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Small-scale harvest of big trees: impacts of land use changes over ~1300 years on SGang Gwaay, Haida Gwaii, BC.

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Abstract

Haida Gwaii (British Columbia, Canada) is the ancestral home of Haida people. At its southwestern extremity lies SG̲ang Gwaay, a small island of ~3 km^2, and SG̲ang Gwaay Llnagaay (UNESCO World Heritage Site), a village inhabited until the 1888 CE smallpox epidemic. We investigated vegetation and limnological changes on SG̲ang Gwaay over ~1300 years with paleolimnological methods integrating sterols and stanols, stable carbon (C) isotopes, inferred lake-water total organic carbon (TOC), diatoms, and chlorophyll *a*. Changes were interpreted with respect to historical events and existing lake sediment palynological records aimed to understand long-term trends in C allocations to the pond. Stable C isotopes, C/N, sitosterol, and campesterol indicate that, historically, the pond C was primarily from terrestrial plants. Trends in these proxies changed in the 13th century, after the expansion of the village and increased harvest of western redcedar (*Thuja plicata*). After ca. 1625 CE, sitosterol/campesterol and chlorophyll *a* indicate a transition to increased autochthonous C sources in the sediment profile. Diatom assemblages after ca. 1388 CE suggest changes in light availability and increased water mixing, as a tychoplanktonic diatom taxon dominates. Our results demonstrate that land-use changes on the island, including small-scale tree harvest, impacted C inputs to the pond and aquatic primary production.

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Keywords: paleolimnological biomarkers, diatoms, ancient civilizations, land use, tree harvest, forest changes, limnology

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Preamble / a small note on place names:

We use Haida names for places. SG̲ang Gwaay ("Wailing Island") is located within Gwaii Haanas ("Islands of Beauty") National Park Reserve, National Marine Conservation Area Reserve and Haida Heritage Site in Haida Gwaii ("Islands of the People"), and the village site is SG̲ang Gwaay Llnagaay ("Wailing Island village"). The village is also referred to as Nang Sdins Llnagaay ("He Who is Two village"). Reported spellings differ: Nang Sdins (Ninstints, Nans Dins); SG̲ang Gwaay (SgA'ngwa-i). For a brief period (1787-2010), as reflected in past literature, these places bore different names: Queen Charlotte Islands, Anthony Island.

1. Introduction

Haida Gwaii is a remote archipelago of ~150 islands off the coast of British Columbia (B.C.) in the Canadian North Pacific (Moss 2008). The earliest dated archaeological specimen of a domestic dog suggests that ~13,100 years ago, shortly after the last glaciation, humans settled in Haida Gwaii (Fedje et al. 2021) from Asia. SG̲ang Gwaay ("Wailing Island") was occupied by the Kunghit, Haida people began living on the southern end of the archipelago, since 1590±160 years B.P (ca. 360 CE), making its SG̲ang Gwaay Llnagaay village site the southernmost, largest, and longest occupied settlement in Haida Gwaii (Acheson 1995; Hebda and Matthewes 1986).

Starting in the 1970s, the proposed expansion of logging activities on the archipelago pushed the Council of the Haida Nation to advocate for

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legal protection of their land and over the following decades the Gwaii Haanas National Park and Marine Reserve boundaries emerged alongside the designation of SG̲ang Gwaay Llnagaay as a UNESCO World Heritage Site. Today's archeological remains include poles and 20 houses of an average floor area of ~109 m^2. In 1984 CE, a paleoecological record spanning the last ~1800 years was obtained from the pond on SG̲ang Gwaay describing the impacts of early human land use on island vegetation composition. Lacourse, Mathewes and Hebda (2007) reported a stable vegetation assemblage with the notable exception of a decline in Cupressaceae pollen after ca. 950 CE likely linked to the selective harvesting of Wester redcedar (*Thuja plicata)* by the Haida. Many western redcedars still stand on the island today; however, starting in the late 19th century, the forest understory was heavily altered by Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) browsing (Martin et al. 1999). Sitka black-tailed deer are not native to Haida Gwaii and were introduced in 1878 CE (Golumbia et al. 2008) rapidly dispersing throughout the archipelago by swimming between islands. Reimchen et al. (2008) estimated that about 1 deer per year dispersed to SG̲ang Gwaay from a source population on Moresby Island. Several culling events were attempted on select islands of the archipelago. On SG̲ang Gwaay, about 59 deer were culled between 1998-2003 (Gaston et al. 2008), and once more in 2018, but this did not result in deer eradication. Irving et al. (2022) recently demonstrated genetic isolation of the remaining deer, which suggests a standalone eradication could be successful. At the time of our study, three

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deer were confirmed to be present on SGang Gwaay from Park Canada's camera-trap observations. To better understand the long-term ecosystem responses to human land use on small islands, we applied a multi-proxy paleoecological approach to pond sediments collected on SGang Gwaay. Our primary objective was to determine whether selective tree harvesting had lasting ecosystem-level effects on carbon delivery and aquatic ecosystem dynamics. We also aimed to assess the relative contributions of additional stressors such as Sitka deer browsing and climatic variability. We evaluated whether ecological changes in the lacustrine environment induced by historical land use were reversible after anthropogenic activity on the island declined, or whether they represented effects that persist today. This has broader implications for understanding the resilience or small island ecosystems in the face of anthropogenic disturbance.

Materials and Methods

2.1. Study area

The study pond is located on SGang Gwaay (52°05'29.5"N 131°12'43.9"W). The pond at its easternmost edge, is ~24 m from the ocean (Fig. 1). SGang Gwaay is within Gwaii Haanas National Park, B.C., in the Haida Gwaii archipelago. The pond has an area of ~2,535 m^2 and is in vicinity (~800 m) to SGang Gwaay Llnagaay (Fig. 1). The climate in this region is mild and temperate with annual temperature variations of ~20°C. The pond is surrounded by a forest composed of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), sitka spruce (*Picea sitchensis* (Bong.) Carr.) and western redcedar (*T. plicata*) with a moss-rich understory. The immediate

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area surrounding the southwest and northwest side of the pond is marsh-like with grass tussocks and sedges. To the east, the pond is adjacent to a rock shelf dropping into the ocean.

2.2. Core collection

We extracted a 123-cm long sediment core from the pond on SGang Gwaay in July 2021. The core sequence was composed of three smaller cores of ~50 cm with an overlap of 15 cm between cores. The pond has a maximum depth of ~80 cm, and the top, unconsolidated part of the core was extracted with a push-corer adapted to shallow lakes for capturing the sediment-water interface (Glew and Smol 2016), whilst the two bottom segments were extracted with a Russian peat corer with a barrel length of 50 cm and diameter of 6 cm. The core extracted with a push-corer was sectioned in 0.5 cm increments on-site using a Glew (1988) extruder. The cores extracted with a Russian peat corer were transferred to aluminium foil and sectioned in 0.5 cm increments off site using a sterile knife, cleaned with alcohol between each sample. Sediment samples were kept frozen at -20°C prior to being lyophilized for analysis.

2.3. Pond water chemistry

To better understand present-day conditions in the pond, water was collected on August 8th, 2022 in 1.0 L Nalgene bottles and refrigerated until processing. Samples were filtered and sent to the National Laboratory for Environmental Testing (NLET, Burlington, ON) to be analysed for

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nutrients, major ions, and trace metals using their standard procedures (Environment Canada Manual of Analytical Methods 1994a, 1994b). The data are available in the supplementary file (Table S-4).

2.4. Core chronology

A chronology was established using ^{14}C (n=6) and ^{210}Pb (n=8) radioisotopes. Sediments from the top of the push core (*n*=8) were dated through ^{210}Pb analysis using gamma spectrometry at the Queen's University Paleoecological Environmental Assessment and Research Lab (PEARL) following methods described by Appleby (2001). Older samples (>~150 years) of the core (*n*=6) were dated with radiocarbon analysis. Macrofossils of well-preserved pine needles (*P. sitchensis*), Sitka alder cones (*Alnus viridis*), and wood fragments (images and further details available in Fig. S-1 and Method S-1)

Age-depth modelling was performed in R v. 4.3.1 (R core team 2020) using results from ^{210}Pb and ^{14}C analysis . Radiocarbon dates were calibrated to calendar years before present (BP) using the 'IntCal20' calibration curve (Reimer et al. 2020). A compound Poisson-Gamma model with a modified Markov chain Monte Carlo fitting algorithm (Haslett and Parnell 2008) was used to calculate a continuous chronology with the function 'Bchronology' in the R package 'Bchron' v 4.7.6 (Haslett and Parnell 2008). This package was selected as it takes into consideration age inversions and the year of the core collection (2021 CE) was forced in the model.

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172 **2.5. Sedimentary chlorophyll *a* and lake-water TOC reconstruction**

173 Trends in the sedimentary concentrations of chlorophyll *a* (chl *a*)
174 were measured on a Model 6500 series Rapid Content Analyzer (FOSS
175 NIRSystems Inc.) at the PEARL lab and inferred using log-transformed data
176 from Michelutti et al. (2010) with the equation chl *a* + derivatives = EXP
177 (0.83784 *LN (peak area 650–700 nm) + (−2.48861)). This method captures
178 all the isomers of chl *a* as well as its main diagenetic products (Michelutti
179 et al. 2010; Michelutti and Smol 2016). Inferred chl *a* values were used to
180 establish periods of change in lake trophic status and primary production.
181 Past total organic carbon (TOC) concentrations in the pond water,
182 including dissolved organic carbon (DOC), were inferred using a partial
183 least squares regression model between the visible near-infrared spectrum
184 of surface sediments and the corresponding measured surface water TOC
185 concentrations from 345 northern lakes (Meyer-Jacob et al. 2017). As
186 modern-day DOC concentrations in the study pond are very high (65.4 mg
187 L^{-1}) and outside of the model's calibration range, inferred TOC trends were
188 expressed as z-scores. Extended methods are in the supplementary file
189 (method S-2).

190

191 **2.6. Diatoms**

192 Diatoms were analysed from 0.1 g of freeze-dried sediment
193 subsampled at 1.0 cm intervals. Sediment was digested using a 1:1
194 molecular weight ratio of sulfuric and nitric acid and heated at 80°C for 2 h.

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After that, the resultant sample was neutralised by consecutive rinses with deionized water. Once a neutral pH was reached, aliquots of the sample were pipetted onto coverslips, which were mounted onto slides using Naphrax®.

At least 400 diatom valves were counted and identified for each sediment interval. Diatoms were identified to the lowest taxonomic level using a Leica DMRB microscope under oil immersion at 1000× magnification, mainly following the taxonomy of Krammer and Lange-Bertalot (1986–1991), and Antoniades et al. (2008). Diatom count data were transformed to percent relative abundances and a stratigraphy was prepared in Tilia software (ver. 2.6.1, E. C. Grimm, Illinois State Museum Research and Collections Center, Springfield, IL, USA).

2.7. %C, %N, and stable carbon isotopes

Element concentrations and stable isotopes (%C, %N, C/N) were analysed at Ján Veizer Stable Isotope Laboratory (JVSIL) at the University of Ottawa. Sample preparation for % organic carbon (%OC) analysis followed methods outlined in Komada et al. (2008). Internal standards are (δ^{15}N, δ^{13}C in ‰): C-51 Nicotiamide (0.07,-22.95), C-52 mix of ammonium sulphate and sucrose (16.58,-11.94), C-54 caffeine (-16.61,-34.46), blind std C-55: glutamic acid (-3.98, -28.53). All δ^{15}N values are reported as ‰ vs. AIR and normalized to internal standards calibrated to International standards IAEA-N1(+0.4‰), IAEA-N2(+20.3‰), USGS-40(-4.52‰) and USGS-41(47.57‰). All δ^{13}C values are reported as ‰ vs. V-PDB and normalized to internal standards

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calibrated to International standards IAEA-CH-6(-10.4‰), NBS-22(-29.91‰), USGS-40(-26.24‰) and USGS-41(37.76‰). Extended methods of stable isotope preparation, analysis and analytical precision are outlined in the supplementary file methods S-3. Atomic C/N and $\delta^{13}C$ values were used to distinguish between terrestrial and aquatic (lacustrine vs. marine) sources of carbon following Meyers (1997) and Meyers and Ishiwatari (1993).

2.8. Lipids

Sedimentary sterols and stanols were determined using methods adapted from Hargan et al. (2019) and are outline in greater detail in Supplementary Methods S-5. One hundred milligrams of copper (Cu; Fisher) were added to ashed scintillation vials and sonicated for 10 min with 10 mL of dichloromethane (DCM). The DCM was discarded after the first sonication and this step was repeated twice more. The Cu was air dried, and to each vial, 100 mg of lyophilized material was added. Sediment was subsampled every 4 cm (n = 28) in the core. Each sample was spiked with 100 µL of 50 mg L^{-1} (3α)-Allopregnanolone. Information about the purity of standards used is presented in Table S-3b. Method blanks containing only copper were spiked with 50 mg L^{-1} 9 standard mix. Lipids were isolated using SPE column with 1.0 g Si bed (LC-Si Millipore) with greater details in Methods S-4. Lipids were corrected to the internal standard, (3α)-Allopregnanolone. All sterols and stanols analysed by GC-MS and their retention time are presented in Table S-3a. All sterols and stanols

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were corrected to organic C by multiplying the organic C content of each sample, reported in μg $(gOC)^{-1}$.

We used sterol ratios to distinguish between plant inputs to the pond. We used sitosterol/campesterol to distinguish between phytosterol sources of higher plants and microalgae inputs (Meyers and Ishiwatari 1993; Carreira et al. 2002; Zhang et al. 2018); sitosterol/stigmastanol was used to assess hydrogenation (Gaskell and Eglinton 1975; Stevenson et al. 2020); sitosterol/cholesterol was used to track sewage input and phytoplankton productivity (Zhang et al. 2018; Mudge et al. 1999) and coprostanol/cholesterol (the Human Index) was used to indicate human presence (Vane et al. 2010; Briles et al. 2019).

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2.9. Numerical analyses

The relationship of chl *a* versus depth was interpreted with break-point analysis in R with the package "segmented" (Muggeo 2008). Changes in diatom assemblages were established by cluster analysis using constrained incremental sum of squares (CONISS) and the number of important zones were determined with a broken-stick model in R with the packages "ggplot2" (Whickam 2016), and "tidypaleo" (Dunnington 2022). A principal component analysis (PCA) was conducted to summarise changes in diatom assemblages over time by using the package "vegan" and 95% confidence ellipses were added with the package "ellipse" (Murdoch 2022).

Trends for stable isotopes, C/N, lake-water TOC, and chl *a* were fitted using a generalised additive model (GAM) using the R package 'mgcv'

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v.1.8-41 (Wood 2011), 'gratia' v.0.7.3 (Simpson 2024), and 'ggplot2' v 3.3.5 (Whickam 2016). This model was used to identify significant change (periods when the derivative of the GAM is not 0). Model outputs provided estimated values for core depths that were not analysed. Sterols and stanols data were modelled using locally estimated scatter-plot smoothing (LOESS) regression curves. Data was verified for outliers using both Z scores and interquartile range (IQR) in R using "stats" v 4.1.2 (R Core team 2020). Values with z-scores of above |3|or above Q3-1.5 IQR and below Q1-1.5 IQR were considered outliers that were excluded from the LOESS regression curves.

3. Results

3.1. Core chronology

^{210}Pb activities were low (surface activity (0-0.5 cm) of 154.8 Bq kg^{-1}; Table S-5). The samples failed the assumptions of the constant rate of supply (CRS) model, in which a main assumption is a constant flux of excess ^{210}Pb. ^{210}Pb decay was observed with core depth; however, at 4 cm depth a fluctuation in the activity was observed. The chronology for the top part of the core was established with the constant flux constant sedimentation (CFCS) model (Table S-5, Fig. 2a). Artificially produced ^{137}Cs and ^{241}Am are used to pin-point chronologies in recent sediment samples. The deposition of these isotopes reached a maximum in ca. 1963 CE with nuclear testing. ^{137}Cs and ^{241}Am activity increases between 0-4 cm in the core (Fig. 2a), indicating that ca. 1963 CE occurs within that period (Vane et al. 2010).

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Ages from the CFCS model, ^{14}C ages (Table 1) and the year of the core collection (2021 CE) were used to generate an age-depth model using Bchron v. 4.7.6 (Haslett and Parnell 2008). Model outputs provide mean, maximum and minimum ages for each depth interval of the cores with a 95% confidence interval (Fig. 2). A single age inversion was observed between samples SG 82-82.5 cm dating at 1055 CE and SG 91-91.5 cm dating at 1371 CE. The mean date for the top of the core based on the Bchron model is 2018 CE (maximum age 2010 CE and minimum age 2021 CE) and the bottom of the core dates to 689 CE (maximum age 587 CE and minimum age 766 CE). SG̲ang Gwaay Llnagaay was established before the oldest age of the core (1377 ± 42 ^{14}C yr BP; 573 CE) and therefore our paleoecological record does not capture data prior to known human presence on SG̲ang Gwaay.

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3.2. Diatoms

From the bottom of the core until ca. 1388 CE, the diatom assemblage is diverse. *Stauroforma exiguiformis* (Lange-Bertalot) R.J. Flower, V.J. Jones & Round and *Eunotia incisa* W.Smith ex W.Gregory dominate with relative abundances between 15-60% and 5-45%, respectively. *Platessa hustedtii* (Krasske) Lange-Bertalot and *Staurosira construens* var. *venter* (Ehrenberg) P.B.Hamilton are also dominant with relative abundances between ~5-40% and 10-30%, respectively, and other species present in low relative abundances around ~5% (Fig. 3). After ca. 1388 CE, *S. exiguiformis* is no longer encountered in the diatom counts,

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whereas early core diatoms with relative abundances of ~5% or less, such as *Neidium sacoense* Reimer, *Pinnularia viridis* (Nitsch) Ehrenberg, *Tabellaria flocculosa* (Roth) Kützing, and *Eunotia intermedia* (Krasske ex Hustedt) Nörpel & Lange-Bertalot, exhibit an increase in percent relative abundances (Fig. 3).

Towards the surface of the core, starting ca. 1588 CE (27 cm) until the top of the core, *Aulacoseira crassipunctata* Krammer becomes highly abundant (relative abundance 60-90%) and *E. incisa* persists with a relative abundance of 5-15% (Fig. 3). Other species disappear or are present in very low (~5%) abundances. A shift in dominant diatom species occurs at the same depth in the core as the increase in chl *a* – 27 cm. Broken-stick model (Fig. S-5a) identified four significant time periods from 700-970 CE, 970-1394 CE, 1394-1600 CE, and 1600-2018 CE (Fig. 3). Principal component analysis shows four distinct diatom assemblages (Fig. S-5b).

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3.3. Chlorophyll *a*, % organic C, $\delta^{13}C$, C/N and lake-water TOC

VRS inferred chl *a* is low and stable throughout most of the core (123-27 cm), with values fluctuating between 0.01 and 0.02 mg g^{-1} D.W. until ca. 1625 CE when it starts increasing significantly to reach ~0.1 mg g^{-1} D.W. over the top part of the core (~10 cm). The break-point analysis indicates a breaking point at 27 cm or ca. 1625 CE (Fig. 3; Fig. S-4).

The SG̲ang Gwaay $\delta^{13}C$ values range between -29.8 and -27.6‰ and, once corrected for the Suess effect, range from -28.5 to -26.7‰ (Fig. S-6).

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Once outliers were removed, values range from -28.5 .to -27.5‰ (Fig. 4) and are therefore a mixture of terrestrial-aquatic (freshwater) derived plant sources throughout the core (Meyers 1997). The GAM fitted model shows a significant period of decline in Suess-corrected $\delta^{13}C$ values between ca. 1400-1875 CE.

C/N trends vary throughout the record (Fig. 4), but are high ranging between 23.4 and 40.1. The GAM fitted model shows a significant period of C/N increase between 800-950 CE and a significant decline between starting ca. 1550 CE until present (Fig. 4). First, there is an increase in C/N between ca. 689-1230 CE (from ~30 to 40). This period of increase is followed by a C/N decline from 40 to ~30 between ca. 1230-1268 CE, and another increase from between ca. 1268-1388 CE. Finally, C/N declines starting at ca. 1388 CE from 37.5 to ~23 (Fig. S-6).

Inferred lake-water TOC shows a significant decline starting ca. 1250 CE and keeps declining until ca. 1850 CE after which it increases until ca. 1925 and seems to plateau until present (Fig. 4). The %OC values range between 17.7 and 47.7% and follow a decrease similar to those of C/N, and $\delta^{13}C$ values (Fig. S-6). Lake water TOC follows a similar trend and declines from a z-score of ~0.7 to -1.7 after ca. 1250 CE until present, except for a small significant period of increase between ca. 1850-1925 CE. The decrease in these proxies (%OC, lake-water TOC, C/N, $\delta^{13}C$) at the top of the core (0-27 cm) contrasts with the increase in chl *a* occurring at the same time (Fig. 4).

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360 **3.4. Lipids**

361 Plant-derived sterols and stanols campesterol, sitosterol, and
362 stigmastanol are predominant throughout the core, while cholesterol and
363 coprostanol are present in lower concentrations (Fig. S-7). Due to
364 significant changes in %OC trends, all sterol and stanol values were
365 corrected to OC and are reported in $\mu g(gOC)^{-1}$. Sitosterol ranges between
366 5.6-23.4 $\mu g(gOC)^{-1}$, stigmastanol ranges between 7.9-33.6 $\mu g(gOC)^{-1}$, and
367 campesterol ranges between 0.1-22.1 $\mu g(gOC)^{-1}$. Sitosterol, campesterol,
368 and stigmastanol follow a similar increasing trend from ca. 725 CE until ca.
369 1100 CE followed by a slightly declining plateau between ca. 1250-1775 CE.
370 The sitosterol/campesterol ranges between 10.2 and 0.28 with the
371 ratio following a decline starting ca. 1325 CE and dropping below 6.6 at ca.
372 1625 CE (Fig. 5). These changes in sitosterol/campesterol ratio follow the
373 decoupling in sitosterol to campesterol trends in the pond starting ca. 1250
374 CE, when campesterol remains stable as sitosterol declines (Fig. 5). The
375 ratio of sitosterol/cholesterol ranges between ~19-15 (more oligotrophic)
376 from ca. 750 CE until ca. 1250 CE when it starts declining to ~8 (more
377 eutrophic), before increasing again at ca. 1700 CE to reach ~12 in recent
378 times (Fig. S-8). Hydrogenation (sitosterol/stigmastanol) increases starting
379 at ca. 1325 CE until ca. 1700 CE (Fig. S-9).
380 Sediment samples from the pond have coprostanol concentrations
381 between 1.8-8.4 $\mu g(gOC)^{-1}$ and cholesterol concentrations between 0.3-3.4
382 $\mu g(gOC)^{-1}$ (Fig. S-7), while the uncorrected concentration of these lipids in
383 sediment samples is between 0.27-1.77 $\mu g\ g^{-1}$ D.W and 0.04-0.83 $\mu g\ g^{-1}$ D.W.

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The Human Index (i.e., coprostanol/cholesterol; Fig. 6) is used to indicate human presence as impacted lakes have values greater than 0.2 (Vane et al. 2010; Briles et al. 2019). In our lake, the Human Index (ranges between 3-6 and peaks at 6.0 at ca. 700 CE before declining to 3.7 at ca. 1050 CE and peaking again at 4.7 at ca. 1040 CE. After this last peak, the Human Index declines to 3 at ca. 2000 CE (Fig. 6). Therefore, the Human Index suggests human presence throughout the paleoecological record.

4. Discussion

Our paleolimnological record of stable isotopes, sterols and stanols, diatom assemblages, and primary production indicators from the pond on SG̲ang Gwaay suggest ecosystem changes that followed population expansion (ca. 1200-1400 CE) and associated tree harvest. Long-term C sources to the pond change after ca. 1250 CE with a shift toward aquatic primary production from mainly allochthonous C sources prior to that period.

4.1. Historical C allocations and changes after intensified activity at SG̲ang Gwaay Llnagaay ca. 1200-1400 CE

Lake sediment comprises both allochthonous and autochthonous organic C. While it is difficult to assess with accuracy the proportion of OM that is autochthonously versus allochthonously derived, elemental chemistry and stable isotopes can help identify C sources (Doi 2009; Guo et al. 2020). Suess-corrected $\delta^{13}C$ values from the SG̲ang Gwaay lake

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sediments indicate that C in the pond sediments originates mostly from land plants and freshwater algae. Freshwater algae inputs increase as $\delta^{13}C$ has a period of significant decline from -27.7 to -28.3‰ starting at ca. 1330 CE until ca. 1810 CE (Fig. 4). The increase in C/N between ca. 689-1230 CE (from ~30 to 40) further indicates that the lacustrine C is derived from C3 land plants; however, after ca. 1475 CE, C/N declines significantly from 37.5 to ~23 (Fig. 4). This significant C/N decrease supports a change in C allocations in the pond and coincides with a potential increase in tree harvest with the expansion of SGang Gwaay Llnagaay ca. 1200-1400 CE. In their palynological study, Hebda et al. (2005) report that high occurrence (~60%) of pine pollen on SGang Gwaay is most likely explained by local disturbance events (e.g., clearing, fire). The authors observe that similar, pine-dominant vegetation assemblages are not reported elsewhere in Haida Gwaii or coastal British Columbia during the late Holocene (1100-500 BP; 850-1450 CE). Lacourse et al. (2007) report a stable vegetation assemblage with the notable exception of a decline in Cupressaceae pollen after ca. 950 CE likely linked to the harvesting of *T. plicata* trees by Haida.

Western redcedars (*T. plicata* Donn) may have a lifespan of over 1000 years and archaeological remains document the cultural importance of large mature trees for the Haida (Franklin and Dyrness 1973; Garibaldi and Turner 2004). Western redcedars were used for houses, carved poles, canoes, and daily objects (e.g., ropes, baskets) (MacDonald 1983; Acheson

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1995; Moss 2008). Poles and house foundations can still be seen today at SG̲ang Gwaay Llnagaay. The historical use of redcedar is inferred in the palynological record of SG̲ang Gwaay with a significant decrease in Cupressaceae pollen after ca. 950 CE (Lacourse, Mathewes and Hebda 2007). Other species (e.g., pine trees) were used for firewood, and some plots on the island might have been cleared as the village expanded (Acheson 1998) or burned to favour growth of fruit-bearing brush (Turner 1998). Hebda et al. (2005), also supports this theory of increased tree use as the population grew; pollen records from SG̲ang Gwaay demonstrate that the landscape around the village site was modified progressively further from the original settlement. While we cannot confirm exactly how many trees and of which species the Haida harvested from SG̲ang Gwaay, these lines of evidence suggest that, as the population expanded and the need for housing, daily objects and canoes grew, trees such as western redcedar trees, that were likely difficult to harvest on other islands and transport over by canoe, could have been harvested on the island.

Complementing the C/N changes, plant sterols and stanols are also indicative of a decline in terrestrial vegetation and an increase in aquatic vegetation within the pond after ca. 1250 CE. Sitosterol is a precursor for cellulose synthesis in higher plants (i.e., pteridophytes, gymnosperms, angiosperms), and is present in almost all land plants alongside campesterol, a lipid playing a role in plant development as a precursor to brassinosteroids (Volkman 1986; Seo et al. 1988; Hartmann 2003; Otto and Simpson 2006). Microalgae (e.g., diatoms) also contain these two

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phytosterols (Nishimura and Koyama 1976; Gladu et al. 1991), but have a lower occurrence of sitosterol (Volkman 1986). From ca. 725 CE until ca. 1100 CE, sitosterol, campesterol, and stigmastanol follow a similar increasing trend until ca. 1250 CE, around the time when the Haida settlement at SG̲ang Gwaay Llnagaay intensified. This suggests that plant phytosterols likely have a common source. However, after ca. 1250 CE, campesterol remains stable in the pond while sitosterol and stigmastanol decrease, suggesting a decoupling of these two phytosterols. While sitosterol and campesterol inputs to the pond are mainly allochthonous prior to ca. 1250 CE, after this date, sitosterol and stigmastanol still originate mostly from terrestrial plants, while campesterol originates mostly from an autochthonous source (e.g., algae). The decline of sitosterol/cholesterol starting ca. 1325 CE provides further evidence of a shift from higher plants to microalgal lipid inputs to sediments and increased primary production in the pond. Following village evacuation in 1888 CE, the ratio of these two sterols is not trending toward a return to primarily higher plant inputs in the pond.

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4.2. Changes of lake-water and diatom assemblages after ca. 1200-1400 CE

Land use change altered the pond's physical environment and/or changed the aquatic habitat within the pond (i.e., light penetration, physical mixing with wind) that led to an increase in primary production, as inferred by chl *a* and its diagenetic products (Michelutti and Smol 2016).

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An increase in autotrophic/mixotrophic production is observed starting ca. 1550 CE. Above and below a certain lake-water TOC threshold in shallow lakes, autotrophs and heterotrophs may be light limited (McGowan et al. 2018). Early land use and forest exploitation led to reduced vegetation cover and lower TOC loadings in Scandinavian lakes during the 15th century (Meyer-Jacob et al. 2015), and although likely less extensive on SGang Gwaay, we suggest that the harvest of large western redcedar trees, as well as previously reported vegetation clearing, reduced the export of terrestrial material and DOC to the pond, leading to the inferred decrease in lake-water TOC.

Prior to ca. 1250 CE, lake-water TOC values fluctuate, but are generally higher compared with trends between ca. 1250-2021 CE. Diatom assemblages change shortly after TOC starts declining. The dominant species before ca. 1250 CE, namely *S. exiguiformis* and *P. hustedtii*, are non-motile and typical of brackish, oligotrophic, acidic water (van Dam et al. 1994; Cameron et al. 1998; Freitas et al. 2021) with the rest of the assemblage, including less abundant and epiphytic species (e.g., *E. intermedia, P. viridis, N. sacoense*), suggesting that more aquatic plants were present in and around the shoreline of the pond (Kundson et al. 1975; DeColibus 2013; Morales and Spaulding 2013; Burge et al. 2017; Rondón and Aragón 2018; Tibby et al. 2019). Many previously less abundant diatom species experience a peak between ca. 1388 CE and 1588 CE (Fig. 3), which may correspond with the continued decline in lake-water TOC and the near disappearance of *S. exiguiformis* and *P. hustedtii* by ca. 1388 CE. The

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peak in *E. incisa*, *E. intermedia, P. viridis* and *N. sacoense*, species typically associated with cool, oligotrophic, acidic environments, may reflect a shift toward clearer, less organically enriched waters. In fact, their increase parallels the decline and eventual disappearance of *S. construens var. venter*, a generalist species, ca. 1588 CE (van Dam et al. 1994). A new assemblage forms starting ca. 1588 CE, with *A. crassipunctata* dominating in relative abundance of 60-100%, and other species declining to relative abundances below 20%. This is paralleled with a chl *a* increase.

A. crassipunctata is typically an open-water species found in systems stained with humic acids, requires turbulence, and indicative of a pH of 5–6 (Bahls et al. 2009). A synthesis of over 200 non-enriched North American and European lakes indicated that *Aulacoseira* species abundance often decreases with climate warming, and that cooler temperatures allow for greater mixing of the water column, and thus allow heavily silicified taxa to thrive (Rühland et al. 2008). The abundance of this taxon may have been promoted by the tree harvest on SGang Gwaay, which likely contributed to reduced foliage cover and increased wind-driven mixing of the pond, further supporting its dominance.

The present-day lacustrine environment remains in a "post-disturbance" state, despite significantly reduced human occupation of SGang Gwaay with its evacuation in 1888 CE. TOC shows a slight increase, but remains overall low compared with pre-1200 CE trends while diatom assemblages and chlorophyll *a* do not change.

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4.3. Haida population and historical events

The Human Index (coprostanol/cholesterol) begins with elevated values (~6.75) ca. 750 CE and follows a declining trend before peaking at ~4.75 or at ca. 1425 CE (Fig. 6). This period roughly corresponds to the time of population increase at SG̲ang Gwaay Llnagaay. However, we interpret the suggested period of human population increase with caution for two reasons. First, there is no indication of a precise date for this increase; Acheson (1998) suggests an expansion between 1200-1400 CE when more archeological artefacts are observed. Second, unpublished data indicate the existence of other village sites on SGang Gwaay (Parks Canada, personal communications 2024) making it difficult to exclude the possibility of an earlier occupation and broader population estimates. Although the population size on SG̲ang Gwaay before European contact is unknown, estimates range from 14 500 Haida (Acheson 2005) to 8 000 in 1780 (Mooney 1928), however, estimates as high as 30-40,000 people are also reported in Haida sources (Jusquam 2009).

Coprostanol signatures in sediment profiles can lag historical human population changes. For example, White et al. (2018) observed that, in their reconstruction of the Cahokia, population changes can take longer to be reflected at watershed levels. Similarly, Gallant et al. (2024) also reported heightened coprostanol concentrations in a high Arctic pond during present day despite abandonment of the site by the Thule ~500 years ago. Meretta Lake, where wastewater from an airport was pumped, presents a peak in coprostanol around 2017 CE, after sewage input ceased in 1998 CE

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(Gallant et al. 2020). Hence, it is likely that the Human Index of our samples presents a delay with respect to historical events. Furthermore, when humans abandon a site that they have occupied for hundreds of years, they leave behind an ecological footprint, including the presence of human feces in the environment. Such materials would continue to be washed into a pond following the physical absence of humans and contribute to heightened coprostanol in the sediment core after the village was abandoned. Therefore, we cannot reasonably expect coprostanol to drop off to concentrations indicating no human absence at the exact timing the Haida left. Humans are still present on the island today on a seasonal basis (e.g., Parks Canada staff and visitors, Council of the Haida watchmen, Canadian Wildlife Service seabird biologists), however there are designated latrine sites.

Population declines prior to the 18th century are hard to explain as pre-contact records are limited; however, it is likely that conflict with Europeans and smallpox and scrofula epidemics were sources of population decline during that time. Although the smallpox epidemic of 1887-88 (which led to the evacuation of the village) is most reported in historical accounts (Acheson 1995), smallpox epidemics that started as early as the 1770s are also reported (Jusquam 2009).

Sedimentation rates increase ca. 1490 CE (Fig. S-3), which could be linked with increased soil erosion from vegetation harvest (McGowan et al. 2016). As the population expanded, it is likely that areas were cleared of vegetation for different purposes; Western redcedars for houses, daily

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575 objects, canoes (MacDonald 1983; Acheson 1995; Moss 2008), and smaller
576 vegetation was likely cleared to make more space and for firewood
577 (Acheson 1998, Turner 1998).

578 **4.4 Climatic events vs. land use as drivers of change**

579 Paleoecological records from two alpine ponds, Lucie Lake and
580 Shangri-La Bog, show that the early Holocene climate in Haida Gwaii was
581 dryer and warmer than later during this epoch. Starting ~3200 years BP,
582 vegetation assemblages are indicative of a cooler climate and increased
583 precipitation as well as an increase in shrub and grass pollen suggesting
584 an opening of the forest and a climate similar to present day (Pellatt and
585 Mathewes 1994; 1997). This cooler climate and more open vegetation are
586 likely to have supported changes in diatom assemblages favouring *A.*
587 *crassipunctata*.

588 Palynological records from SGang Gwaay also suggest a period of
589 cooling and increased precipitation starting ~4300 years ago with the rise
590 of western redcedar on the island (Hebda et al. 2005). Records from various
591 sites on SGang Gwaay shows high abundance (~60%) of pine pollen in the
592 late Holocene ca. 850 CE. This is unique to this site and not observed
593 elsewhere in the region, thus it is interpreted as a result of forest clearing
594 rather than climatic change (Hebda et al. 2005).

595 To our knowledge, no local reconstruction studies have commented
596 on climate variations during the Little Ice Age (LIA). Thus, the closest
597 Holocene climatic conditions records during the LIA are based on tree-ring
598 models from Vancouver Island (Zhang and Hebda 2005). These models

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show a moderate increase in precipitation ca. 1560-1760 CE (Zhang and Hebda 2005). However, major declining trends in vegetation proxies (C/N, $\delta^{13}C$) and changes in diatom assemblages begin many hundred of years before ca. 1560 CE and persist beyond the LIA, suggesting that these changes are unlikely to be solely climate-driven. In fact, unprecedented declines in TOC in lakes of central Sweden were attributed to land use changes rather than cooling during the LIA (Meyer-Jacob et al. 2015). Thus, we suggest that early land use and the selective harvest of Western redcedar is at the root of the lake-water TOC, $\delta^{13}C$, and C/N declines and changes in diatom assemblages on SG̲ang Gwaay as hemlock-spruce-cedar vegetation assemblages were reported to be stable elsewhere on the island throughout the late Holocene and changes in proxies start well before LIA climate variations, if there were any on the archipelago.

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4.5. Impacts persist beyond initial disturbances

Many of the ecological changes observed in our paleoecological record persist well beyond the evacuation of SGang Gwaay in 1888 CE. Despite significantly reduced anthropogenic activity, the pond ecosystem has not returned to pre-disturbance conditions. TOC remains lower than before ca. 1200 CE, C/N ratios and $\delta^{13}C$ values continue to reflect dominance of aquatic primary production, and diatom assemblages remain dominated by *A. crassipunctata*.

The lack of recovery is consistent with paleolimnological evidence from other systems that have experienced long-lasting impacts following

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623 modest land use changes. Scheffer et al. (2001) describe how ecosystems
624 can undergo regime shifts once thresholds are crossed, establishing new
625 stable states that resist reversal. Mills et al. (2017) emphasize that lack of
626 ecological recovery is a common feature in long-term sediment records,
627 especially where multiple stressors such as land use changes and
628 introduced herbivores interact over time.

629 Pollen samples from the village site show successional vegetation
630 changes after village evacuation in the 19th century; Poaceae and Picea
631 pollen dominate (Hebda et al. 2005). While some forest cover might have
632 returned naturally, forest recovery may still be incomplete compared with
633 conditions prior to ca. 1200 CE. Limited forest recovery, potentially limiting
634 the supply of allochthonous organic matter to the pond, may be explained
635 by introduced Sitka black tailed-deer browsing.

636 Ecological impacts of Sitka black-tailed deer on Haida Gwaii's forest
637 composition are well summarized by Pojar (2008) and outlined in numerous
638 studies comparing browsed sites with an enclosure site. Martin and
639 Baltzinger (2002) found seedling and sapling densities to be lower on deer-
640 browsed sites and Stroh et al. (2008) showed a lack of Western redcedar
641 recruitment. On islands where deer are present, studies on areas that
642 cannot be browsed (e.g., rocky outcrops) have led to similar conclusions;
643 Chollet et al. (2013) found higher plant density and coverage in rocky areas
644 that are difficult to browse on deer-invaded islands. Martin et al. (2010) found
645 that on islands browsed for more than 50 years, vegetation below the
646 browse-line was converging to coniferous trees. This had a top-down effect

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on community composition; understory-dependent invertebrates and songbirds also became simplified. This pattern was reversed post culling events with an increase in plant and bird species (Chollet et al. 2016). Although not very many are present on SGang Gwaay today, based on documented observations it is known that they consistently browsed the island for at least 62 years preventing vegetation recovery to a deer-free state (Gaston et al. 2008). These findings support our hypothesis that deer contribute to the lack of recovery in the lacustrine environment on SGang Gwaay, even following decreased anthropogenic disturbances.

5. Conclusions

Using a multiproxy analysis, we reconstructed environmental change on SGang Gwaay since the establishment of the island's main pond, and then interpreted our stratigraphic changes with respect to anthropogenic activities at SGang Gwaay Llnagaay prior to and following European contact. We infer that tree harvest by the Haida likely altered the dominant source of C to the pond on SGang Gwaay during the ~1300-year period covered by our study. It is likely that the decrease in vegetation identified by Lacourse, Matthewes and Hebda (2007) also decreased terrestrial matter delivery to the pond starting ca. 1250 CE, as large cedar trees were harvested in greater numbers starting ca. 1200 CE. It is possible that removal of large trees on SGang Gwaay, a small island, thinned the forest, which could explain reduced terrestrial C delivered to the pond and a change in environmental conditions (i.e., light penetration, mixing) that were favourable for an increase in autotrophic/mixotrophic aquatic

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primary production starting ca. 1550 CE. Following a reduction in lake-water TOC, microbial activity increased. This was followed by an increase in chl *a* and changes in the diatom assemblage, which became dominated by *A. crassipunctata,* an open-water species that typically requires turbulence to allow its suspension in the water column. Recovery to pre-disturbance conditions is thus far limited and may be explained by deer browsing hampering tree recruitment and vegetation recovery starting in the 18th century

This study demonstrates that even small land use changes can leave persistent ecological imprints on aquatic ecosystems, and underscore the importance of considering the cumulative effects of multiple stressors in understanding ecosystem resilience and recovery.

Our findings are limited to aquatic ecosystems and further investigations on terrestrial C allocations are needed to understand how the selective harvest of western redcedar alters terrestrial C allocations below and above ground in Haida Gwaii. Our study complements previous palynological reconstructions on SGang Gwaay and demonstrates how lacustrine environments can respond to changes in vegetation dynamics and the lasting effects of even small-scale human activities. Our data indicate that this region has been highly sensitive to landscape alterations with impacts at the ecosystem level persisting well beyond the initial disturbances occurring ~800 years ago. We conclude that even small-scale tree harvest can reduce the terrestrial C supply and change the sources to lacustrine C pools.

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Data Availability statement

All data is available in the Supplementary material (Table S-5, Table S-6, Table S-7, Table S-8). Please contact the first author before any use.

Competing Interests

The authors declare there are no competing interests.

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Table 1. ^{14}C ages and errors used in the Bchron model with their sample number, depth and calibration curves in Bchron. The name in quotes below the sample ID corresponds to the label in the Figure 2a.

Figure captions

Figure 1. Map of SGang Gwaay (A) Island within Canada (B and C). The pond where sediment cores and water were collected in July 2021 (D). The pond is adjacent to a steep rock shelf, well above tide line, that drops in the ocean (F). Village site with standing poles made with Western red cedar (E). Map made with ArcGIS Pro 3.4.2 in WGS 1984 Web Mercator (auxiliary sphere) projection. Satellite imagery source: Esri, Maxar, Earthstar Geographics, and the GIS User Community.

Figure 2. a) ^{210}Pb, ^{137}Cs, ^{241}Am decay profiles and ^{210}Pb age-depth CFCS model; **b)** Age-depth model generated in R with Bchron (v. 4.7.6) with 95% confidence intervals displayed in dark blue using both 210Pb constant flux-constant supply (CFCS) dates and ^{14}C ages in Table 1. ^{14}C ages were calibrated with InterCal20.

Figure 3. Diatom assemblages (>2% relative abundance) plotted as percent relative abundance and sedimentary chlorophyll a (mg/g dry weight) trends in the SGang Gwaay core. Red lines identify the significant changes in diatom assemblages determined using constrained sum of squares (CONISS) and broken stick analysis. The different colours indicate

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diatoms assemblage based on the PCA analysis (supplementary material Fig.S-5b).

Figure 4. Proxies related to limnological, carbon, and vegetation changes in the SG̲ang Gwaay pond. Data are fitted with a general additive model (GAM) and periods of significant decrease are depicted in orange while periods of significant increase are depicted in green. Shaded areas around the trend lines represent 95% confidence intervals. Known major historical events on the island are identified with vertical grey lines and shaded areas. We depict a grey shaded area for the height of village expansion and human presence on the island because the exact date is not known. This shaded bar also captures dating error in our sediment core chronology. The inferred lake-water TOC is represented as Z-score.

Figure 5. Plant lipid profiles in the SG̲ang Gwaay core. Data are fitted with LOESS smoothers. Vertical lines and shaded areas mark notable events on SG̲ang Gwaay and the horizontal line marks a sitosterol/campesterol ratio of ~6.6, a threshold at which plant lipids shift from higher plants to microalgae (Zhang et al. 2018). Shaded areas around the trend lines represent 95% confidence intervals. Known major historical events on the island are identified with vertical grey lines and shaded areas.

Figure 6. The Human Index is the ratio of coprostanol/cholesterol. The ratio values were modelled with a LOESS and the shaded area represent the 95% confidence intervals.

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