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An ~1,100-year record of human and seabird occupation in the High Arctic inferred from pond sediments – Supporting Information

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Study site and sample collection

Cape Vera is an Arctic coastal environment on Devon Island, Nunavut, Canada (Figure 1), located beside a recurrent polynya that has been free of ice in summer and much of the winter in modern times (Mallory and Fontaine, 2004). As a result, many migratory seabirds occupy this area during their migrations to other breeding locations, and thousands nest here in the summers (Black et al., 2012). Northern fulmars are the dominant species at this site, consisting of a colony of about 10,000 breeding pairs on the cliffs at the east end of the escarpment (Keatley et al., 2011). An apron of freshwater ponds is located below the cliff where the seabirds nest (Figure 1), with each pond named as CV(number) following previous studies at this site (Blais et al., 2005; Cheng et al., 2016; Keatley et al., 2011). These ponds are generally small and shallow, less than 100 m^2 in area and typically less than 1.5 m deep. Ponds were completely ice-free when sampled in July of both 2006 and 2007.

Pond CV9 is near the base of the cliff (Figure 1), and is hypereutrophic from fertilization by the fulmar colony (Blais et al., 2005; Cheng et al., 2016; Foster et al., 2011; Keatley et al., 2009). Pond CV30 is close to, but hydrologically-isolated from CV9 (Figure 1). It is also one of the most avian-fertilized ponds in the apron. For pond CV13, located about 1 km from the seabird colony, there are at least seven identifiable stone rings along its shoreline, which are the remains of human (likely Norse, but possibly Thule) habitation (McGhee, 1984; Schledermann and McCullough, 2003). Sediment cores were obtained in ponds CV9, CV30 and CV13 by pushing a 7.6 cm diameter plastic tube vertically into the sediment at the center of each pond from an inflatable boat. Then the tube was sealed in the top and pulled up carefully to retrieve the sediment cores. The sediment cores retrieved in CV9, CV30 and CV13 were 22.5 cm, 23.5 cm and 9.5 cm long, respectively. The CV9 and CV13 cores were sectioned at 0.5 cm intervals on site, while the CV30 core was sectioned at 1 cm intervals. The sectioned sediment cores were immediately sealed in Whirlpak® bags and frozen within 24 h, then kept frozen during transport to the University of Ottawa for further analysis.

Analytical methods

Chronologies in sediment cores were obtained with a combination of ^{210}Pb-^{137}Cs and ^{14}C dates. ^{210}Pb and ^{137}Cs measurements were performed at the Laboratory for the Analysis of Natural and Synthetic Environmental Toxicants (LANSET), University of Ottawa. Approximately 2.5 cm^3 of freeze-dried sediment of each section was added in a plastic tube and sealed with epoxy resin (Devcon 2-tonne). The samples were allowed to equilibrate for three weeks prior to isotopic analysis. ^{210}Pb and ^{137}Cs activities were measured in these sediments with an Ortec High Purity Germanium Gamma Spectrometer (Oak Ridge, Tennessee, USA). Chronologies were calculated with ScienTissiME (Barry's Bay, Ontario, Canada) using the constant rate of supply (CRS) model. Certified Reference Materials obtained from the International Atomic Energy Association (Vienna, Austria) were used for efficiency corrections.

Macrofossils for ^{14}C dating (Table S1) were picked and identified by the late Alice Telka of Paleotec Service (Ottawa, Canada). ^{14}C activities of the macrofossils were measured at the W. M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory, University of California, Irvine. Possible fractionation during sample graphitization were corrected with $\delta^{13}C$ values of prepared graphite, which were measured by isotope-ratio mass spectrometry in the same lab. ^{14}C ages were calibrated with IntCal13 (Reimer et al., 2013).

Sterols and stanols in the sediment samples were extracted with dichloromethane under sonication, cleaned up with dichloromethane on LC-Si SPE columns, derivatized with BSTFA (N,O-Bis-(trimethylsilyl) trifluoroacetamide) and quantified with an Agilent Model 6890 series gas chromatograph coupled to an Agilent Model 5973 triple quadrupole mass selective detector (GC-MSD), which was equipped with a capillary column of Agilent 19091J-433 HP-5 5% phenyl methyl siloxane at Laboratory for the Analysis of Natural and Synthetic Environmental Toxins (LANSET), University of Ottawa. 5α-cholestane was added as the internal standard in each sample before GC-MSD analysis. Detailed methods are available in our previous publication (Cheng et al., 2016).

Stable isotopes (i.e., $\delta^{15}N$ and $\delta^{13}C$) were analyzed with an Elemental Analyzer coupled to a DeltaPlus XP isotope ratio mass spectrometer (Thermo-Finnigan, Germany) at the G.G. Hatch Stable Isotope Laboratory, University of Ottawa. Samples were freeze dried and weighed into a tinfoil capsule with tungsten oxide and analyzed for $\delta^{15}N$ isotope values. For $\delta^{13}C$ analysis, samples were soaked in 6N hydrochloric acid (HCl) for 24 h at room temperature, in order to remove any carbonate that may affect $\delta^{13}C$ results.

The soaked samples were then freeze dried and weighed into a tinfoil capsule with tungsten oxide and analyzed for $\delta^{13}C$ isotope values. Internal standards of C-51 Nicotinamide, C-52 mix of ammonium sulphate + sucrose, C-54 caffeine and C-55 glutamic acid were used for data quality control, covering a $\delta^{15}N$ range of -16.61‰ to +16.58‰ and a $\delta^{13}C$ range of -34.46‰ to -11.94‰, respectively. The resulting $\delta^{15}N$ and $\delta^{13}C$ values of the internal standards were within the range of analytical precision of the certified values (±0.2‰ for $\delta^{15}N$ and ±0.15‰ for $\delta^{13}C$, respectively).

Chronology of the Sediment cores

The ^{137}Cs peaks were found at 1.25 cm (central depth of section, the same below) in both CV9 and CV30. The excess ^{210}Pb reached equilibrium at 4.25 cm and 3.25 cm in CV9 and CV30 core, respectively. Hence the ^{210}Pb -^{137}Cs chronology could only be used to date the most recent intervals of the two cores. As a result, the ^{210}Pb -^{137}Cs ages were mainly used to support the ^{14}C chronology, helping to determine the reservoir effect of the ^{14}C dates. The identified macrofossils and macrofossils for ^{14}C chronology were mostly purple saxifrage (*Saxifraga oppositifolia*) leaves, moss, water fleas (*Daphnia ephippia*) and larvae midge head capsules (Table S1). Terrestrial plants assimilate atmospheric ^{14}C, thus are best suited for ^{14}C dating (Stuiver and Polach, 1977). The latter two macrofossils may be affected by ‘old’ carbon and show older apparent ages up to 1000 years offset (Abbott and Stafford Jr, 1996), because the seabirds transport marine organic carbon from the oceans to the ponds and old carbon can also be leached from the local catchment (Blais et al., 2005; Blais et al., 2007).

The radiocarbon age of unidentified organic carbon in the 4.25 cm section in the CV9 core was dated to 486±27 y BP or 1464±13 CE (Table S1). In the ^{210}Pb -^{137}Cs chronology, this section was dated to 148±12 years before sample collection (2006 CE), or 1858±12 CE. The difference between the two chronologies was ~400 years, which we estimated to be the reservoir age for this sediment core in the sedimentary bulk organic carbon. A review of reservoir radiocarbon ages in Arctic Canada suggested a 335±85 years reservoir offset in the Northwest Canadian Arctic Archipelago, which approximates our estimate (Coulthard et al., 2010). In particular, studies in this area suggested reservoir ages between 200 and 400 years by radiocarbon dating whale bones, mollusc shell fossils and terrestrial plants (Coulthard et al., 2010; Vare et al., 2009). The 400-year reservoir age was applied to all radiocarbon ages from aquatic or mixed macrofossils in this study, while radiocarbon ages from terrestrial macrofossils (*Saxifraga*) were not reservoir corrected (Table 1). Ages of the other sections in the cores were determined with linear extrapolation and interpolation using IntCal13 (Reimer et al., 2013).

Despite the possibility that marine 'old' carbon changed over time, as the seabird population changed, there were not enough macrofossils to obtain a dual ^{14}C date of both terrestrial and marine ages. In addition, ^{14}C ages are available at 'crucial' intervals where proxies showed visible changes, so we do not suspect that the lack of terrestrial ^{14}C ages affects the major conclusions of this study.

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Figure S1. Atlas bone remains of a bowhead whale. Found near pond CV13. Pen used as a scale reference.