2016 AERIAL SURVEY OF THE WESTERN HUDSON BAY POLAR BEAR SUB-POPULATION

FINAL REPORT

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Disclaimer

Summary

Climatic change has been experienced across the globe during the past 30 years with some transformations now being observed in the Arctic. For example, the sea-ice habitat for some polar bear subpopulations is now experiencing later freeze-up and earlier melt. Other studies documented correlations between these environmental changes and reduction of body mass, survival rates, and reproductive performance of a few polar bear subpopulations. These type of population-wide changes require careful, and at times intense, monitoring in order to inform the status of these subpopulations.

In August 2016, the Government of Nunavut (GN) conducted an aerial survey of the Western Hudson Bay (WH) polar bear subpopulation in order to update its status. Pre-survey consultations with Nunavut HTOs and communities, and with the Manitoba Department of Sustainable Development were conducted in order to utilize local and traditional knowledge in the study design. Nunavummiut living within the range of this subpopulation have repeatedly indicated that they feel the abundance of polar bears has increased within Nunavut. Other studies of WH suggest that numbers appear to have stabilized between 2001-2011 following a period of decline between 1987-2004. The last GN aerial survey produced an estimate of 1030 bears (95% CI: 745–1406) in 2011. Final survey results of this study (2016) produced an estimate of 842 bears (95% CI: 562–1121). The estimate is not significantly different from the 2011 aerial survey estimate of 949[1] bears (95%CI: 618–1280) based upon similar transect sampling methods and analysis of covariates.

A double observer distance-sampling method was employed to estimate abundance. During this survey, bears were observed by front and rear observers from aircraft following inland transects oriented perpendicularly to the coastline. During August 2016, the majority of bears were distributed within 10km of the coast, with the exception of Wapusk National Park where some bears were observed greater than 80 km inland. Very few bears were observed in Nunavut, and a substantial proportion of

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[1] During the 2011 aerial survey, coastal and inland transects were flown, which were not identical to the 2016 survey and therefore these estimates are not directly comparable. Regardless, when the derived abundance estimate of 1030 bears from the 2011 survey is statistically compared with the 2016 estimate, no significant difference between those two estimates can be detected.

bears, mostly adult males, were encountered in large concentrations in the south-east section of the study area towards the Manitoba-Ontario border. Cubs and yearlings comprised a small proportion of the sample size, which was also observed during previous studies. This suggests that reproductive performance is low for this subpopulation but this was not a specific objective of this study.

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ᓯᓚᐅᑉ ᐊᓯᔾᔨᖅᐸᓪᓕᐊᓂᖓ ᖃᐅᔨᔾᔭᑕᐅᓯᒪᖕᒪᑦ ᓄᓇᕐᔪᐊᓕᒫᒥ ᐊᕐᕌᒍᑦ 30 ᐊᓂᒍᖅᑎᓪᓗᒋᑦ ᐊᓯᔾᔩᓂᖃᖅᑐᓂ ᖃᐅᔨᓴᖅᑕᐅᓪᓗᓂ ᐅᑭᐅᖅᑕᖅᑐᒥ. ᐆᒃᑑᑎᒋᓗᒍ, ᐃᒪᕐᒥᐅᑕᓄᑦ ᐃᓚᖏᓐᓄᑦ ᓇᓄᕐᓄᑦ ᓇᓅᖃᑎᒃᑲᓐᓂᖏᓐᓄᑦ ᖃᐅᔨᔾᔪᑎᖃᖅᓯᒪᓕᕐᒪᑕ ᕿᐊᖅᓴᕋᐃᙱᓐᓂᖅᓴᐅᓕᖅᑐᒥᒃ ᐊᒻᒪ ᐊᐅᒃᓵᓕᓂᖅᓴᐅᓕᖅᑐᒥᒃ. ᐊᓯᖏᑦ ᖃᐅᔨᓴᕈᑕᐅᔪᑦ ᑎᑎᖅᑕᐅᔪᑦ ᐊᕙᑎᒧᑦ ᐊᓯᔾᔨᕐᓂᒃᑯᑦ ᐊᒻᒪ ᐊᑦᑎᒃᓯᒋᐊᕐᓂᒃᑯᑦ ᑎᒥᐅᑉ ᐅᕐᑯᒪᐃᓐᓂᖓᓂᒃ, ᖃᓄᖅ ᐊᑯᓂᐅᑎᒋᔪᖅ ᐆᒪᕙᒻᒪᖔᑕ, ᐱᓕᕆᔪᓐᓇᑦᑎᐊᕐᓂᕐᒧᑦ ᐱᓕᕆᓂᕆᔭᖏᑦ ᓇᓄᕐᓄᑦ ᓇᓅᖃᑎᒃᑲᓐᓂᖏᓐᓄᓪᓗ. ᑕᒪᒃᑯᐊ ᐃᓄᒋᔭᐅᔪᓕᒫᓄᑦ-ᐊᔾᔨᒌᙱᑦᑐᓘᔭᖅᑐᓄᑦ ᐊᓯᔾᔨᕐᓃᑦ ᐅᔾᔨᖅᓱᑦᑎᐊᕐᓗᓂ, ᐃᓛᓐᓂᒃᑯᓪᓗ ᐊᒃᓱᕈᖅᓴᖅᓗᓂ, ᓇᐅᑦᑎᓱᖅᐸᓪᓕᐊᓂᖅ ᓇᓗᓇᐃᖅᓯᓂᕐᒧᑦ ᖃᓄᐃᓕᖓᓕᕐᓂᕆᔭᐅᔪᓂᑦ ᑖᒃᑯᐊ ᓇᓅᖃᑎᒃᑲᓐᓂᖏᓪᓗ.

ᐊᐅᔭᖓ 2016-ᒥ, ᓄᓇᕗᑦ ᒐᕙᒪᖓ ᐱᓕᕆᐊᖃᓚᐅᕐᒪᑦ ᖃᖓᑕᓲᒃᑯᑦ ᓈᓴᐃᓂᕐᒥᒃ ᑕᓯᐅᔭᕐᔪᐊᑉ ᐱᖓᓐᓇᖓᓂ ᓇᓄᖕᒋᑦ ᓇᓅᖃᑎᒃᑲᓐᓂᖏᓪᓗ ᓄᑖᙳᕈᐊᖅᑎᑦᑎᓂᕐᒧᑦ ᖃᓄᐃᓕᖓᓕᕐᓂᕆᔭᐅᔪᕐᒥᒃ. ᓇᐃᓴᖅᑕᐅᓚᐅᙱᑎᓪᓗᒋᑦ ᐅᖃᖅᑎᒌᒃᑎᑦᑎᓂᖅ ᓄᓇᕘᒥ ᐊᖑᓇᓱᒃᑐᓕᕆᔨᖏᓐᓂᒃ ᓄᓇᓕᖕᒥᐅᓂᓪᓗ, ᐊᒻᒪ ᒫᓂᑑᐸᒥᑦ ᐃᑯᐱᒃᓴᓕᕆᔩᒃᑯᑦ ᐱᓕᕆᐊᖃᓚᐅᖅᑐᑦ ᐊᑐᓕᖅᑎᑦᑎᓂᕐᒧᑦ ᓄᓇᓕᖕᓂ ᐊᒻᒪ ᐃᓄᐃᑦ ᖃᐅᔨᒪᓂᑐᖃᖏᑦ ᖃᐅᔨᓴᕐᓂᕐᒧᑦ ᐋᖅᑭᐅᒪᓂᖓᓂᒃ. ᓄᓇᕘᒥᐅᑦ ᓄᓇᖃᖅᑐᑦ ᐊᔪᙱᓂᖃᖅᑐᑎᒃ ᓇᓅᖃᑎᒃᑲᓐᓂᖏᓐᓂᒃ ᓇᓗᓇᐃᖅᔫᓇᖅᑐᑦ ᖃᓄᖅ ᐅᓄᖅᑎᒋᓂᖏᓐᓂᒃ ᓄᓇᐃᑦ ᐅᓄᖅᓯᒋᐊᖅᓯᒪᔪᖅ ᓄᓇᕘᑉ ᐃᓗᐊᓂ. ᐊᓯᖏᑦ ᖃᐅᔨᓴᕈᑎᑦ ᑕᓯᐅᔭᕐᔪᐊᑉ ᐱᖓᓐᓇᖓᓂ ᐅᖃᖅᓯᒪᔪᖅ ᖃᑦᓯᐅᓂᖏᑦ ᓴᖅᑭᓐᓂᖏᓐᓄᑦ ᓇᖕᒋᐊᕐᓇᖅᑑᑦᑎᑦᑐᓐᓃᖅᑎᑕᐅᔭᓇᐊᖃᕐᓂᖏᓐᓄᑦ 2001-ᒧ 2011-ᒧ ᐊᑯᓐᓂᖓᓂᒃ ᒪᓕᒃᓗᓂ ᐊᖏᖅᑕᐅᓚᐅᖅᓯᒪᙱᑦᑐᒥᑦ 1987-ᒥᑦ 2004-ᒧᑦ. ᑭᖑᓪᓕᖅᐹᖅ ᓄᓇᕗᑦ ᒐᕙᒪᖓᑕ ᖃᖓᑕᓲᒃᑯᑦ ᖃᐅᔨᓴᕐᓂᖓᑦ ᓴᖅᑭᑦᑎᓚᐅᖅᐳᖅ ᐃᒪᓐᓇᐅᓇᓱᒋᔭᐅᔪᓂᒃ 1030 ᓇᓄᐃᑦ (95% CI: 745-1406) 2011-ᒥ. ᐋᖅᑭᒋᐊᖅᑕᐅᒃᑲᓂᔾᔫᙱᑦᑐᑦ ᓇᐃᓴᖅᑕᐅᓂᖏᑦᑕ ᓴᖅᑭᓐᓂᖏᑦ ᑕᒪᑐᒧᖓ ᖃᐅᔨᓴᕐᓂᐅᔪᒧᑦ (2016ᒧᑦ) ᓴᖅᑭᑦᑎᓚᐅᖅᐳᑦ ᐃᒪᓐᓇᐅᓇᓱᒋᔭᐅᔪᓂᒃ 842 ᓇᓄᐃᑦ (95% CI: 562–1121). ᑕᒪᓐᓇ ᐃᒪᓐᓇᐅᓇᓱᒋᔭᐅᓂᖅ ᐅᔾᔨᕐᓇᖅᑐᒻᒪᕆᐅᒥ ᐊᓯᔾᔨᕐᓂᖃᕐᒪᑦ 2011-ᒥᑦ ᖃᖓᑕᓲᒃᑯᑦ ᖃᐅᔨᓴᕐᓂᖅ ᐃᒪᓐᓇᐅᓇᓱᒋᔭᐅᔪᖅ 949[2] ᓇᓄᐃᑦ (95% CI: 618-1280) ᐊᑐᖅᓱᑎᒃ ᐊᔾᔨᑲᓴᖕᒋᓐᓂᒃ ᐃᓂᖏᓐᓂᒃ ᖃᐅᔨᓴᕋᒃᓴᑦ ᓇᓗᓇᐃᔭᖅᓯᒪᔪᑦ ᐅᕝᕙᓘᓐᓃᑦ ᖃᐅᔨᓴᕐᑕᐅᓯᒪᔪᑦ ᓇᓗᓇᐃᔭᖅᓯᒪᓂᖏᑦ.

ᖃᐅᔨᓴᐃᒃᑲᓂᖅᑎ ᐅᖓᓯᒃᑎᒋᔪᓐᓇᕐᓂᕆᔭᖓᓂᒃ ᐊᑐᖅᑕᐅᔾᔪᖓᓄᑦ ᐃᖅᑲᓇᐃᔭᕝᕕᐅᓚᐅᖅᑐᖅ ᒥᔅᓴᐅᓴᒃᑕᐅᓯᒪᔪᑦ ᖃᓄᖅ ᐅᓄᖅᑎᒋᓂᖏᑦ. ᑕᒪᑐᒪᓂ ᓇᐃᓴᐃᓂᕐᒥ, ᓇᓄᐃᑦ ᖃᐅᔨᔭᐅᓯᒪᔪᑦ ᓯᕗᓂᐊᒍᑦ ᑭᖑᓂᐊᒍᓪᓗ ᖃᐅᔨᓴᖅᑎᓂᒃ ᖃᖓᑕᓲᒃᑯᑦ ᒪᓕᒃᓱᑎᒃ ᖃᕝᕙᓯᒃᑐᖅ ᐃᓂᖏᑦ ᖃᐅᔨᒪᑎᑕᐅᓂᖅ ᓴᓂᖓᔪᓕᕐᓂᒃ ᓯᒡᔭᒧᑦ. ᐊᐅᔭᖓ 2016-ᒥ, ᐅᓄᕐᓂᖅᓴᐃᑦ ᓇᓄᐃᑦ ᓇᓂᔭᐅᓚᐅᖅᑐᑦ 10kmᒥ ᐅᖓᓯᒃᑎᒋᔭᒥ ᓯᒡᔭᒥ, ᑕᐃᒪᓐᓇᐅᓚᐅᖅᓯᒪᒐᓗᐊᕐᓂᓪᓗᓂ ᕗᐊᑑᒃ ᒥᕐᖑᐃᖅᓯᕕᖕᒥᑦ ᓇᓄᐃᑦ ᖃᐅᔨᔭᐅᓚᐅᖅᑐᑦ 80km ᐅᖓᑖᓂ ᖃᕝᕙᓯᒃᑐᒥ. ᖃᔾᔫᓇᑯᓗᐃᑦ ᓇᓄᐃᑦ ᖃᐅᔨᔭᐅᓚᐅᖅᑐᑦ ᓄᓇᕗᒻᒥ, ᐊᖏᕚᑎᒻᒪᕆᖓᓂᒃ ᓄᓇᓕᒃ, ᐃᓐᓇᐅᓂᖅᓴᐅᓪᓗᑎᒃ ᐊᖑᓴᓪᓗᐃᑦ, ᓇᓂᔭᐅᓚᐅᖅᑐᑦ ᓂᕆᖅᑲᓇᖕᓇᖅᐸᓯᐊᕐᒥ ᖃᐅᔨᓴᖅᑕᐅᓂᓇᔭᕐᓂᖏᓐᓂᒃ ᒫᓂᑑᐸᐋᓐᑎᐅᓇᔾ ᑭᓪᓕᖓᓂ. ᐊᑎᖅᑕᓛᑦ ᐊᒻᒪ ᐊᑎᖅᑕᕙᓃᑦ ᐃᓚᒋᔭᐅᓚᐅᖅᑐᑦ ᒥᑭᑦᑑᕋᓗᐊᒥᑦ ᖃᐅᔨᓴᕋᒃᓴᓄᑦ, ᖃᐅᔨᓴᖅᑕᐅᓚᐅᖅᑐᑦ ᖃᐅᔨᓴᐃᓚᐅᖅᑎᓪᓗᒋᑦ. ᑕᐃᒪᓐᓇ

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[2] 2011-ᒥ ᖃᖓᑕᓲᒃᑯᑦ ᖃᐅᔨᓴᕐᓂᖅᑕᖅᑎᓪᓗᒍ, ᓯᕗᖅᐸᓯᕐᒥᐅᑦ ᐊᒻᒪ ᖃᕝᕙᓯᒃᑐᑦ ᐃᓂᖏᑦ ᓇᒃᓯᐅᔾᔭᐅᓚᐅᕐᒪᑕ, ᐊᔾᔨᒋᙱᓪᓗᓂᒋᑦ 2016-ᒥ ᓇᐃᓴᖅᑕᐅᓯᒪᔪᓂ ᑕᐃᒪᐃᓐᓂᖓᓄᑦ ᑖᒃᑯᐊ ᒥᔅᓴᐅᓴᒃᑕᐅᓯᒪᔪᑦ ᐊᔾᔨᒌᒍᓐᓇᙱᓂᖏᓐᓄᑦ. ᑕᐃᒪᐃᒃᑲᓗᐊᖅᑎᓪᓗᒍ, ᐱᔭᐅᓚᐅᖅᑐᑦ ᖃᓄᖅ ᐅᓄᖅᑎᒋᓂᖏᑦ ᒥᔅᓴᐅᓴᒃᑕᐅᓯᒪᔪᑦ 1030 ᓇᓄᐃᑦ 2011-ᒥ ᓇᐃᓴᖅᑕᐅᓂᖏᑦ ᐊᔾᔨᒌᙱᓐᓂᖏᓐᓂᒃ ᐊᔾᔨᒌᓐᓂᖏᓐᓂᓪᓗᓐᓃᑦ ᖃᐅᔨᓴᕐᓂᒃᑯᑦ 2016-ᒥ ᒥᔅᓴᐅᓴᒃᑕᐅᓯᒪᔪᓂᑦ, ᐊᔾᔨᒌᙱᓂᖃᓗᐊᓚᐅᙱᑦᑐᑦ ᑖᒃᑯᐊᒃ ᒪᕐᕉᒃ ᒥᔅᓴᐅᓴᒃᑕᐅᓯᒪᔪᑦ ᐅᔾᔨᕆᔭᐅᔪᓐᓇᕐᓂᖏᓐᓄᑦ.

ᐃᓱᒪᒋᔭᐅᖕᒪᑦ ᐃᕐᓂᐅᕐᓂᖅ ᐊᑦᑎᖕᓂᖕᒐᓄᑦ ᓇᓅᖃᑎᒋᖕᓄᑦ ᑭᓯᐊᓂ ᑕᒪᓐᓇ ᑐᕌᒐᕆᔭᐅᖖᒋᓪᒪᑦ ᑕᒪᑐᒧᖕᒐ ᖃᐅᔨᓴᕐᓂᕐᔪᑦ.

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Person Days

Field work during the 2016 field season (12 – 21 August) involved approximately 76 person days (24 person days by Twin Otter, 52 person days by helicopters).

Aircraft Hours

We flew a total of approximately 132.5 hrs during our field study, including ferry times. These hours were distributed as follows: 55.2 hrs by Twin Otter, 33.7 hrs by the EC135, and 43.6 hrs by the Bell 206 L4.

Field Dates

Field activities for the aerial survey of the western Hudson Bay (WH) polar bear subpopulation took place between 12 and 21 August 2016. There was only one weather delay day during the survey affecting only the EC135 crew. The Bell LR4 crew was stationed in a different field location and was able to fly all survey days.

Fieldwork Location

The survey began with a Twin Otter aircraft positioned initially in Rankin Inlet, Nunavut. We worked the Nunavut coastline including islands, south towards Churchill, Manitoba. During the Nunavut portion of the survey we were positioned in Rankin Inlet and Arviat, finally completing the Twin Otter portion in Churchill, Manitoba. Once in Churchill, the survey utilized two helicopters including an EC135, which was based in Churchill and working south, and a Bell LR4 which was positioned in the York Factory area (Marsh Point) and working north within Wapusk National Park. Once the high-density area between Churchill and the Nelson River was completely surveyed, the EC135 relocated to York Factory National Historic Site while the LR4 remained positioned at Marsh Point, and surveyed the Cape Tatnam area west to Kaskattama near the Manitoba/Ontario border. Both field camps were used to complete the survey area between the Nelson River and the eastern extent of the study area (Figure 1). For this survey we flew a total (transect) distance of approximately 9,700 km.

1. INTRODUCTION

Polar bears (*Ursus maritimus* Phipps, 1774) hold a place of cultural and spiritual significance in Inuit traditional lifestyles (Honderich 2001; Henri et al. 2010). Aside the spiritual value, in many communities polar bears are also utilized as a source of food, material for clothing and crafts, social/cultural bonding, transfer of hunting and land-use skills, and economic benefits through sport hunting and the sale of hides and skeletal materials (Wenzel 1983, 1995, 2004; Freeman and Wenzel 2006; Freeman and Foote 2009). As the Arctic became more attractive to European explorers in their efforts to map northern sea routes, other resource exploitation including the harvest and sale of marine mammal products including the fur trade, polar bears began facing threats largely due to their prized hides. Historical records estimate a non-native harvest of 55,000 polar bears within the Canadian arctic alone between 1700 and 1935 (Honderich 2001; Wenzel 2004). With seemingly unsustainable harvest rates, and drastically reduced abundance levels on a global scale, the polar bear was becoming endangered (Prestrud and Stirling 1994; Freeman 2001). Concern over such depletion caused the five range states (Canada, United States, Russia, Greenland [Denmark before Home Rule Government], and Norway) to sign an international agreement and to implement conservation and management actions, including quotas, protection of family groups, and hunting prohibitions/restrictions to allow recovery (Fikkan et al. 1993; Prestrud and Stirling 1994; Freeman 2001).

After approximately 45 years of conservation actions as laid out in the international agreement (Fikkan et al. 1993; Prestrud and Stirling 1994), global polar bear abundance estimates increased from a questionable 5,000-19,000 in 1972 to about 26,000 (95% CI: 22,000-31,000) in 2015 (Freeman 1981, 2001; Wiig et al. 2015). This increase in abundance also was confirmed and supported by many Inuit living across the Canadian Arctic (Tyrrell 2006, 2009; Dowsley and Wenzel 2008; Henri et al. 2010). Despite this management success (Prestrud and Stirling 1994; Freeman 2001), polar bears are facing a new potential threat in the form of climatic changes (Derocher et al. 2004; Stirling and Derocher 2012). Across the Arctic, warming temperatures and changes in circulation patterns have led to a deterioration of sea-ice availability, quality and quantity (Maslanik et al. 2007; Stroeve et al. 2012; Intergovernmental Panel on Climate Change 2013; Overland and Wang 2013; Stern and Laidre 2016).

Out of the 19 polar bear subpopulations recognized world-wide (Obbard et al. 2010), the western Hudson Bay subpopulation (WH) in Canada is one of the most-studied large carnivore populations (Jonkel et al. 1972; Stirling et al. 1977; Derocher and Stirling 1995; Regehr et al. 2007; Stapleton et al. 2014). Long-term monitoring and research, predominantly through a capture-mark-recapture program, suggest that the abundance increased during the 1970s, remained somewhat stable, and then declined by an estimated 22% between 1987 and 2004 (Derocher and Stirling 1995; Lunn et al. 1997; Regehr et al. 2007). A more recent analysis suggests that the population remained stable between 2001 and 2011 which appears to be due to temporary stability in sea-ice conditions (Lunn et al. 2016; but see Castro de la Guardia et al. 2017).

In more recent decades polar bear research and monitoring has increased though not without challenges. Concerns over wildlife handling (e.g., immobilization, collaring, tagging, etc.) were expressed by Nunavut hunters and Inuit organizations over the past decade (Henri et al. 2010; Lunn et al. 2010; Wong et al. 2017). As a response to these apprehensions the Government of Nunavut collaborated with the University of Minnesota to develop less-invasive monitoring techniques, such as aerial surveys (Stapleton et al. 2014). Although only fairly recently applied to study polar bear abundance, aerial surveys have not only proven effective in monitoring the abundance of other wildlife species but have also become more technically advanced over the last two to three decades (e.g., through the introduction of survey methods such as distance sampling and double observer sight and re-sight methodologies) (e.g., Norton-Griffiths 1978; Caughley et al. 1976; Tracey et al. 2008; Aars et al. 2009; Stapleton et al. 2014, 2015; Obbard et al. 2015; Lee and Bond 2016). Aerial surveys have become the method of choice in Nunavut to monitor this sentinel polar bear subpopulation over the long-term to provide less invasive, less expensive, up-to-date information to decision makers and user groups (Yuccoz et al. 2001; Nichols and Williams 2006; Peters 2010; Stapleton et al. 2014). In keeping with community recommendations and previous aerial survey methods used in August 2011, we set out to up-date the status of the WH subpopulation using a distance sampling, and double observer sight re-sight method in August 2016 during the ice-free period.

2. METHODS

2.1. Study Area

The WH polar bear subpopulation is part of the Hudson Bay complex that includes the neighboring Foxe Basin and southern Hudson Bay subpopulations (Obbard et al. 2010; Thiemann et al. 2008, Peacock et al. 2010; Figure A4.1). Although there is spatial overlap of polar bear movements from these three subpopulations apparent on the sea-ice (e.g., Stirling et al. 1999; Obbard and Middel 2012; Sahanatien et al. 2015), past capture-mark-recapture studies (Stirling et al. 1977; Derocher and Stirling 1990; Ramsay and Stirling 1990; Kolenosky et al. 1992; Taylor and Lee 1995; Derocher et al. 1997; Lunn et al. 1997, 2016), genetic studies (Paetkau et al. 1995, 1999; Crompton et al. 2008; Malenfant et al. 2016), and analyses of satellite telemetry data (Stirling et al. 1999; Sahanatien et al. 2015; Obbard and Middell 2012) support the currently accepted WH subpopulation boundary (Obbard et al. 2010).

Our study area has been well-described by Brook (2001), Dredge and Nixon (1992), Ritchie (1962), Clark and Stirling (1998), Peacock et al. (2010) and Richardson et al. (2005) and includes the areas described by Stapleton et al. (2014) and Lunn et al. (2016). The terrestrial portion of the study area stretches for approximately 1,500 km from about 35 km southeast of the Manitoba-Ontario border all the way into Nunavut (approximately 20 km south of Chesterfield). In general, the southern portion of the study area displays the characteristics of the Hudson Plains ecozone and the Coastal Hudson Bay and Hudson Bay Lowlands. The northern portion exhibits Taiga and the Southern Arctic ecozone (Ecological Framework of Canada 2016). Where trees (black spruce [*Picea mariana*], white spruce [*P. glauca*], and tamarack [*Larix laricina*]) are quite common in the southern extents, dwarf birch (*Betula nana)*, willows (*Salix* spp.), and ericaceous shrubs (*Ericaceae* spp.) are the norm to the north. The near-coastal southern areas exhibit elevated beach ridges, marshes and extensive tidal flats. There is very little relief (<200 m) with underlying continuous and semi-continuous permafrost.

Sea-ice is absent in this region generally from July to November (Stirling et al. 1999; Scott and Marshall 2010; Stern and Laidre, 2016), and biting insects are plentiful during the summer (Twinn 1950).

Polar bears of WH come ashore when sea ice levels diminish to ≤ 50% (Stirling et al. 1999; Cherry et al. 2013, 2016), which generally occurs during July (Stern and Laidre, 2016). Once on land, the bears segregate by sex, age class, and reproductive status within the study area where they exhibit fidelity to their terrestrial summer retreat areas (Stirling et al. 1977; Derocher and Stirling 1990). Adult males are generally found along the coastline, pregnant females and females accompanied by offspring are found in the interior denning area which is mostly included within Wapusk National Park, and subadults are distributed throughout the study area (Stirling et al. 1977; Derocher and Stirling, 1990; Ramsay and Stirling 1990; Clark and Stirling 1998; Clark et al. 1997; Richardson et al. 2005). When sea ice reforms during November all bears except pregnant females return to the ice. Pregnant females give birth in terrestrial dens during December and early January, and family groups generally depart their dens in March and April to return to the sea ice (Jonkel et al. 1972; Stirling et al. 1977; Ramsay and Stirling 1988).

2.2. Survey design

The 2016 WH polar bear distance sampling abundance survey used double observer pairs (sight/re-sight) and was based out of the communities of Rankin Inlet and Arviat within the Nunavut Settlement Area, and Churchill and the remote camps of York Factory and Marsh Point within northern Manitoba. The comprehensive stratified aerial survey was flown between 12 and 21 August. The survey was timed to coincide with the ice-free period because; (a) all polar bears of the WH population are forced to be on land during this time, (b) any overlap with neighboring subpopulations is very likely minimal, and (c) bears are readily visible against the terrestrial landscape. In addition, females will likely not have begun to den yet and can be detected while moving towards their inland denning area (Stapleton et al. 2014). The survey was structured into two main components: 1) Pre-stratification using telemetry, past survey results and traditional, local, and ecological knowledge collected during the consultation process, and 2) Distance sampling double observer pair (sight re-sight) aerial visual survey methods using fixed and rotary wing aircraft.

The establishment of the survey area and the division of that study area into strata of individually consistent relative densities of polar bears was modeled after Stapleton et al. (2014). Modifications were based on their 2011 aerial survey results as well as previous and current telemetry findings (n = 8 collared bears in summer of 2016, A. Derocher, University of Alberta and Environment and Climate Change Canada, unpublished data; Manitoba Sustainable Development, unpublished data; Derocher and Stirling 1990; Lunn et al. 1997; Stirling et al. 2004; Richardson et al. 2005; Towns et al. 2010; Stapleton et al. 2014). In addition, we consulted coastal survey maps and den emergence information provided by Manitoba Sustainable Development.

Following a thorough review and spatial plotting of past survey observations across the WH polar bear population boundary, an in-depth round of HTO (Hunters and Trappers Organizations) and community-based consultations were undertaken in January and February of 2016. During those consultations, HTOs from the communities of Baker Lake, Rankin Inlet, Chesterfield Inlet, Whale Cove and Arviat were invited to comment on preliminary stratification of polar bear densities as well as transect placement. Comments and concerns raised during these meetings were incorporated into the survey design. The merging of past survey observations and telemetry data, with the mapped density distributions from consultations, yielded 4 survey strata that slightly varied from those used by Stapleton et al. (2014) in 2011. The 2016 survey strata included the following derived polar bear density distributions: 1) very low, 2) low, 3) moderate, and 4) high (Figure 1).

All survey transects were oriented perpendicular to the bear density to improve precision and to reduce possible bias during sampling (Buckland et al. 2001) (Figure 1). Survey effort, measured as transect spacing, was then allocated across survey strata based on the following constraints: strata with the highest estimated polar bear density for the survey period would receive the highest level of coverage with survey effort for the remaining strata being allocated proportionally to the approximate relative density of polar bears. Effective strip width varied depending on sightability, which in turn was dependent on measured covariates including cloud cover, speed, ground cover, terrain, and observer ability.

The very low density strata and transects represented the inland portions of the survey area outside of the Wapusk National Park high density stratum boundaries (Figure 1). These strata were divided further into two main areas, one north and west of the Churchill River up to the Nunavut/Manitoba boundary in the north, and the second south and east of the Nelson River bounded to the east by Cape Tatnam. The very low density strata covered only inland transects generally ending within 20 to 30 km of the Hudson Bay coastline. Transect spacing was irregular but averaged 17 km across the strata.

The low-density stratum and transects occupied the northern extents of the WH polar bear population boundary (approximately 20 km south of Chesterfield Inlet) to the Nunavut/Manitoba border (Figure 1). Modifications from Stapleton et al. (2014) included IQ-based transect extensions both over water and inland within the northern extent of this stratum. Overwater extensions within the remaining extents including 2 transects bi-secting Sentry Island were derived solely from *Inuit Qaujimajatuqangit* (IQ) reports and recommendations. Transect lines in this stratum were spaced 10 km apart, and extended up to 90 km inland, and up to 30 km into Hudson Bay beyond the coast to incorporate the many off-shore islands characterizing this coastline. The development of this stratum was largely based on local knowledge which strongly recommended the extension of coastal transects inland and across open water and coastal islands.

The moderate-density strata and transects were divided into two areas, one north and west of the Churchill River up to the Nunavut/Manitoba boundary in the north, and the second south and east of the Nelson River, approximately 60 km east into Ontario to the eastern extent of the WH polar bear population boundary. These strata primarily covered a Hudson Bay coastal strip that was approximately 20 to 30 km wide. Transect spacing within this strata was 7 km with transects extended beyond the tidal flats into open water. Recent information collected by the Manitoba Department of Sustainable Development on summer and spring polar bear habitat including denning sites, spring emergence habitat, and coastal summer retreat, led this survey effort to modify Stapleton et al. (2014) survey design to define a moderate-density stratum from Cape Tatnam east toward East Penn Island with transects extending beyond the coastal strip up to 70 km inland into known denning habitat (Figure 1).

The high-density survey stratum and transects followed those described by Stapleton et al. (2014). The stratum boundary ran between the Churchill River in the west to the coast of Hudson Bay in the east with Churchill forming the northern boundary and the Nelson River approximating the southern boundary. The core of the high density stratum included Wapusk National Park which is known to be a high density summering area, and further inland, a heavily used denning area (Lunn et al. 2016). Transects in this stratum extended up to 100 km inland and were spaced 6 km apart. As with all other survey strata, all transects were extended 5-30 km beyond the coast into Hudson Bay which enabled the survey design to include bears either in water or on the extensive tidal flats known to be occupied by bears during summer and fall periods (Dyck, 2001; Clark and Stirling 1997).

Financial and logistical constraints as well as examination of weather patterns dictated the survey window and total number of aircraft required to successfully and efficiently complete the survey without the concern over long-disance polar bear movements between survey days. One de Haviland Twin Otter fixed wing aircraft with radar altimeter, a Eurocopter (model EC135) twin engine rotary wing aircraft with radar altimeter, and a Bell Long Ranger (model L4; Bell LR4) single-engine rotary wing aircraft with pop-out floats were used to complete the August 2016 WH polar bear abundance survey. All aircraft throughout the survey maintained, as close as possible, an altitude of 400 feet above ground level (AGL) and an air speed of between 70 and 90 knots for the fixed wing, and 70 to 80 knots for the rotary wing aircraft while flying on transect. The Twin Otter fixed wing aircraft was used to complete the low density stratum within Nunavut and the very low and moderate density strata west and north of the high density stratum bounded by the Churchill River, Manitoba, in the south. The twin engine fixed wing configuration and its ability to fly on one engine was chosen to increase safety while flying over extensive water transects characteristic of the northern half of the survey study area within Nunavut.

The Eurocopter EC135 helicopter was incorporated into the survey study design as it has the ability to seat six (6) forward facing observers, four dependent observers (two on the left side of the aircraft and 2 on the right) and two non-dependent observers (a data recorder/observer on the left and a pilot/observer on the right; Appendix 1). We utilized this configuration to test the assumptions that the pilot and navigator, considered non-dedicated observers due to their additional roles that at times would impact continuous observations and associated search patterns. The goal of this configuration was to test whether these non-dedicated observer positions could observe polar bears as effectively as a dedicated observer.

The LR4 was used within the more remote extents of identified survey strata south of Churchill due to its greater fuel economy while operating out of remote fuel caches. The LR4 was configured for four (4) observers: two dedicated observers in the left and right secondary (rear) positions and a data recorder/observer in the front left primary position and a pilot/observer in the front right primary position. Both rotary wing aircraft were used to complete the remaining high, moderate, and very low density strata within the southern half of the survey study area in northern Manitoba.

2.2.1. Double observer pair

The double observer pair (sight/resight) method is a variation of physical mark-recapture (Pollok and Kendall 1987). Simply, the aircraft's front and rear observers comprise two independent survey teams, visually 'marking' (i.e., front observers' sighting) and 'recapturing' (i.e., rear observers' resighting) polar bears. Observer teams must be independent to estimate detection probabilities (see Appendix 2). This resultant information provides an independent estimate of the number of bears present in the survey strip that were not observed by either team (Laake et al. 2008; Buckland et al. 2010).

The double observer pair method requires two pairs of observers on each of the left and right hand sides of the aircraft (Figure 2) (Buckland et al. 2001; Pollock and Kendall 1987). One "primary" observer sits in the front seat of the aircraft and a "secondary observer" is located behind the primary observer on the same side of the aircraft. To insure visual isolation, a barrier was installed between same side observers to remove any visual cues that could modify an observer's ability to sight the animal (Appendix 1). Observers waited until bear groups passed before calling out the observation to ensure independence of observations. The data recorder/recorders, categorized and recorded counts of each bear (group) into "primary only", "secondary only", and "both"; The observers switched places approximately half way through each survey day (i.e. at lunch or during re-fueling stops) as part of the survey methods to address possible differences in sightability between the primary and secondary positions. Though the methods during all phases of the survey followed these 4 basic steps, there were differences in the methods deployment made between the three aircraft.

2.2.2. Fixed wing

Within the fixed wing aircraft we utilized an 8 person platform; 4 dedicated observers, 2 data recorders (for each of the left and right primary and secondary observer pairs) and a pilot and co-pilot. Observers within the fixed wing survey crew included two experienced Hunters and Trappers Organization (HTO) observers (one from Rankin Inlet and one from Arviat), 3 experienced wildlife biologists (two from the Government of Nunavut – Department of Environment and one NTI wildlife biologist), and one experienced wildlife technician. The observers were further divided into primary and secondary teams, each isolated from the other using visual barriers between the seats as well audio barriers through the use of two independent intercom systems monitored by each of a primary data recorder/navigator and a secondary data recorder/navigator (Appendix 2). The pilot's responsibilities were to monitor air speed and altitude while following transects pre-programmed on a Garmin 650T Geographic positioning system (GPS). The data recorder/navigators were responsible for monitoring a second and third identically programmed GPS unit for the purposes of double-checking the position as well as to record the geographic position, body condition, composition and numbers of observed polar bear groups on data sheets. The pilots, data recorders, one right side observer, and both left side observers remained consistent throughout the fixed wing portion of the survey, while one right observer position was occupied by 3 different individuals. The primary and secondary observer pairs were alternated between the front and rear positions halfway through the day during scheduled re-fueling stops.

2.2.3. Rotary wing

The EC135 rotary wing platform was configured to have 6 forward facing seats with observation windows, 3 on the left side of the aircraft and 3 on the right. We utilized a 6 person configuration for the first two days of surveying and a 5 person platform for the remainder of the survey to address weight and balance issues as they pertained to extending endurance.

Within the EC135 six (6) person configuration, 4 were dedicated observers, two on the left side of the aircraft and 2 on the right. The remaining 2 positions were within the forward most seats and included a data recorder/observer on the left side and a pilot/observer on the right. Though the final population analysis utilized the observations exclusively from the 4 dedicated observers, the data recorder/observer and pilot/observer observations were also recorded to compare with the observations from respective side dedicated observers for an assessment of a non-dedicated observer’s ability to sight bear groups. As only one data recorder could be accommodated using this configuration, front and rear audio isolation was not possible leading to a modification of the fixed wing configuration where the two front most observers (pilot and data recorder) waited until the observation moved to their 5 and 7 o’clock positions respectively to ensure all same side dedicated observers had ample time to independently sight the group. Additionally the primary dedicated observers waited until the bear observation passed their 4 o’clock (right) and 8 o’clock (left) position to allow the secondary observers ample opportunity to make their sighting. As in the fixed wing, the same-side dedicated observers changed between primary and secondary positions half way through the day. Only one change was made between dedicated observers over the two day period. Additionally all but one dedicated observer remained consistent over the period.

The EC135 five (5) person configuration followed the same basic configuration indicated for the 6 person configuration with the single exception of the removal of the pilot as an observer. The data recorder/observer position continued to further test the comparability between a dedicated and non-dedicated observer. All observers were experienced and remained consistent throughout the remainder of the survey. For this configuration the data recorder/observer position moved back one seat to the left primary position opposite the right primary dedicated observer. Once again primary and secondary positions were exchanged half way through the day.

The Bell LR4 only allowed for a four person configuration due to weight and balance issues while carrying full fuel as well as seating configuration. Using this configuration only the secondary observers were dedicated observers while the left primary observer seat was occupied by a data recorder/observer and the right primary position by a pilot/observer. Additionally, observers could not exchange primary and secondary positions using this configuration to determine sightability differences between seating positions. Though only two dedicated observers could be accommodated within the LR4 configuration, this study used the assessment of non-dedicated observers within the EC135 to inform on the reliability of the non-dedicated observers within the LR4. While the methods used during this study generally followed those used by Stapleton et al. (2014), it is important to note that no pooling of front and rear observers was made. All observations made during this study were independent.

2.2.4. Distance Sampling

In addition to the deployment of the double observer pair method within all aircraft, we also collected observations using distance sampling. The distance sampling method followed Buckland et al. (1993, 2004, 2010) and used Program Distance, Version 6.0

(Thomas et al. 2009), to model stratified line transect observation data and estimate density and abundance for polar bears. Using the conventional distance sampling approach (CDS), we modeled the probability of detecting a group of polar bears and their densities within five delineated strata as a function of distance where the detection function represents the probability of detecting a group of polar bears, given a known distance from the transect (Buckland et al. 2001). Recognizing that other variables may affect the detection probability, density estimates were also derived using multiple covariate distance sampling (MCDS), which allowed us to model probability of detection as a function of both distance and one or more additional covariates (Buckland et al. 2004). This approach was explored in order to increase the reliability of density estimates made on subsets of the data based on terrain, vegetation, and environmental conditions, and to increase precision of the density estimates within each unique density-derived strata (Marques et al. 2007).

For the fixed wing portion of the survey only, and in addition to flying to the observed bears for position and data collection, we also used distance bins marked out with streamers and tape on the wing struts after Norton-Griffiths (1978) (Figure 4). In total, 6 distance bins were used including the following; 0-200 meters, 200-400 meters, 400-600 meters, 600-1,000 meters, 1,000-1,500 meters, and 1,500-2,000 meters. Though binned observations were not used during analysis, they did inform on the precision of binning for distance sampling platforms when compared to the actual observation waypoint recorded.

2.2.5. Observations

Polar bears observed while flying along a transect line were considered on-transect while those observed while ferrying to, from, or between transects, or to bear and/or wildlife sightings, where considered off-transect. Because polar bears are often found in groups, each observation (whether individual or group) represented a group of polar bears. In this work a group of polar bears was defined as one or more individuals within a visually estimated 100 meter radius of one another. All observations were investigated by moving off the transect line to the center of the group as they were initially observed, to record the location, group size, sex/age classes, body condition, and activity. Additional covariates including topography, habitat, visibility, cloud cover, and ground speed were also recorded for each observation. Observation times were kept to a minimum to reduce disturbance and stress. All distances to the observations were measured perpendicularly (90^0) from the transect line to the center of the observation, and recorded along with the observation's date and time of day.

We determined gender and body condition, to the extent possible, from approximately 30 meters altitude. A general, relatively robust though subjective fat index has been successfully used in past studies to assess body condition of polar bears (Stirling et al. 2008; SWG 2016; Government of Nunavut, unpublished data). Gender of bears was determined based on body size, the presence of morphometric characteristics (e.g., such as scars, large head, thick neck, long fur on front legs, vulva patch and urine stains) and behavior when encountered (SWG 2016). Age class assessment from the air can be accomplished reliably for adult males, pregnant females, and members of family groups (Government of Nunavut, unpublished data; SWG 2016). Based on these methods, polar bears were classified as male or female, and as adult males (6+ years), adult females (5+ years), sub-adult males (2 to 5 years), sub-adult females (2 to 4 years), yearlings (>1 and < 2 years), and cubs of the year (<1 year). Standardized body condition indices [i.e., poor (1), fair (2), good (3), excellent (4) and obese (5)] were scored for each individual bear (Stirling et al. 2008) as was the activity at the time of observation (i.e., either laying down, sitting, walking, running or swimming). Each aircraft had at least one experienced biologist on board that could identify age classes and body conditions of observed bears with confidence.

For each observation, habitat structure and topography were recorded as covariates as well as cloud cover, visibility and ground speed. Habitat structure was recorded as rocky (1), boulders (2), trees (3), high shrubs (4), grassland (5), sand/mudflats (6), open water (7) and lichen tundra (8). Topography was broken down into an index for slope measured as flat (1), moderate (2) or steep (3), and an index for terrain measured as flat (1), rolling (2) and mountainous (3). By way of example a moderate slope within a rolling terrain would receive a score of 2/2. Visibility of 100%

was indexed as excellent (1), moderate or 75% to 100% (2), and poor or less than 25% (3). All aircraft deployed the distance sampling methods and collection of covariate data consistently across the study.

2.3 Analyses

2.3.1. Data screening and truncation

Data were initially screened for outlier observations that occurred at far distances therefore creating a tail on the detection function that can be difficult to fit. A right truncation distance that eliminated the upper 5% of observations was considered to minimize the influence of these observations (Buckland et al. 1993, Stapleton et al. 2014). Unlike the previous survey (Stapleton et al. 2014) we left-truncated both the front (pilot and data recorder) observations from the Bell helicopter rather than only left truncating the rear observations. The rationale for this was that we wanted to keep the data sets as similar as possible for the double observer analysis. There were 3 observations of 7 bears that were only observed in the rear observer blind spot by the front observers in the Bell helicopter. Therefore, the degree of reduction due to left truncation of the Bell helicopter data was not large.

The blind spot under each aircraft was estimated using geometric formulas. From this, left truncation distances were estimated for the twin otter as 98.9m, 67.2m for the EC135 helicopter, and 73.5 m for the Bell L-4 helicopter. Adjusted distance from the transect line was then estimated as the distance from the transect line minus the left truncation distance for each aircraft.

2.3.2. Co-variates

Covariates that affected bear sightability were considered that included environmental, observer and survey factors (Table 1). These covariates included group size, aircraft type, observer, and visibility. Visibility was reasonably good during the survey where only 15 of 178 observations were recorded as non-optimal conditions. Therefore, visibility was reduced to a binary covariate as was done in previous analyses (Stapleton et al. 2014).

A habitat (*hab*) category based on classification by observers was derived from field observations. This classification included open, shore, shrub, tree, and water habitat classes. A shrub habitat category was also initially considered, however, the number of observations was low and the distribution of observations was disjoint. Therefore, this category was pooled with shore category for observations that occurred on the shore and tree for inland observations.

A remote sensing based covariate (*RSveg*) based on LANDSAT 8 vegetation classification was also considered (Figure 5). The rationale behind this covariate was that it would systematically index dominant vegetation types in the proximity of observations therefore providing the best comparison of habitat and potential obstruction of observations across all observations. Remote sensing covariates based upon the habitat class of the pixel ($625m^2$) where the observation occurred as well as the dominant habitat class within a 90X90m and 150X150m area around the observation were used. The main categories in Figure 5 that were present in the study area were gravel, shrub, trees, low vegetation, and water.

A combination of remote sensing and observer-based habitat scores was also considered (*RSveg-hab*) which re-classified the *RSveg* water category based upon observer habitat scores. For this category *RSveg* that were classified as water were reassigned to gravel (habitat class shore or habitat class water), low-vegetation (habitat class open), shrub (habitat class shrub), and tree (habitat class tree).

All of the survey aircraft except the Bell LR4 (and 3 survey days in the EC135 with only 3 dedicated observers and one observer-recorder on the left hand side) helicopter had 2 dedicated observers per side. The Bell LR4 had 2 dedicated surveyors in the back seat of the helicopter and the pilot and data recorder/navigator as observers in the front. The pilot and data-recorder did not have the same view as the observers, and were distracted by piloting the helicopter and navigating/data recording. Therefore, special covariates were formulated for the pilot and data recorder/observers in this aircraft.

We also noted that the angle of the sun in the afternoon affected our ability to sight bears given that cloud cover was minimal during the survey. This occurred when the sun was lower on the horizon and was directed towards the observers reflecting of the many lakes and ponds characteristic of the survey area. To test for this effect we calculated sun azimuth (e.g., the direction of the sun in the sky) and altitude relative to the path of the survey aircraft. From this we were able to determine when the sun was directed towards the observers (based on sun azimuth relative to flight path) and sun altitude based on time of day. Using this information we constructed a sun covariate which was only considered if the sun was facing the observers. If the sun was facing the observers then sun altitude relative to the horizon was tested as a sightability covariate with the expectation that sightability would be lower at lower sun angles.

2.3.3. Models and modeling approach

Mark-recapture distance sampling methods were applied to the survey data (Buckland et al. 2004, Laake et al. 2008a, Laake et al. 2008b, Buckland et al. 2010, Laake et al. 2012). A mark-recapture/distance sampling model assuming point independence was used which allows estimation of the detection probabilities at the transect line (or left truncation distance) using independent double observer pair methods with distance sampling methods used to model the decline in sighting probabilities as a function of distance from the survey line.

A sequential process was used for model building. First, parsimonious distance sampling models were formulated using a mark recapture model with constant detection probabilities. Once the most supported distance model was determined, parsimonious mark-recapture models were formulated using the most supported distance model as a base model in the mark-recapture model analysis. As a final step, optimal distance and mark-recapture models were combined and assessed for goodness of fit and overall parsimony. Information theoretic methods (Burnham and Anderson 1992) were used to assess relative model fit. More exactly, Akaike Information Criterion (AIC) were used as an index of model parsimony with lower scores indicating a model that explained the most variation in the data set with the least number of parameters. The difference between the most supported model and given model was evaluated (ΔAIC) to indicate relative support with models at ∆AIC values of less than 2 being of interest. Akaike weights were used to estimate proportional support of models. Models were averaged based on AICc weights using the *AICcmodavg* (Mazerolle 2016) package in program R (R Development Core Team 2009). The AIC score indexes relative fit but does not provide a test of overall goodness-of-fit. Goodness-of-fit tests incorporated in program DISTANCE were used to further evaluate fit of the most supported models.

The 2016 data set was also analyzed using only distance sampling methods to assess if estimates were significantly different when mark-recapture double observer methods were used given that previous surveys did not use the mark-recapture method.

One of the primary objectives of the analysis was to compare the 2011 and 2016 distance survey estimates given that the field sampling designs for the 2 surveys were nearly identical. To ensure that estimates were comparable, the 2011 data set was re-analyzed with the remote sensing based *RSveg* habitat classes to assess whether inclusion of this covariate would influence abundance estimates compared to the structure covariate used in the 2011 analysis (Stapleton et al. 2014). A t-test was used to compare estimates with degrees of freedom estimated using the formulas of Gasaway et al. (1986).

Analyses were conducted using program DISTANCE 7.0 (Thomas et al. 2009) for initial model input and fitting with additional analyses conducted in the *mrds v2.1.1.17* (Laake et al. 2012) R package version 3.3.3 (R Development Core Team 2009). Data were explored graphically using the *ggplot2 R* package v 2.2.1 (Wickham 2009) and QGIS program (QGIS Foundation 2015).

3. RESULTS

3.1. Sightings, Habitat, and Detection

The WH polar bear survey was flown between August 12 and 21, 2016. Survey strata flown between Chesterfield Inlet and Churchill with the Twin Otter took 4 days to complete. The remainder of the study area was completed utilizing 2 rotary wing aircraft in 5 days. During the survey we flew approximately 35 hrs with the Twin Otter and 80 hrs total with the two rotary wing aircraft for an estimated total distance of approximately 17,100 km, including ferry time.

In total, 339 bears were observed during the survey (Table 2). Of these observations, 17 were in the blind spot of the plane and 25 were beyond the right truncation distance. The remaining 297 bears were in the survey strip, however, 280 of these were seen by one or both of the dedicated observers and only 17 were observed by non-dedicated observers including the data recorder/observers and pilot/observers.

Graphical illustration of the distribution of observations revealed differences for our initially selected habitat types. More distant observations occurred within coastal as well as more open habitats whereas reduced detections and detection distances were observed for the water and tree habitat categories (Figure 6). The majority of observations occurred at distances of less than 2700 meters from survey aircraft (Figure 7). The 95th percentile of this observation data was within 2250 meters of the aircraft and therefore the data was right truncated to this distance value. Sensitivity analyses were conducted at a later stage of the analysis to determine if estimates were sensitive to both left and right truncation distances.

The distribution of LANDSAT remote sensing categories (*RSveg* covariate) revealed a broad distribution for the gravel category with sparse distributions of low vegetation (Figure 8). The tree category had most observations close to the survey line suggesting lower sightability, while the shrub distribution suggests moderate sightability. In contrast to the observation-based habitat water classification (Figure 6), the LANDSAT classification of water in Figure 8 reflected habitat in and around water as opposed to water alone as indicated by the presence of non-water habitat class observations, such as shore, in the water *RSveg* class. As a result, the water category had higher sightability with more observations further from the survey line than the water observation-based habitat class. Most of the gravel category corresponded to observations that occurred on the shore line with mixed distributions of habitat categories for the other *RSveg* classes. The distribution of the low vegetation class was potentially problematic due to few observations close to the survey line. This issue, which was most likely due to sparse data, was alleviated by pooling the shrub and low vegetation classes (Figure 9). This new pooled covariate class was called *RSveg2*.

Distributions of detections for aircraft type were relatively similar with relatively similar ranges of distance for observations (Figure 10). The main difference was the relative number of observations for each aircraft which created distributions that were more disjoint when the number of observations was lower.

Twelve observers were used during the survey of which 2 also were data recorders for at least part of the survey (Table 3). Naïve detection probabilities were estimated as the total number of times a bear was detected when an observer was active divided by the total number of observation event/trials. This is a naïve estimate given that other factors such as distance from the aircraft of the bear is not considered and therefore this probability will underestimate the detection probability on the survey line for any observer. In addition, the actual probability of detection on any side of the aircraft is based on 2 observers and will be higher than a single observer detection probability. Regardless, the average naïve detection probability for an observer was 0.77. Of most interest were detection probabilities below this amount. The Bell LR4 pilot and recorder both had lower detection probabilities and were therefore considered in detail in subsequent analyses.

We observed 39 cubs of the year (COY), and 10 yearlings (YRLG), which resulted in a mean COY and YRLG litter size of 1.63 (SD: 0.49; n = 24) and 1.25 (SD: 0.46; n = 8), respectively. COYS and YRLGs represented 11.5% and 2.9% of the entire observed sample of 339 bears. Approximately 53% of all observations were adult males (Table 4).

3.2. Distribution

A break-down of observed bears by strata, and across the study area is shown in Figure 11 and Table 2. The distribution of bears within the study area during August 2016 was not uniform. The majority (93.5%) of observations occurred in the high and moderate density strata. When the WH polar bear population study area was broken down into areas according to Lunn et al. (2016), Nunavut (their area A or our low density strata) exhibited the lowest bear density whereas area C (i.e., the high density area) contained 50% of all observed bears (Table 4). Area D (or the area east of the high density area) had the highest density of adult males. We only report the pooled mean ± SD distance from coast for areas C and D since these are the areas with the highest sample size. In general, adult males were found near the coast (1.3 ± 1.8 km; range: 0.02 – 12.1 km), whereas adult females were found an average of 25.5 ± 23.4 km (range: 0.5 – 84.3 km) from the coastal areas. For family groups, the mean distance from shore was 11.5 ± 16.2 km (range: 0.1 – 54.2 km).

3.3. Distance/Mark-recapture analyses

3.3.1. Distance analysis

The distance component of the analysis used a constant mark-recapture model probability which basically assumed that detection at the left truncation distance did not vary (but was less than 1). Initial fitting revealed that both the hazard rate and half normal models showed some support from the data with a tendency of the hazard rate to be supported when covariates were not used (Table 5, model 13). Of covariates considered, models with group size (*size*), habitat (*hab*), remote sensing veg (*RSveg2*) and visibility (*vis*) were more supported than constant models. Of all models considered, a model with a hazard rate detection function with sightability varying by *RSveg2* and *size* was most supported. However, models with just *RSveg2* as well as models with the half normal detection function with habitat and visibility as covariates (model 3) also showed some support as indicated by ∆AICc values of less than 2. Therefore, these models were considered further in the joint distance/mark-recapture phase of the analysis.

The most supported hazard rate (*RSveg2*+*size*) model was used for the mark-recapture analysis phase. Estimated abundance varied between 770 and 966 for models with abundance around 850 for the more supported models in the analysis (Table 5).

3.3.2. Mark-recapture analysis

The most supported distance model (HR (*RSveg2+size*) was then used as a baseline distance model for the mark-recapture component of the analysis (Table 6). Of covariates considered, *group size, aircraft type, sun*, and *observers* were more supported than a constant model (model 12). Of the observer models, a model with unique detection probabilities for the Bell LR4 pilot (*Bellp*) and data recorder/navigator (*Bellr*) and equal probabilities for all other observers (model 4) was more supported than a model with all observer detection probabilities being different (model 6). Overall, a model with the Bell pilot, Bell recorder, sun, and group size was most supported (model 1). A model without group size included (model 2) also had marginal support as indicated by ΔAICc values of less than 2.

3.3.3. Distance/mark-recapture analysis

The most supported covariates for distance sampling (Remote sensing vegetation (*RSveg2*), observer-based habitat class (*hab*), visibility (*vis*), and group size (*size*)) and mark-recapture (group size (*size),* Bell pilot *(Bellp),* Bell recorder *(Bellr), and sun angel (sun)*) were considered in the joint distance/mark-recapture analysis. Of the models considered, a model with the most supported stand-alone distance sampling covariates (Table 7; *RSveg2+size*) and most supported mark-recapture covariates (Table 5; (*Bellp +Bellr+sun+size*) was most supported (Table 7; model 1). Other models that did not include group size for distance (model 2), used a half-normal detection function with habitat visibility (model 3) as well as other combinations of covariates with a hazard rate detection function (models 4-6) were supported as indicated by ΔAICc values of less than 2. Estimates from the most supported models were close ranging from 774 to 896 with reasonable levels of precision for all models.

3.3.4. Goodness of fit

Goodness of fit for the most supported model (Table 7) revealed acceptable fit for the distance component (χ^2=4.33,df=2, p=0.11) with 250meter bin intervals and the mark-recapture component (χ^2=12.4,df=13, p=0.49) leading to an overall acceptable goodness of fit score of (χ^2=16.7,df=15, p=0.34). Kolmogorov-Smirnov tests (0.045, p=0.91) and Cramer-Von-Mises tests (0.035, p=0.89) also suggested reasonable fit.

Predictions for various combinations of distance sampling and mark-recapture covariates were plotted to explore the effect of covariates on detection probabilities as well as assess fit to the main *RSveg2* classes (Figure 12). If model fit is adequate then the general pattern of points should parallel the histogram bars. The size of each data point was proportional to group size with larger groups having larger symbols. Larger groups had higher detection probabilities than smaller groups which created the most scatter in the observation points at different distance intervals. In addition, observations that were most affected by sun altitude (as indicated by a sun altitude of less than 30 degrees) are denoted as red dots with yellow dots representing situations where the sun was facing the observer but was higher in altitude (with less of an estimated effect on detection probabilities). Finally, black dots indicate when the sun was behind the observer therefore not affecting detection probabilities. A few patterns arise from Figure 12. First, the fit of the data to each *RSveg2* class is reasonable with the general pattern of observations following the shape of the histograms. Most notably, the tree observations decline steeply with distance with moderate declines in vegetation-shrub, lesser declines in habitat areas in and around water, and minimal decline in the gravel categories. Larger group sizes of bears show a less substantial decline compared to smaller group sizes with some large groups having higher sighting probabilities at further distances from the survey aircraft. However, observations that were affected by the sun (denoted by red points) have lower detection probabilities than other observations at similar distances and group sizes.

The other factor affecting sightability was reduced sightability near the line for the Bell helicopter recorder and pilot. This basically reduced the y-intercept of the detection probability to be lower than one; an effect that is most noticeable when group size is smaller (Figure 13). A plot of pooled detection probabilities superimposed on the detection frequencies also suggests reasonable fit (Figure 14). The points on Figure 14 are for each observation whose probability will vary by covariates such as habitat, visibility, group size, and observer as described in Figures 12 and 13.

Average front observer detection probabilities for the front and rear observer was 0.63 and 0.76 which resulted in a combined double observer detection probability of 0.90 at the survey line (Figure 15). Plots of detections by front (observer=1) and rear observer (observer=2) reveal similar detection function shapes for situations when a bear was only detected by a single observer as well as both observers (duplicate detections) (Figure15). The conditional detection probabilities were similar with distance for observer 1 given detection by observer 2 but slightly higher for observer 2 when detected by observer 1 at further distances. This could be due to cueing or more time for the rear observer to spot animals at further distances.

3.3.5. Abundance estimates

A model averaged estimate of abundance that considered all of the candidate models in the analyses (Tables 5-7) was 842 bears (SE=142.6, CV=16.9%, CI-562-1121) during August 2016. This estimate was very close to the most supported model estimate of 831 (Table 7). The corresponding model averaged estimate of density is 9.9 bears per 1000 km^2 (SE=1.67, CI=6.62 -13.18).

Abundance estimates are given by strata for the most supported model (model 1) in Table 7. One issue we encountered was that only one observation of 8 bears occurred in the very low strata leading to very imprecise estimates. The low and very low could be pooled into a single strata to confront this issue. However, the actual estimates will not be affected greatly (Table 8).

3.3.6. Sensitivity of estimates to truncation

The most supported model (model 1, Table 7) was rerun at various right truncation distances to determine the overall sensitivity of estimates to deletion of observations that occurred far from the transect line. Decreasing the right truncation distance to 1800 meters which is closer to the data limit by the previous survey (Stapleton et al. 2014) decreased the estimate slightly to 826 bears whereas increasing the right truncation distance to 2700 m include further observations (Figure 7) decreased the estimate by 6 bears. Overall, the effect of truncation was minimal on estimates (Table 9).

3.3.7. Analysis of the 2016 data set using only distance sampling methods

The data were also run through the most supported distance model (HR(*RSveg2*+size) to assess estimates if data observed by non-dedicated observers was included but with sightability assumed to be 1 on the survey line. For this analysis the 17 bears that were not observed by the 2 dedicated observers were included in the analysis given that they were observed from the aircraft by data recorders or pilots . Of the 17 bears not seen by the dedicated observers, 7 were observed by the front left data recorder at 696 meters on the EC135, 7 were observed on the twin otter by the front right data recorder, and 3 were observed by the front left pilot on the twin otter. All of these bears were within the survey strip.

The HR (*RSveg2*+size) displayed adequate fit to the data ($\chi 2=7.71$,df=6, p=0.26). Kolmogorov-Smirnov tests (0.041, p=0.95) and Cramer-Von-Mises tests (0.032, p=0.97) also suggested reasonable fit. The resulting abundance estimate was 843 bears (SE=104.2, CV=16.8%, CI=607-1170) which is very close to the mark-recapture/distance sampling estimate of 831 (Table 8).

3.3.8. Additional analyses

We conducted additional analyses with the main objective of comparing abundance estimates from the 2011 and 2016 surveys to allow a robust estimate of trend. The rationale behind these analyses was to ensure similar modelling and analysis methods were used in each survey year therefore allowing direct comparison of the estimates.

3.3.8.1. Re-analysis of 2011 data set using LANDSAT covariates

We re-analyzed the 2011 data set using the remote sensing (LANDSAT) based habitat classification scheme to determine if this covariate was also supported as a detection function covariate for the 2011 data set, and to assess any change in estimates with this covariate. A full suite of models were considered including those from the original analysis (Stapleton et al 2014). A model with the LANDSAT covariate (along with visibility and habitat structure) with a hazard rate detection function was most supported. The model averaged estimate of abundance from this analysis was 949 bears, (SE=168.9, CI=618-1280, CV=17.7%). This analysis is detailed in Supplemental Material 1.

3.3.8.2. Trend analysis based on distance sampling and coastal surveys

The 2011 estimate of 949 derived from the LANDSAT covariate analysis was used to estimate trend between the two surveys with the rationale that the most comparable estimates would be obtained by models that used the same covariates for sightability and employed similar survey methodologies. We note that another estimate of abundance of 1030 that combined coastal surveys and inland samples was produced for the 2011 data set (Stapleton et al 2014). Coastal surveys were not conducted in unison with distance sampling in 2016 and therefore this type of estimate could not be derived for 2016. Therefore, the most comparable estimates in terms of assessing trends are the distance sampling only estimates from the two years which used similar methodologies and detection function covariates.

A comparison of model averaged abundance estimates from 2011 using the LANDSAT covariate of 949 bears (SE=168.9, CI=618-1280, CV=17.7%) and the 2016 estimate of 842 bears bears (SE=142.6, CV=16.9%, CI-562-1121) using t-tests suggested the difference between the 2 estimates was not significant (t=0.48, df=452,p=0.63). The ratio of the 2 estimates resulted in a 5-year change of 0.89 which translates to an annual change (λ) of 0.98 (0.89-1.07). The λ estimate in this case suggests a very slight annual decline in abundance, however, the confidence intervals overlap 1 and therefore this decrease is not significant.

We also performed a trend analysis that used coastal survey data collected by the government of Manitoba and compared trend estimates from these surveys to trend based on the ratio of the distance sampling estimates. Estimates of trend based on coastal surveys from 2011 to 2016 suggested a non-significant annual increase (λ=1.06, CI=0.98-1.14) in abundance based on coastal surveys.

One relevant question was whether changes in abundance were apparent in adult male and adult female bears. To explore this we conducted a post-stratified analysis with age-sex groups defined by adult males and adult females (lone and with offspring). Subadults and unknown bears, for which classification is less certain, were excluded from this analysis. The 2011 and 2016 distance sampling estimates were post-stratified to produce estimates for each age-sex group. In addition, trend analyses were conducted for coastal surveys based on these 2 groups.

Results from both the distance sampling and coastal survey analyses suggest a stable to declining adult female segment of the population and an increasing adult male segment. While trends are apparent in both data sets, neither are statistically significant. These results suggest that any apparent increase in abundance may be more based upon increase in adult males compared to adult females. The details of this analysis are described in Supplementary Material 2.

4. DISCUSSION

4.1. Distribution

As with the previous 2011 aerial survey (Stapleton et al. 2014), the 2016 data provide a comprehensive and detailed overview of summer polar bear distribution across the entire study area. The recent data suggest that, at least during the summer, the majority of WH polar bears reside in Manitoba; only about 5.3% of the sightings occurred in Nunavut. These findings are consistent with previous studies (Stapleton et al. 2014, Peacock and Taylor 2007) but are in contrast to local knowledge where communities along the Nunavut coastline report increasing numbers of polar bears (Tyrell 2006, 2009; Kotierk 2012). Kotierk (2012) suggested that Inuit see more bears in coastal areas than they ever have and that this creates a number of public safety concerns. However, that report is not specific about the time of year. It is generally understood that more bears frequent the Nunavut coastline during fall before freeze-up when compared to summer, but more empirical or traditional data should be collected to verify the timing.

With the exception of the high density strata, bears generally occupied a narrow strip along the coastline (Figure 11), rarely farther inland than 20 km. Most adult males were observed < 10 km from the coastline. Polar bears are sexually dimorphic with males being about twice as large as females (Derocher et al. 2005, 2010). Being near the coastline likely offers opportunities to reduce thermal stress, and may also be beneficial in reducing attacks by biting insects due to the cooler temperature and ability to enter the water. In the high density stratum (or area C in Lunn et al. 2016) bears were distributed throughout the general area with distances ranging up to > 80 km from the coastline for solitary adult females. Sexual segregation became most apparent in this stratum, which has been reported in previous studies (Derocher and Stirling 1990; Jonkel et al. 1972; Stirling et al. 1977).

4.2. Abundance

As in 2011, the 2016 WH polar bear study represents a systematic and geographically comprehensive survey of the WH polar bear population (Stapleton et al. 2014). Thus, we provide an updated abundance estimate for the WH polar bear population as well as a comparison between the two aerial study results. Additionally the current study's methods parallel those of Obbard et al. (2015) who also used a distance mark-recapture sampling method to estimate polar bears in southern Hudson Bay.

Stapleton et al. (2014) produced two population estimates. An estimate of 1030 bears was derived that combined coastal surveys and inland transect observations for the 2011 data set (Stapleton et al 2014). In 2016, because two helicopters were utilized to conduct a systematic transect survey to cover the entire study area, a separate coastal strip survey was not required. Therefore, we used estimates that were the most comparable between 2011 and 2016 to assess trend. In general it is challenging to detect declines in abundance between two surveys unless the change is quite large (Gerrodette 1987, Thompson et al. 1998). In addition, comparison of two survey estimates does not allow separation of sampling variance from natural "process" variance in the population (Buckland et al 2004). For this reason we also considered annual coastal survey trend estimates (conducted by Manitoba) as well as an estimation of age-sex group specific trends to allow further inference on overall population trend and demography. Coastal surveys assume that similar proportions of the population occur on the coast during the survey each year. This assumption needs to be vigorously investigated prior to validation of this key assumption. For example, documented long range movements of male bears suggest that their aggregation points and localized movement rates may not be consistent and less predictable. A comparison of counts of adult males in coastal surveys suggest a larger degree of annual variation compared to females with offspring (as detailed in Supplementary Material). Despite these differences, the coastal surveys and distance sampling surveys suggest similar trends with the adult male segment increasing and adult females (with offspring) stable to decreasing from 2011– 2016.

Very few bears were observed in Nunavut, and a substantial proportion of bears, mostly adult males, were encountered in the south-east section of the study area towards the Manitoba-Ontario border. Cubs and yearlings comprised a small proportion of the sample size, which was also observed during previous studies. This suggests that reproductive performance is low for this subpopulation but this was not a specific objective of this study (Table 10). These findings are consistent with previous mark-recapture studies (Regehr et al. 2007). Of three polar bear subpopulations that inhabit the Hudson Bay complex, WH had the lowest reproductive performance values (Table 10). Whether this phenomenon is linked to a reduction in sea ice (e.g., Stirling et al. 1999), high intra-species offspring predation due to a high proportion of adult males in the population (Table 4), or a combination would require further examination. Until recently, the neighboring southern Hudson Bay (SH) polar bear subpopulation has exhibited a relatively healthy reproductive performance despite observed long-term changes in sea-ice conditions in the area (Gagnon and Gough 2005, Etkin 1991, Hochheim and Barber 2014, Stern and Laidre 2016, Obbard et al. 2016).

Southern Hudson Bay polar bears have been experiencing a significant decline in body condition between 1984 and 2009 that was linked to a later sea ice freeze-up (Obbard et al. 2016). The decline in body condition for cubs, however, was less than for adult males, suggesting that adult females may be allocating a greater amount of energy to their dependent offspring at an energetic cost to themselves. Obbard et al.

(2016) argue that declines in reproductive success are likely in the future if body condition of reproductive-age females continues to decrease.

Aerial surveys (e.g., distance sampling methods) rely on techniques that minimize heterogeneity of sighting conditions with one of the assumptions that similar sighting probabilities exist by a given observer for all encountered animals or animal groups. Sightability may also be affected by internal factors (e.g., observer fatigue, observer skill, and/or aircraft type), external factors such as animal behavior, group size, and distance from observer, and environmental factors (e.g., cloud cover, topography, vegetation cover, sun angle, etc.) (Ransom 2012, Fleming and Tracey 2008, Lubow and Ransom 2016). The 2016 WH survey protocol and analyses included several topographical and vegetation indices, and land classification studies (including post-survey inclusion of LANDSAT imagery), sun angle and position, and observer position and function as covariates which were most supported through our modeling approach (Tables 1, 3, 5-7).

It has been assumed that there was little difference between a dedicated and non-dedicated observer's ability to observe and detect wildlife during an aerial survey, meaning that sightability is equal. We were able to demonstrate for this survey that the ability of the pilot and data recorder for all aircraft to detect animals appeared to be influenced by their primary responsibilities (e.g. flying the aircraft and observing weather conditions and aircraft equipment, and recording observation data and monitoring transects and survey equipment, respectively). Even when animals are conspicuous against their background and environment (e.g., polar bears during the summer against a white/green environment), we recommend individually assessing the detection ability of animals by all dedicated and non-dedicated observers, so that the option to include observer performance as a co-variate into final models remains open and some assurances that model assumptions are not being violated.

We included sun angle and position into our modeling approach because observers found that this factor reduced sightability. When facing the sun during aerial surveys, additional glare is created on lighter-coloured background (e.g., lichen, water body surfaces) that makes the detection of animals more difficult, which can subsequently lead to missed observations, even within a double observer pair platform.

4.3. Assumptions and potential biases

One assumption during aerial surveys is that animals are detected at their initial location (Buckland et al. 2001). During the 2016 WH survey, behavioral response to survey aircraft varied depending on age and sex class and distance from aircraft. Adult males appeared to be the least affected by aircraft, while other age and sex classes appeared to react more strongly to aircraft when groups were approached that were close to transect lines or being overflown by survey aircraft to record detailed group and animal observational data. The majority (approximately 88%) of bears when first observed from survey transects were either laying down, sitting, standing, or swimming. Given an aircraft speed of 130 to 148 km per hour, any movement that may have occurred prior to detecting the bears further away from transects was minimal (Buckland et al. 1993, 2001). Bears did, however, display greater avoidance behaviors when aircraft broke off transect and flew to the observed group for age and sex determination. In many cases and depending on proximal habitat, bears fled into water in order to avoid the aircraft while some moved into thick shrub to hide from the oncoming aircraft. Large mature males appeared to be the least disrupted upon initial approach of the aircraft, with some exceptions.

The analysis also assumed that the distance from the survey line was measured accurately and that detections were independent of each other. Each observation was marked at the exact point at which the group was observed from transect even in the instance where bears had moved off that location assuring accurate off transect measurements. We used groups to define observations and ensured that observers did not search for additional bears while flying to observed groups to waypoint and classify the animals, therefore ensuring independence of observations. Additionally, observers on the same side were at all times visually separated by a screen therefore ensuring that detections were independent between observers.

It is possible that some bears were missed during the survey because they were unavailable for observations when in a den or visually obscured by vegetation. Dens are used quite frequently during the ice-free period by WH polar bears, at times as early as mid-to-late August, where pregnant adult females are more likely to be missed if inside a den (Stirling et al. 1977, Clark et al. 1997, Clark and Stirling 1998, Richardson et al. 2005, Jonkel et al. 1972). We encountered several freshly constructed dens excavated into peat. In several instances the bear was standing near the den entrance and could be observed. Moreover, our methods allowed for aerial inspection of any den to check for bear presence. Most freshly excavated dens that were observed during the 2016 survey effort also observed a polar bear and/or polar bear group in the vicinity. Therefore, the number of bears hidden from sight inside dens was low.

Habitats within the 2016 survey study area are diverse ranging from both coastal and fresh water shoreline, open tundra, to densely vegetated areas of shrubs and trees farther inland, where the detection of bears becomes challenging (Appendix 3). Including vegetation as a covariate into our modeling approach was important to capture the variation of detection among these varying habitats (Figure 9). Detection distances were reduced in treed habitat when compared to the other habitat types.

The point independence mark-recapture distance sampling model that we used in our analysis assumes that sightability at the left truncation distance (closest distance to the plane) is in part accounted for by covariates. However, variation in sightability due to vegetation and other factors away from the survey line can occur with minimal effect on estimates (Laake et al. 2008, Burt et al. 2014). Similar to Obbard et al. (2015) we found that sightability at the left truncation distance was not exact (or 1). Through the use of covariates in our analysis, factors influencing sightability both on the survey line as well as the shape of the detection functions were utilized to account for these potential biases to produce more robust abundance and density estimates.

5. CONCLUSION

The WH polar bear population has been subjected to changes in sea ice conditions reported in other studies resulting in reductions of body condition and vital rates (Gagnon and Gough 2005, Scott and Marshall 2010, Regehr et al. 2007, Stirling et al. 1999, Lunn et al. 2016). Under such conditions, and in order to provide goal-oriented conservation and management recommendations, up-dated information is needed in regular monitoring intervals. Traditional capture-mark-recapture studies are logistically challenging, locally unpopular, and they are time-consuming until results are disseminated. Comprehensive aerial surveys have become a useful monitoring tool for this subpopulation especially in response to the apprehension by Inuit toward intrusive physical handling of wildlife. As with any research methods, aerial surveys have their own limitations in terms of the scientific information that they can provide. Nevertheless, they have been proven to be an additional tool that can provide quick and updated information on the abundance, trend, distribution, and insights into reproductive success of a population.

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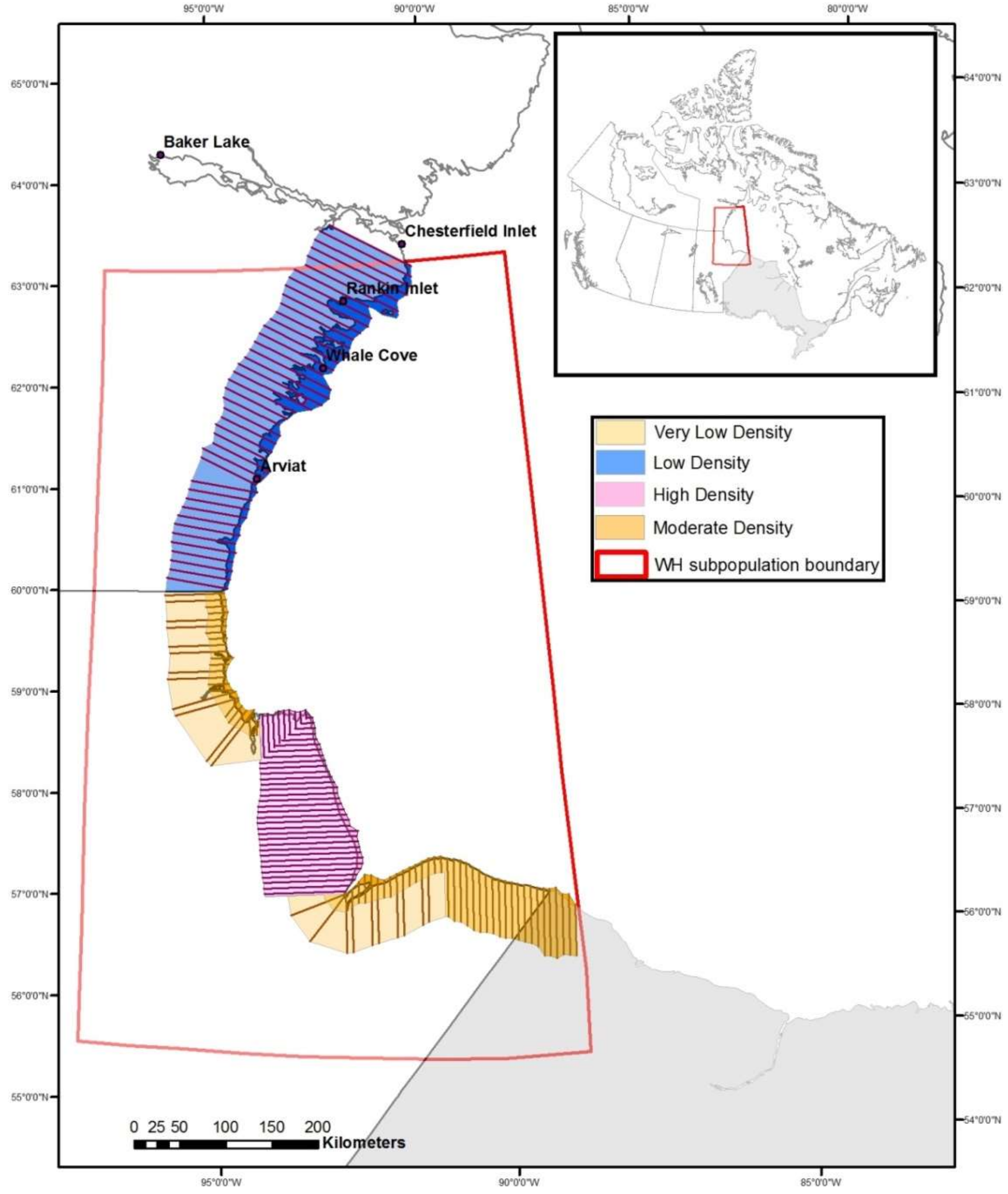


Figure 1. The August 2016 western Hudson Bay (WH) polar bear abundance survey strata and transects. All transects were run perpendicular to known polar bear densities. Extension of transects outside of the delineated WH polar bear population boundaries were based on Inuit knowledge of the area.

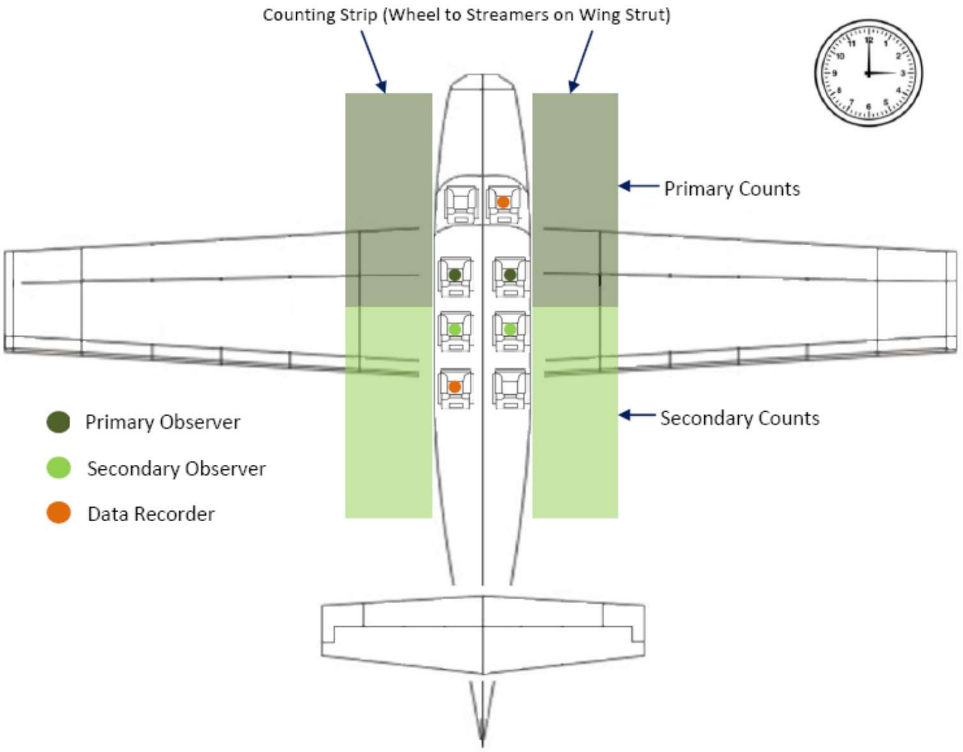


Figure 2. Observer position for the double observer method employed on this survey. The secondary observer calls polar bears not seen by the primary observer after the polar bear/bears have passed the main field of vision of the primary observer at a point half way between same side primary and secondary observers. The small hand on a clock is used to reference relative locations of polar bear groups (e.g. “Polar bear group at 3 o’clock” would suggest a polar bear group 90o to the right of the aircrafts longitudinal axis.).

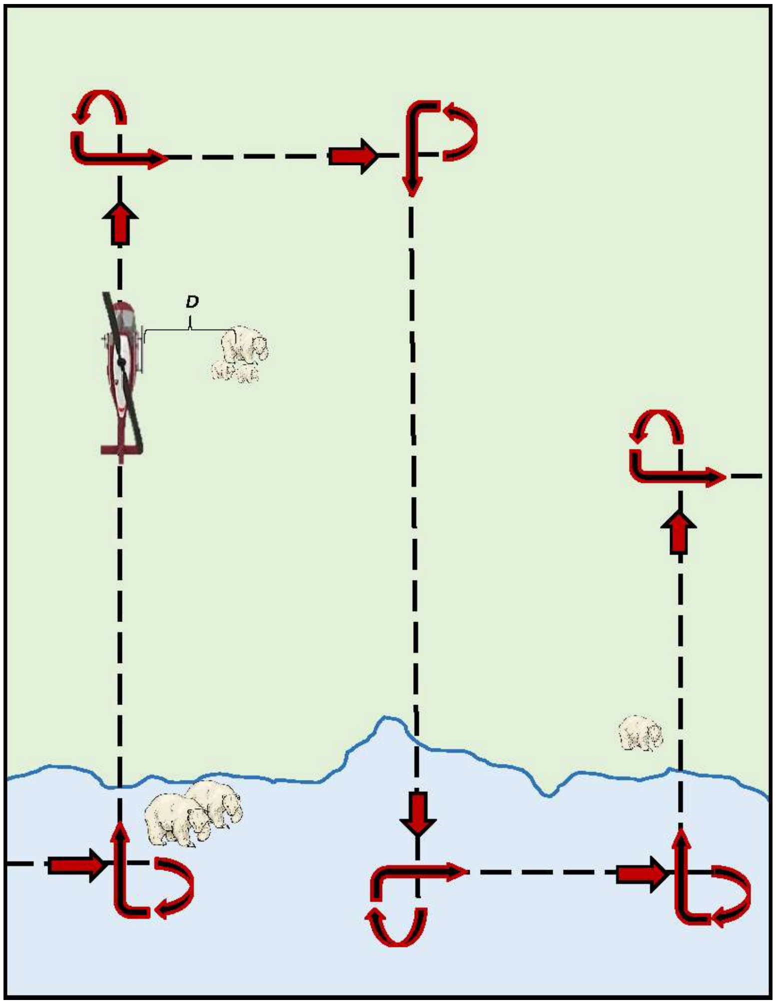
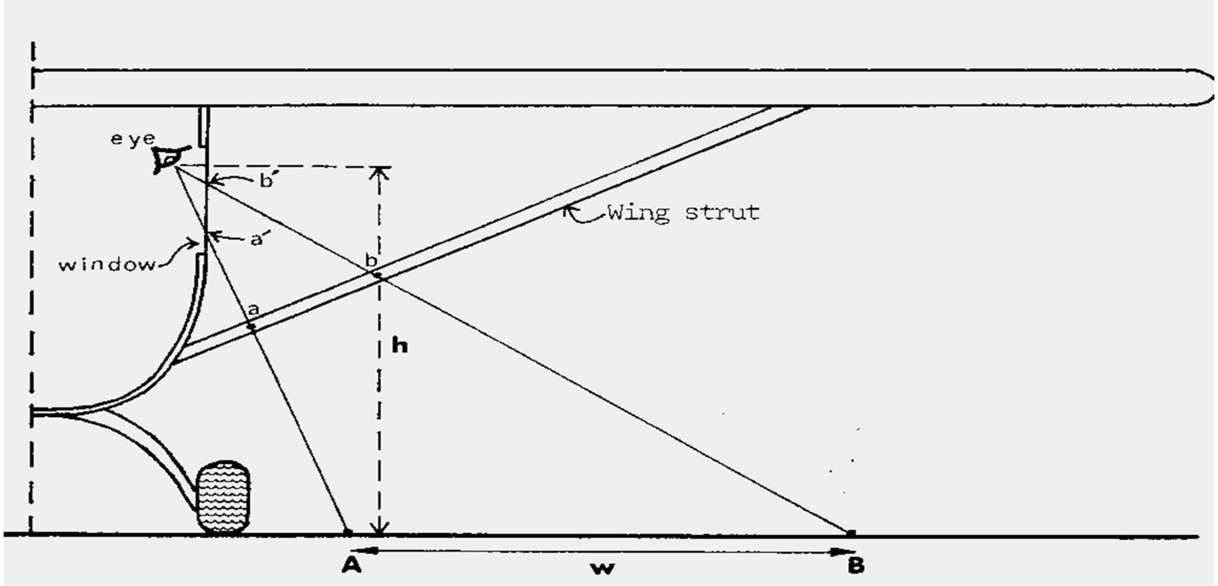


Figure 3. **Application of the distance sampling method during the August 2016 polar bear aerial survey in western Hudson Bay. Once observed the aircraft would move off the transect to the center of the observation to record location via a GPS, and assess and record field age, sex, and body condition for all individuals within the group as well as environmental covariate information (Note: D = the distance as measured 900 from the transect to the center of the observation/group).**



$$w = W * h/H$$

Where:

W = the required strip width;

h = the height of the observer's eye from the tarmac; and

H = the required flying height

Figure 4. Schematic diagram of aircraft configuration for strip width sampling (Norton-Griffiths, 1978). W is marked out on the tarmac, and the two lines of sight a' – a – A and b' – b – B established. The streamers are attached to the struts at a and b, whereas a' and b' are the window marks.

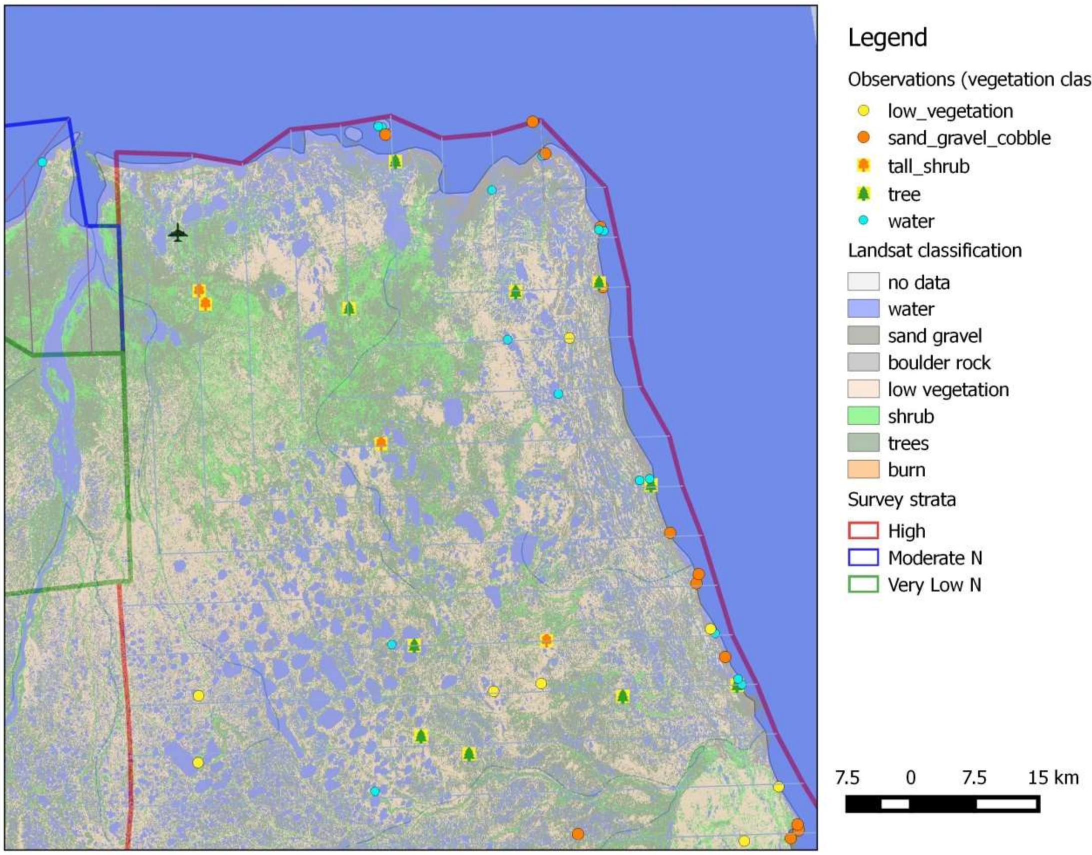


Figure 5: Landsat habitat classification and observations for a section of the high-density stratum of the 2016 study area.

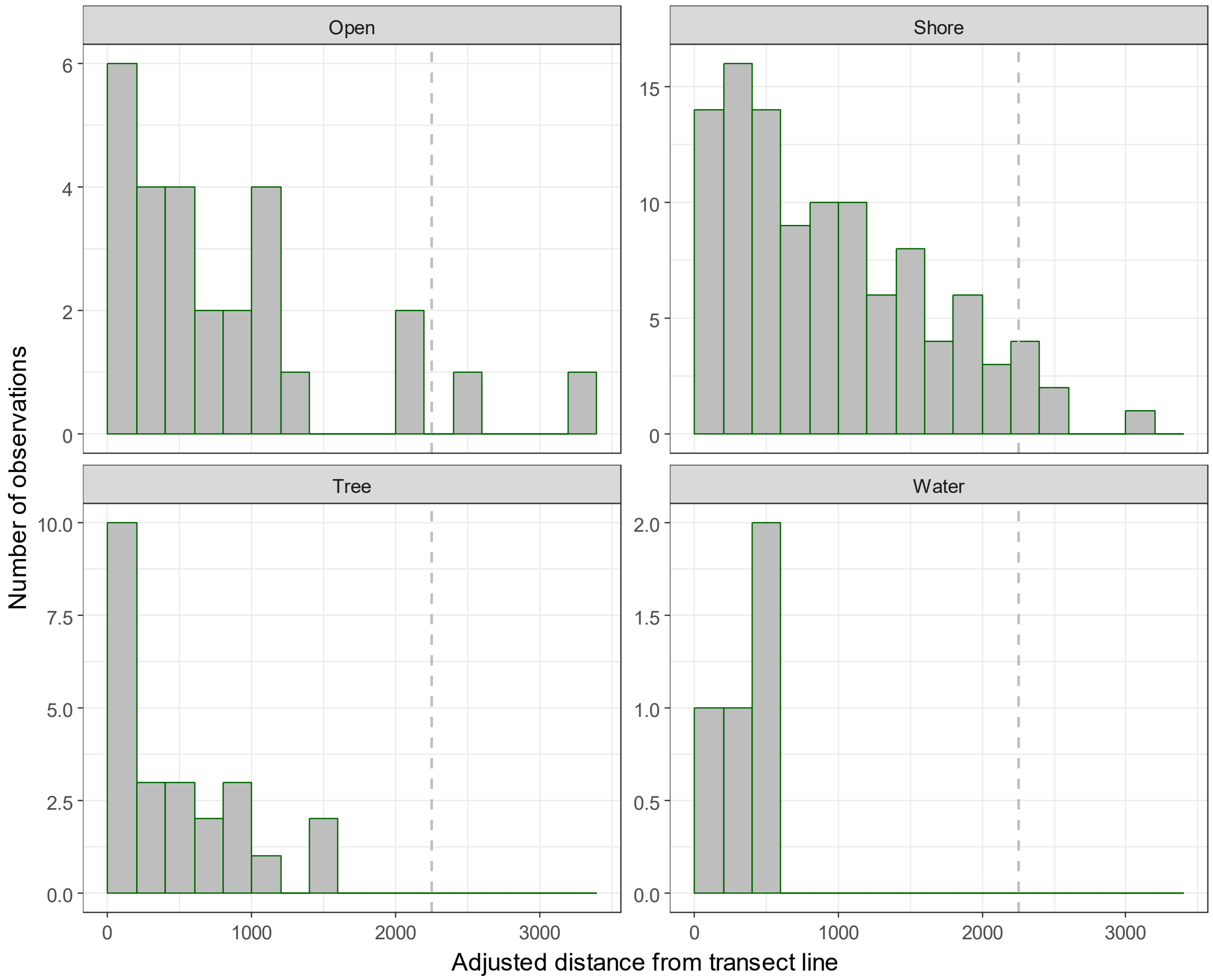


Figure 6. Distributions of detections for habitat classes.

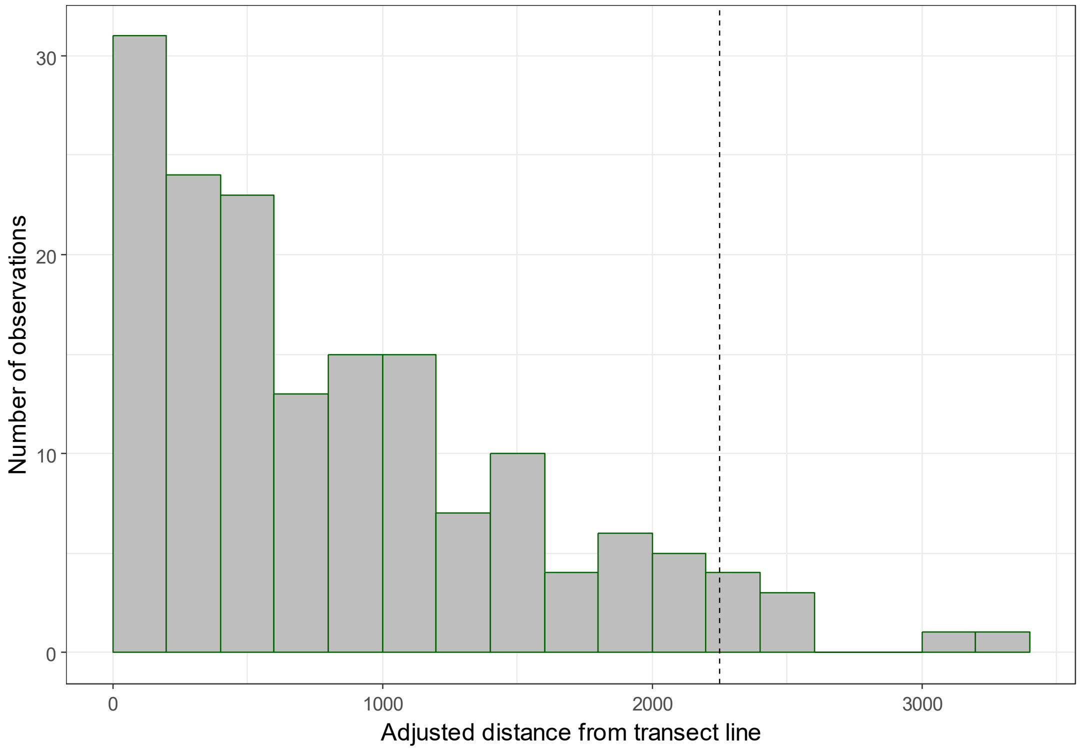


Figure 7. The distribution of observations relative to adjusted distance from the survey line (Distance from transect line-blind spot distance for each aircraft). The right truncation distance of 2250 meters used in the analysis is shown as a vertical line.

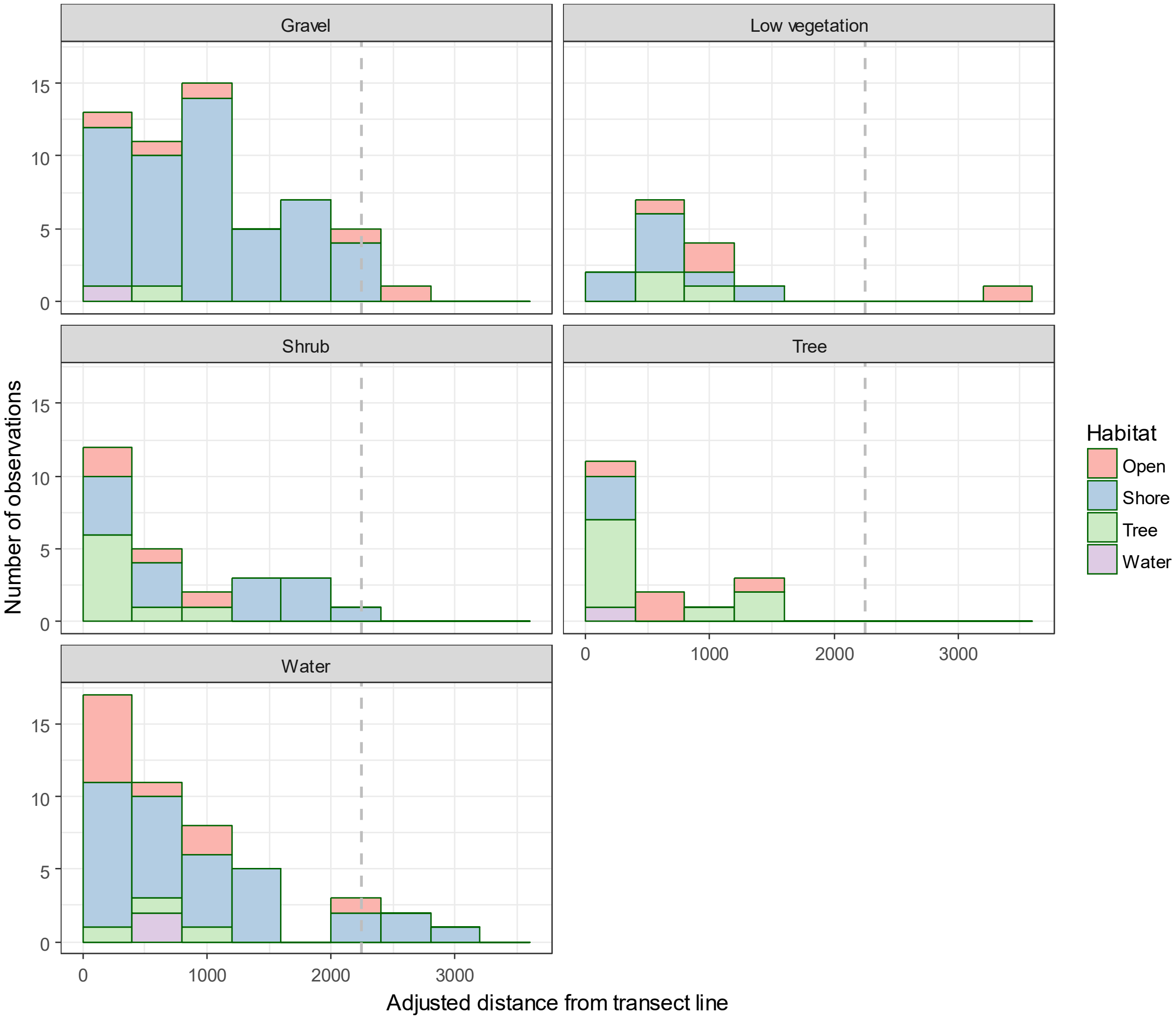


Figure 8. **Distributions of detections for Landsat remote sensing-based covariates with observer-based habitat classes shown as sub-bars to allow comparison of the 2 methods of habitat classification.**

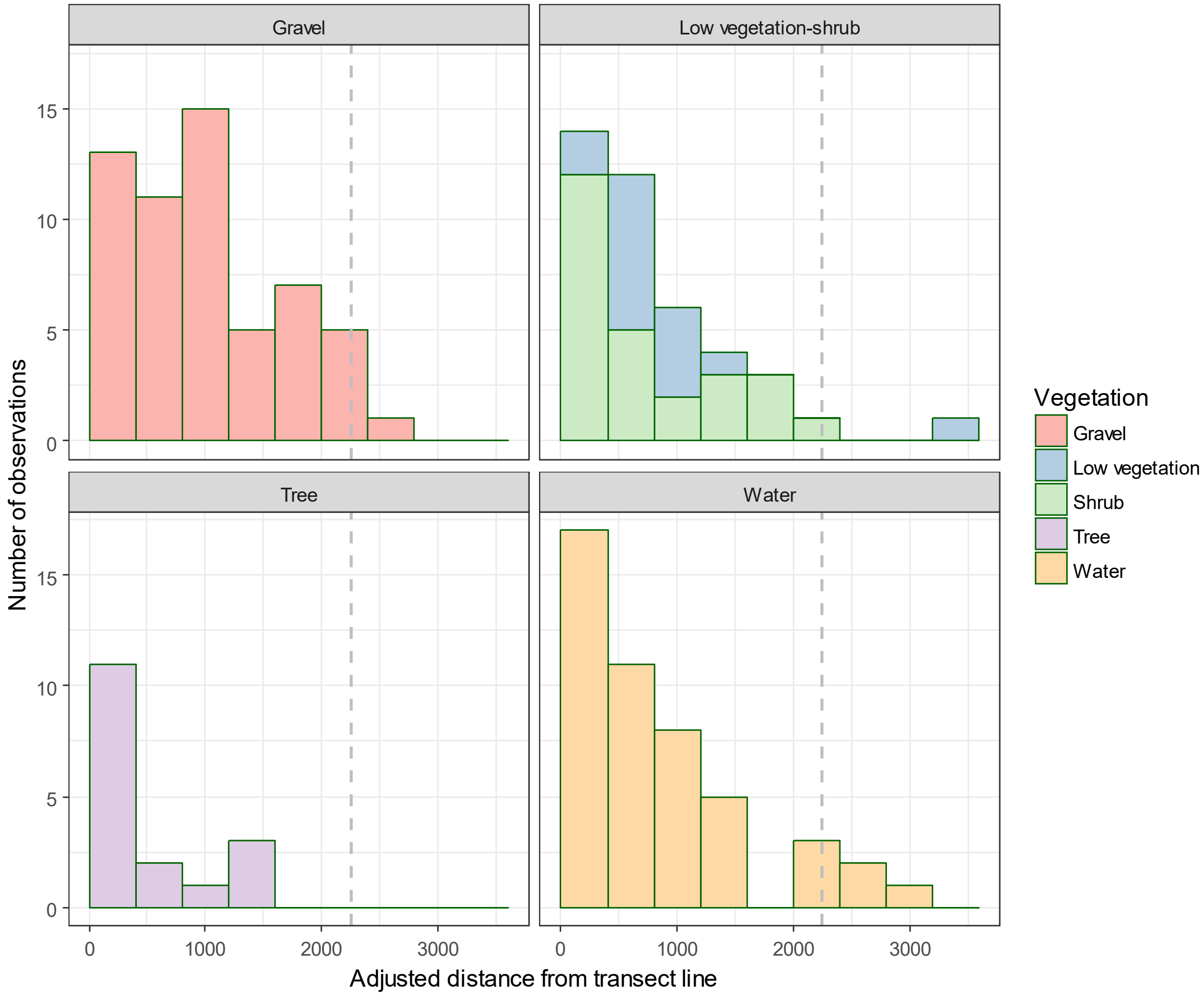


Figure 9. **Remote sensing vegetation classes with the shrub and low vegetation category pooled. This covariate was termed RSveg2.**

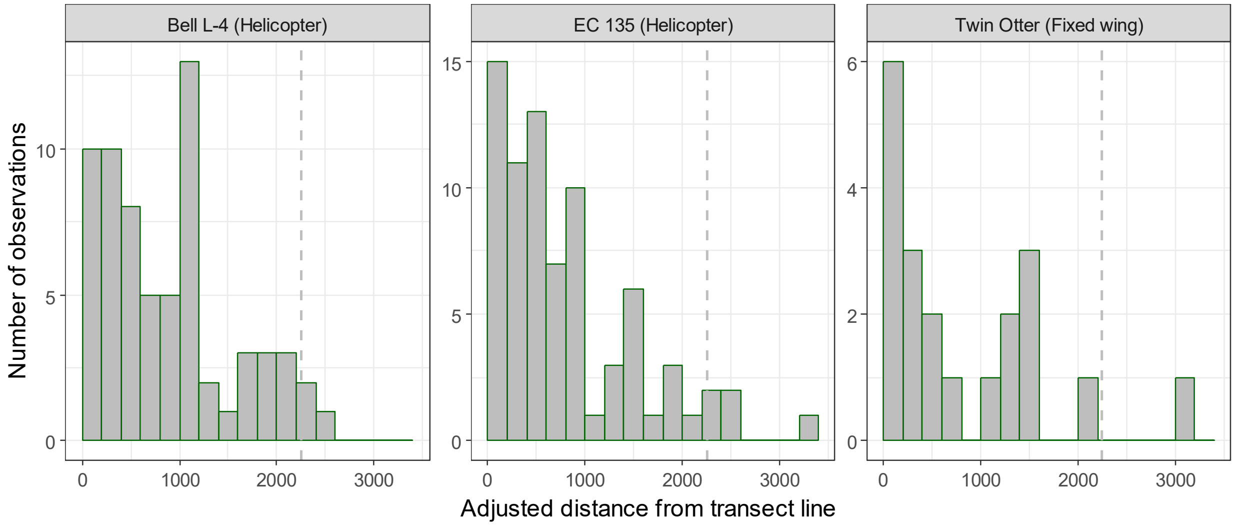


Figure 10. Distributions of detection for aircraft type.

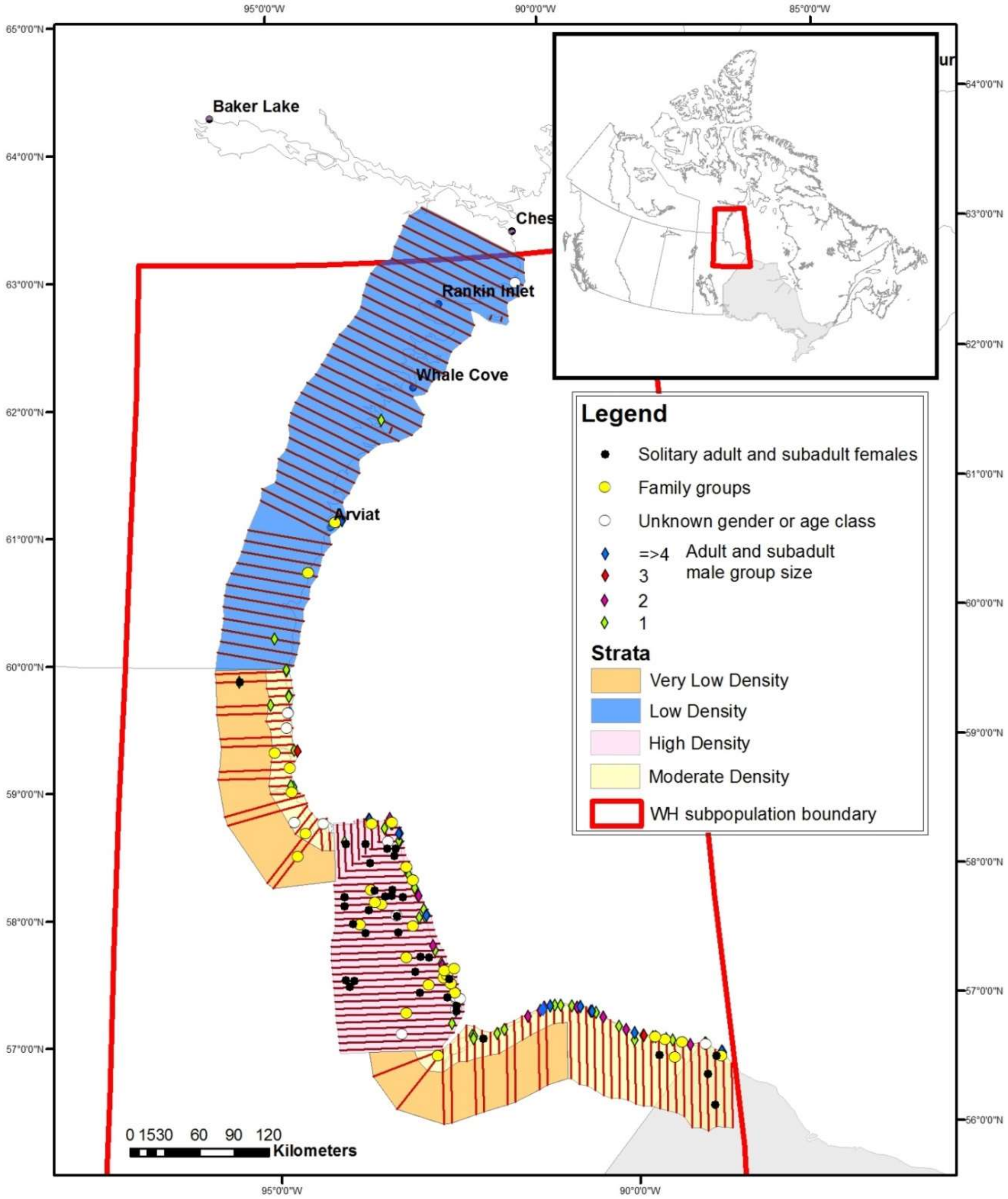


Figure 11. Distribution of polar bear group observations by age/sex class and strata within the study area during the 2016 western Hudson Bay aerial survey. Note that classifications of bears are based on aerial inspection.

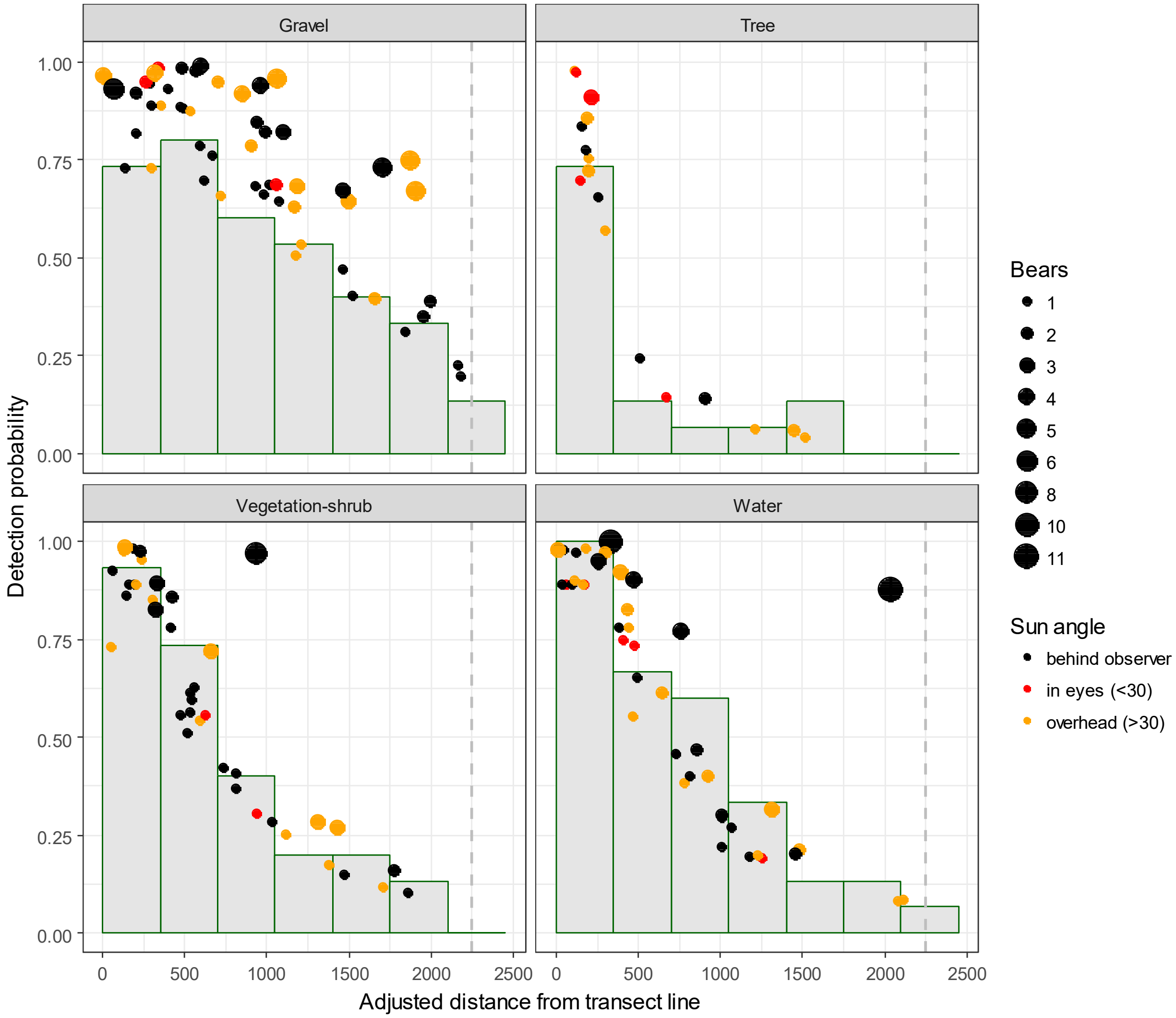


Figure12. Comparison of the observed detection distributions with predicted detection probabilities as a function of remote sensing vegetation classes (RSveg2) , group size (Bears), and angle of the sun from model 1 (Table 6).

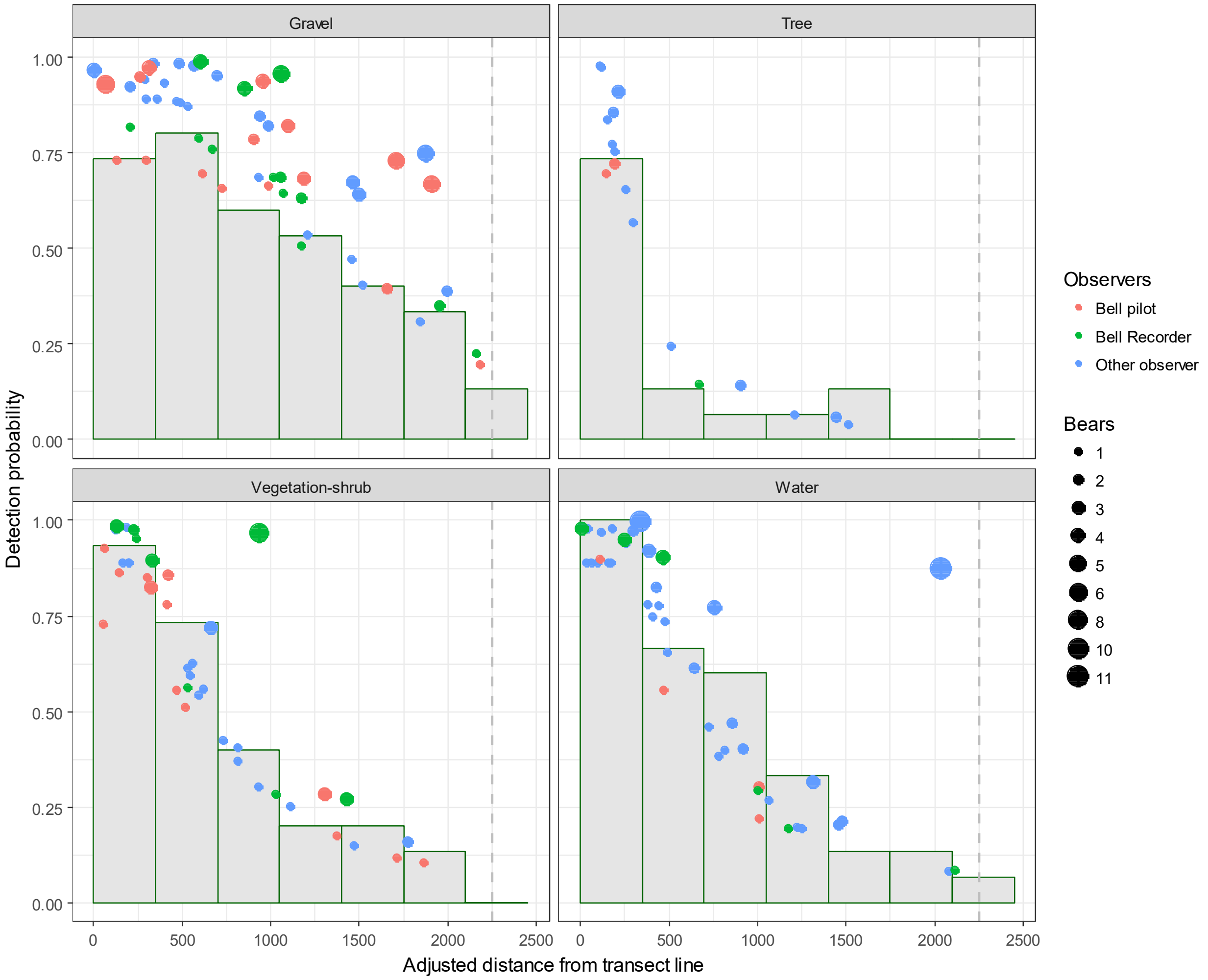


Figure 13. **Comparison of the observed detection distributions with predicted detection probabilities as a function of RSveg2 class, group size (Bears), and observer type from model 1 (Table 6).**

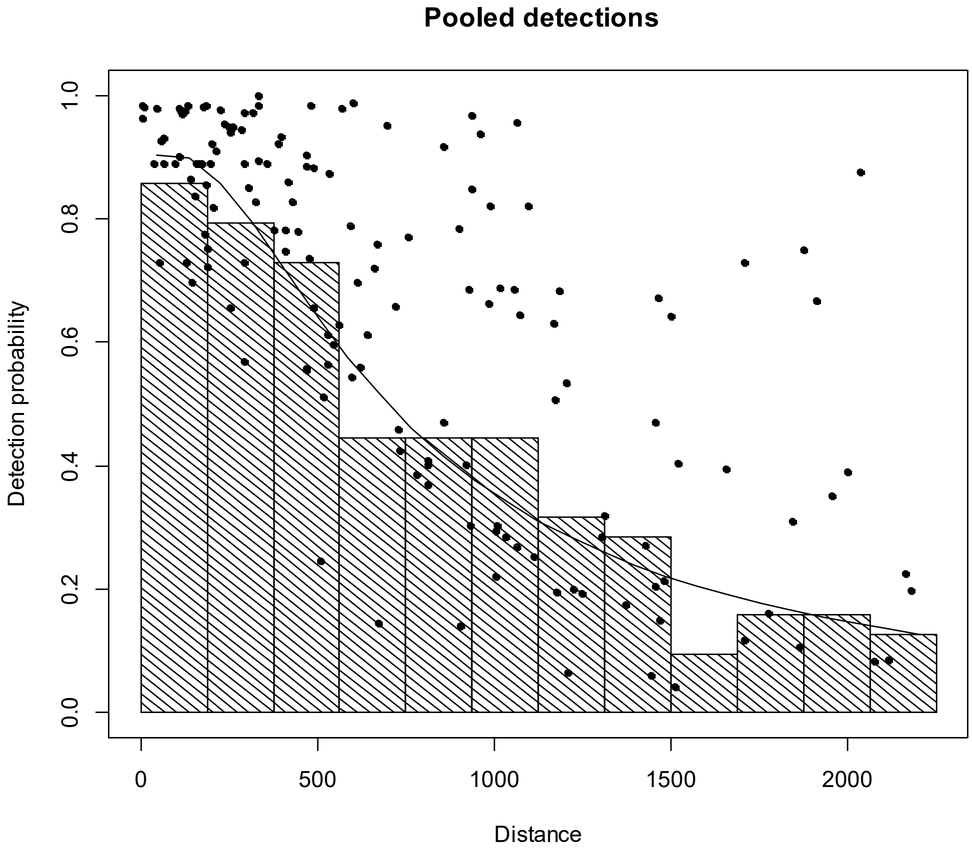


Figure 14. Predicted double observed detection probabilities (points) and mean detection (line) superimposed on detection frequencies for model 1 (Table 6).

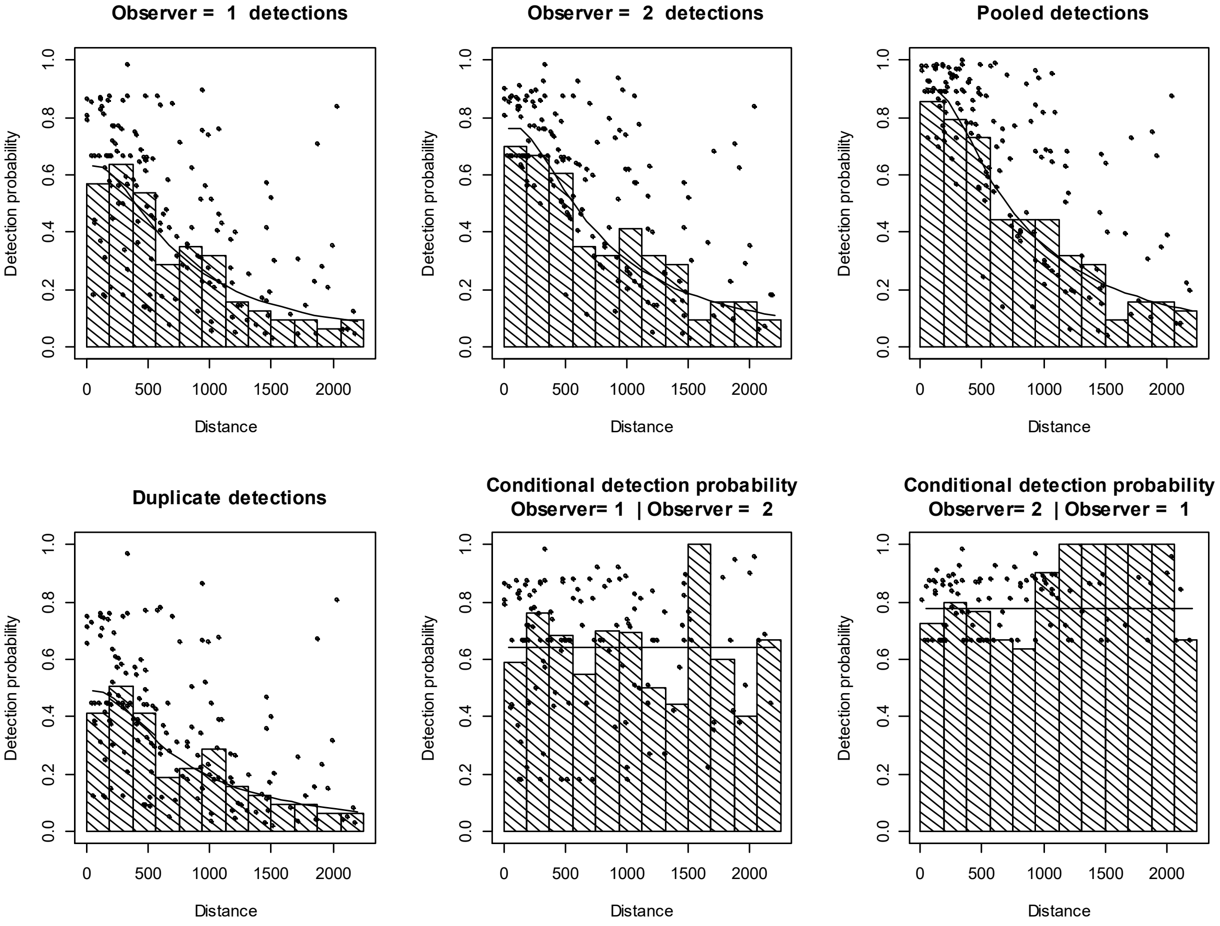


Figure 15. Detection plots for the front observer (1) and rear observer (2), pooled observers and duplicate observations (where both observers saw a bear. Conditional probabilities are also given for detection of bear by observer 1 given detection by observer 2 and vice versa. All estimates are from model 1 in Table 6.

Table 1. Covariates considered in the mark-recapture/distance sampling analysis. The primary use of the covariate for distance sampling analysis (DS) and mark-recapture analysis (MR) is denoted.

Covariate	Type	DS	MR	description
size	continuous	x	x	group size
aircraft	categorical	x	x	aircraft (Twin Otter, Bell, or EC135)
heli	binary	x	x	helicopter or airplane
Bell	binary	x	x	Bell helicopter
Bellp	binary	x	x	Pilot of Bell helicopter
Bellr	binary	x	x	Recorder/Navigator of Bell helicopter.
hab	categorical	x	x	habitat within 30m of observation as classified by observers (Open, Water, Shore, and Tree)
RSveg	categorical	x	x	Landsat habitat (Gravel,Low vegetation, Shrub, Tree, and water) at pixel (625 m^2) scale
RSveg2	categorical	x	x	RSveg habitat category with the Low vegetation and shrub category pooled.
RSveg90	categorical	x	x	RSveg at 90X90m scale
RSveg150	categorical	x	x	RSveg at 150X150m scale
RSveg-hab	categorical	x	x	RSveg water class re-assigned based on habitat classes.
vis	binary	x	x	ideal (163) or marginal (15 observations)
obs	categorical		x	Observers (12)
Sun	continuous	x	x	Sun altitude; only in equation if sun was facing observer
pilot	binary	x	x	if observer was a pilot
rec	binary	x	x	if observer was a data recorder

Table 2. Summary of observations by strata. Mean group sizes and numbers of bears by distance category are shown. LT (Blind spot) observations occurred under the planes and were usually only seen by the pilot and front seat navigator. Bears in the survey strip were observed by at least one of the 2 observers, or only seen by data recorders or non-observer personnel.

Strata		Group size				Numbers of bears by distance category				
	n	mean	std	min	max	LT (Blind spot)	Observed	Not observed	RT >2250m	Total
High	98	1.72	1.17	1	7	5	150	7	7	169
Low	8	2.25	2.12	1	7	1	6	4	7	18
Moderate	69	2.14	1.98	1	11	8	123	6	11	148
Very Low	3	1.33	0.58	1	2	3	1	0	0	4
Totals	178					17	280	17	25	339

Table 3. Summary of observer data during the Hudson Bay polar bear survey. The naïve probability is the number of detections divided by the total trials. The Bell pilot had the lowest probability.

Individual	Role	Bear observations			Naïve probability
		Not detected	detected	Total trials	
1	observer	2	22	24	0.92
2	observer	3	28	31	0.90
3	Bell recorder	11	20	31	0.65
4	observer	6	16	22	0.73
5	observer	4	10	14	0.71
6	observer	1	6	7	0.86
7	observer	5	15	20	0.75
8	observer	12	35	47	0.74
9	Recorder	1	14	15	0.93
10	observer	3	37	40	0.93
11	Bell pilot	22	13	35	0.37
12	observer	4	34	38	0.89
		74	250	324	0.77

Table 4. Overview of observed polar bears during the western Hudson Bay aerial survey, August 2016, by field age class and spatial occurrence. Areas A-D are defined as in Lunn et al. (2016).

Age Class§ 1	Area					
	NU (A)	MB (B)	MB/WNP (C)	MB EAST (D)	Total (bears or km)	PPN
ADF+1COY	0	2	7	0	18	0.053
ADF+2COY	2	2	7	4	45	0.132
ADF+1YRLG	0	1	4	1	12	0.035
ADF+2YRLG	0	0	2	0	6	0.018
ADF+1 2-yr old	0	0	1	0	2	0.006
ADF	0	1	27	5	33	0.097
ADM	11	23	63	84	181	0.532
SAM	0	0	21	4	25	0.074
SAF	0	0	2	0	2	
U	1	5	9	1	16	0.047
Flown distance (km)	4 900	1 870	6 200	4 300	17 270	
Transect flights (km)	3 511	1 053	2 881	2 237	9 682	
TOTAL bears observed	18	41	173	108	340	
PPN	0.053	0.121	0.509	0.318		

§ ADF=adult female; COY=cub-of-the-year; ADM=adult male; SAM=subadult male; SAF=subadult female; U=unknown; YRLG=yearling; 2-yr=2-year old.

[1] all classifications are based on aerial assessments from helicopters

Table 5. Model selection results for distance sampling analysis. The mark-recapture component of the MRDS model was set at constant for this analysis step. Covariates are listed in Table 1. Estimated abundance is given for reference purposes. Constant models are shaded. Akaike information criterion (AIC), the differences between AIC of the given model and most supported model ΔAIC, Akaike weight (wi), and Log-likelihood of each model is also shown.

No	DF	Distance	AIC	ΔAIC	w_i	K	LogL	N	Conf. int		CV
1	HR	Rsveg2 +size	2611.6	0.00	0.22	7	-1298.8	836	602	1160	16.7%
2	HR	Rsveg2	2612.3	0.78	0.15	6	-1300.2	908	644	1279	17.5%
3	HN	hab+vis	2612.9	1.31	0.12	6	-1300.4	816	625	1067	13.6%
4	HR	RSveg2+size+vis	2613.2	1.67	0.10	8	-1298.6	833	603	1152	16.5%
5	HN	hab+vis+size	2613.5	2.00	0.08	7	-1299.8	779	588	1033	14.4%
6	HR	RSveg-hab	2613.7	2.14	0.08	6	-1300.8	900	643	1262	17.2%
7	HR	Rsveg2+vis	2613.7	2.19	0.07	7	-1299.9	898	641	1258	17.2%
8	HN	hab	2613.8	2.26	0.07	5	-1301.9	813	622	1065	13.7%
9	HN	hab+size	2614.0	2.46	0.06	6	-1301.0	770	581	1019	14.3%
10	HR	hab+vis	2617.0	5.48	0.01	7	-1301.5	862	633	1173	15.7%
11	HR	size	2617.4	5.82	0.01	4	-1304.7	773	578	1035	14.9%
12	HN	vis	2619.2	7.68	0.00	3	-1306.6	800	615	1040	13.4%
13	HR	Constant	2619.9	8.33	0.00	3	-1306.9	931	658	1316	17.7%
14	HR	RSveg90m	2619.9	8.33	0.00	7	-1302.9	966	675	1381	18.3%
15	HR	RSveg150m	2620.0	8.42	0.00	7	-1303.0	955	670	1362	18.2%
16	HR	bellheli	2620.5	8.91	0.00	4	-1306.2	904	644	1269	17.3%
17	HN	Constant	2620.6	9.05	0.00	2	-1308.3	799	614	1040	13.4%
18	HR	bellpilot+bellrec	2621.4	9.80	0.00	5	-1305.7	922	652	1302	17.7%
19	HR	Sun	2621.6	10.04	0.00	4	-1306.8	939	661	1333	18.0%
20	HR	vis	2621.7	10.17	0.00	4	-1306.9	917	652	1290	17.5%
21	HR	aircraft	2622.1	10.59	0.00	5	-1306.1	944	661	1348	18.2%

Table 6. Model selection results for mark-recapture analyses. The most supported distance model (HR(RSveg2+size)) was used in all the models in this analysis. Covariates are listed in Table 1. Estimated abundance is given for reference purposes. . Akaike information criterion (AIC), the differences between AIC of the given model and most supported model ΔAIC, Akaike weight (wi), and Log-likelihood of each model is also shown.

No	Mark-recapture model	AIC	ΔAIC	w_i	K	LogL	N	Conf. Limit		N CV
1	Bellp+Bellr+sun+size	2575.5	0.00	0.65	11	-1278.1	896	638	1258	17.4%
2	Bellp+Bellr+sun	2577.0	1.48	0.31	10	-1279.9	911	647	1282	17.5%
3	Bellp+Bellr+size	2582.2	6.70	0.02	10	-1282.5	884	630	1240	17.3%
4	Bellp+Bellr	2584.0	8.52	0.01	9	-1284.4	897	638	1260	17.4%
5	aircraft+Bellp+Bellr	2585.1	9.61	0.01	11	-1282.9	893	634	1256	17.5%
6	observers	2591.9	16.47	0.00	18	-1279.4	891	633	1255	17.5%
7	sun	2605.1	29.64	0.00	8	-1295.9	922	654	1301	17.6%
8	aircraft	2605.6	30.08	0.00	9	-1295.2	926	658	1304	17.5%
9	heli	2607.9	32.37	0.00	8	-1297.3	914	648	1288	17.5%
10	size	2611.2	35.75	0.00	8	-1299.0	896	637	1259	17.4%
11	constant	2611.6	36.08	0.00	7	-1300.2	908	644	1279	17.5%
12	vis	2612.2	36.72	0.00	8	-1299.5	908	645	1279	17.5%
13	pilot	2612.2	36.73	0.00	8	-1299.5	908	645	1279	17.5%
14	hab	2613.2	37.71	0.00	10	-1298.0	921	652	1300	17.7%
15	recorder	2613.5	38.06	0.00	8	-1300.2	908	644	1279	17.5%
16	distance	2613.5	38.06	0.00	8	-1300.2	908	644	1279	17.5%
17	Rsveg	2617.0	41.55	0.00	11	-1298.9	915	648	1292	17.7%

Table 7. Model selection results for the combined distance and mark-recapture analysis. The most supported distance model and mark-recapture models given in Tables 4 and 5 were considered in this analysis. Covariates are listed in Table 1. Estimated abundance is given for reference purposes. Akaike information criterion (AIC), the differences between AIC of the given model and most supported model ΔAIC, Akaike weight (wi), and Log-likelihood of each model is also shown.

No	DF	Distance	MR	AIC	ΔAIC	wi	K	LogL	N	Conf. Limit		N CV
1	HR	Rsveg2+size	Bellp+Bellr+sun+size	2575.5	0.00	0.22	11	-1276.7	831	599	1151	16.7%
2	HR	Rsveg2	Bellp+Bellr+sun+size	2576.3	0.78	0.15	10	-1278.1	896	638	1258	17.4%
3	HN	Hab+vis	Bellp+Bellr+sun+size	2576.8	1.30	0.11	10	-1278.4	808	619	1056	13.6%
4	HR	Rsveg2+size	Bellp+Bellr+sun	2577.0	1.48	0.10	10	-1278.5	840	605	1165	16.7%
5	HR	Rsveg2+size+vis	Bellp+Bellr+sun+size	2577.1	1.67	0.10	12	-1276.6	828	600	1143	16.5%
6	HN	Hab+vis+size	Bellp+Bellr+sun+size	2577.5	2.00	0.08	11	-1277.7	774	585	1024	14.3%
7	HR	Rsveg2+vis	Bellp+Bellr+sun+size	2577.7	2.19	0.07	11	-1277.8	887	635	1238	17.1%
8	HR	RSveg2	Bellp+Bellr+sun	2577.7	2.26	0.07	9	-1279.9	911	647	1282	17.5%
9	HN	Hab+vis	Bellp+Bellr+sun	2578.3	2.78	0.05	9	-1280.1	823	627	1079	13.8%
10	HN	Hab+vis+size	Bellp+Bellr+sun	2578.9	3.47	0.04	10	-1279.5	785	590	1045	14.6%

Table 8. Strata-specific and total estimates of abundance for model 1 (Table 6).

Strata	Individuals	N	SE	CV	Conf. Limit	
High	150	471	103.0	21.9%	307	723
Low	6	27	13.8	50.8%	10	71
Moderate	123	323	63.4	19.6%	220	475
Very Low	1	9	9.7	102.2%	2	54
Total	280	831	138.5	16.7%	599	1151

Table 9. Sensitivity of MRDS models to left and right truncation. The most supported MRDS model from Table 6 was used for estimates.

Right Truncation	N	CV	Conf. Limit	
2250	831	16.7%	599	1,151
2700	825	16.4%	599	1,136
1800	826	17.9%	581	1,173

Table 10. **Mean (standard error) polar bear cub-of-the-year (COY) and yearling (YRLG) litter sizes of populations that inhabit the Hudson Bay complex, also presented as proportion of total observations during the respective studies.**

Subpopulation	Litter size		Proportion of total observations		Source
	COY	YRLG	COY	YRLG	
Western Hudson Bay (2016)	1.63 (0.10)	1.25 (0.16)	0.11	0.03	GN (unpublished data)
Western Hudson Bay (2011)	1.43 (0.08)	1.22 (0.10)	0.07	0.03	Stapleton et al. (2014)
Southern Hudson Bay (2011)	1.56 (0.06)	1.49 (0.08)	0.16	0.12	Obbard et al. 2015
Foxe Basin (2009-2010)	1.54 (0.04)	1.48 (0.05)	0.13	0.10	Stapleton et al. (2015)

Appendix 1

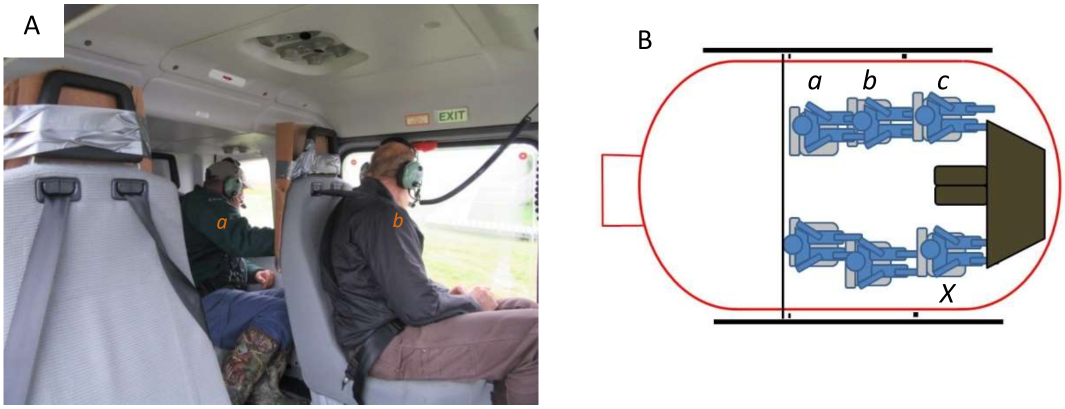


Figure A1: Overview of the EC135 rotary wing seat/observer configuration with separation wall set-up. Left photograph (A) depicts position *a* and *b* in the schematic diagram (right panel, B; *c* not shown in photograph A, *X* denotes pilot).

Appendix 2

Figure A2. Depicted are the front observers (local members of the Rankin Inlet and Arviat Hunters and Trappers Association) in a Twin Otter fixed-wing survey platform, separated by a cardboard barrier from the rear observers. Not shown are the recorders.

Appendix 3

Figure A3.1. Extended tidal flats in the western Hudson Bay study area. Red circle indicates 2 polar bears near boulders observed during the August 2016 aerial survey.

Figure A3.2 Boreal forest several kilometers inland interspersed with ponds and lakes. Red circle indicates a swimming polar bear seen during the August 2016 aerial survey.

Figure A3.3 View of the coastal plains interspersed with lichen/peat tundra and pond/lakes. Red circle indicates a polar bear seen resting next to a pond during the August 2016 aerial survey.

Figure A3.4 Polar bear (red circle) seen near the shore in the water at high tide during the August 2016 aerial survey in western Hudson Bay.

Appendix 4

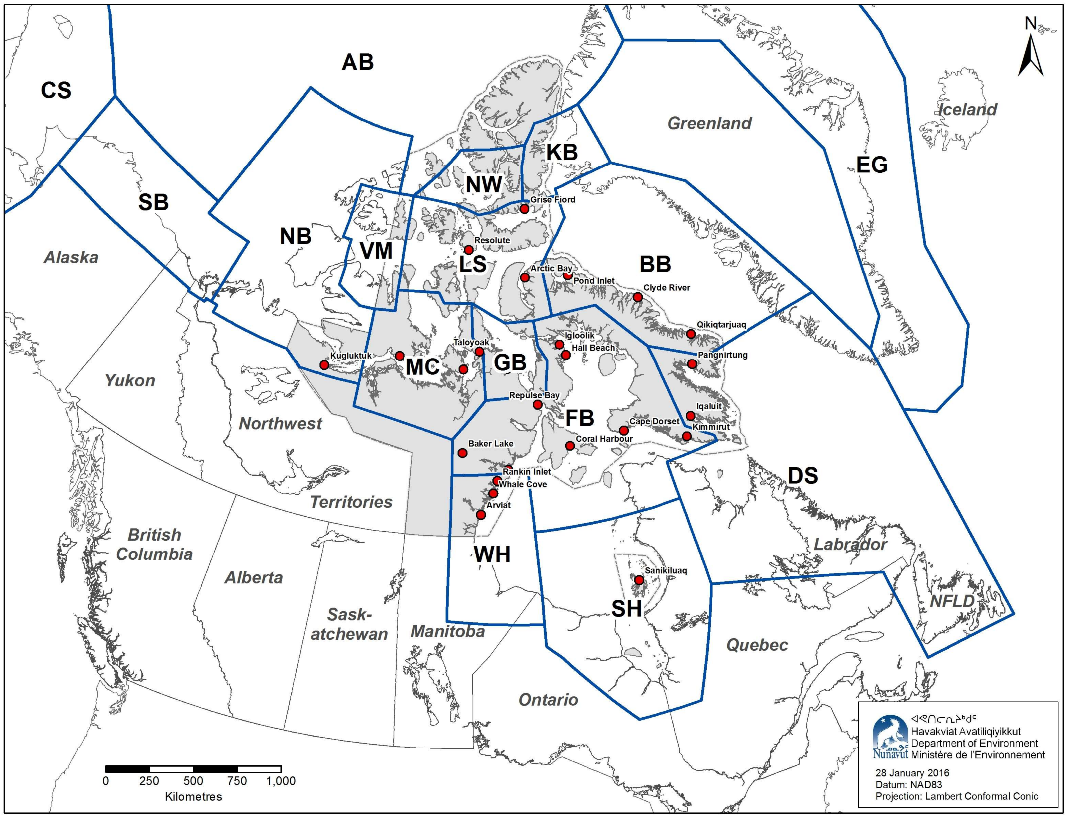


Figure A4.1. Canadian and Nunavut (dark grey) polar bear subpopulations [BB = Baffin Bay; DS = Davis Strait; SH = Southern Hudson Bay; WH = Western Hudson Bay; FB = Foxe Basin; GB = Gulf of Boothia; MC = M'Clintock Channel; LS = Lancaster Sound; KB = Kane Basin; NW = Norwegian Bay; VM = Viscount Melville Sound; NB = Northern Beaufort Sea; SB = Southern Beaufort Sea.