhals (Monodon Monoceros) in Greenland and Adjacent Waters, 15.

Krasnova, V. V., V. M. Bel'kovich, and A. D. Chernetsky. 2006. Mother-infant spatial relations in wild beluga (Delphinapterus leucas) during postnatal development under natural conditions. Biology Bulletin, 33(1):53–58, https://doi.org/10.1134/S1062359006010079.

Krasnova, V. V., V. M. Bel'kovich, and A. D. Chernetskii. 2009. Formation of behavior in the White Sea beluga calf, Delphinapterus leucas, during early postnatal ontogenesis. Russian Journal of Marine Biology, 35(1):53–59, https://doi.org/10.1134/S1063074009010088.

Legg, C. J., and L. Nagy. 2006. Why most conservation monitoring is, but need not be, a waste of time. Journal of Environmental Management, 78(2):194–199, https://doi.org/10.1016/j.jenvman.2005.04.016.

Mann, J. 2000. Cetacean Societies: Field Studies of Dolphins and Whales. University of Chicago Press, pp.

Mann, J., and Smut. 1999. Behavioral development of wild bottlenose dolphin newborns. Behaviour, 136(5):529–566, https://doi.org/10.1163/156853999501469.

Mansfield, A. W., T. G. Smith, and B. Beck. 1975. The Narwhal, Monodon monoceros, in Eastern Canadian Waters. Journal of the Fisheries Research Board of Canada, 32(7):1041–1046, https://doi.org/10.1139/f75-122.

Marcoux, M., M. Auger-Méthé, and M. M. Humphries. 2009. Encounter frequencies and grouping patterns of narwhals in Koluktoo Bay, Baffin Island. Polar Biology, 32(12):1705–1716.

Richard, P. 2010. Stock Definition of Belugas and Narwhals in Nunavut. Fisheries and Oceans Canada, Science, Central and Arctic Region, pp.

Richard, P., and P. Weaver. 1994. Distribution and numbers of Canadian High Arctic narwhals (Monodon monoceros) in August 1984. Meddelelser Om Grønland, Bioscience, 39.

Silverman, H. B. 1979. Social organization and behavior of the narwhal: Monodon monoceros L. in Lancaster Sound, Pond Inlet, and Tremblay Sound, Northwest Territories. p.

Thomas, L. 1996. Monitoring Long-Term Population Change: Why are there so Many Analysis Methods? Ecology, 77(1):49–58.

Whitehead, H., J. Christal, and P. L. Tyack. 2000. Studying cetacean social structure in space and time. Cetacean Societies: Field Studies of Dolphins and Whales, 65–86.