



Utility of Dendrochronology Crossdating Methods in the Development of Arctic Coralline Red Algae *Clathromorphum compactum* Growth Increment Chronology for Sea Ice Cover Reconstruction

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Paleoclimate and paleoenvironmental reconstructions from increment-yielding archives strongly depend on precise age models. Like bivalves, corals, trees, and speleothems, the coralline alga *Clathromorphum compactum* produces annual growth increments and shows considerable promise as an environmental archive for arctic and subarctic regions. Though their growth increment widths correlate with temperature and sea ice cover in high Arctic regions, existing timeseries have not been crossdated. In fact, previous studies have shown a lack of inter-sample correlation in non-crossdated timeseries suggesting possible age model dating errors. Here, we use dendrochronology crossdating techniques and COFECHA software to ensure and validate synchrony between *C. compactum* timeseries (<141 years) from three specimens collected near Beechey Island, Nunavut, Canada. Results showed that non-crossdated timeseries constructed by four coralline red algae researchers using annual increments of the same *C. compactum* samples were highly variable and showcase the likelihood of dating errors in non-crossdated timeseries. Crossdating improved inter-series correlations, and correlations to sea ice-related records, suggesting that at least three crossdated timeseries are required to isolate paleoclimate signals. Our findings suggest that future reconstructions with *C. compactum* should employ crossdating techniques to reduce dating errors and allow for more precise climate reconstructions.

Lay Abstract: Long-term environmental records provide a critical baseline to examine how humans have impacted Earth's natural climate. An important piece to consider is sea

ice's role in natural climate variability because its brightness limits warming by reflecting solar irradiation back to space. However, instrumental records of sea ice rarely extend beyond the early satellite era (late 1970s), limiting our understanding of how sea ice affects natural climate variability in the preindustrial era. A lack of historical baseline prompted the development of sea ice proxies, including the long-lived marine alga, *Clathromorphum compactum*. Similar to tree-rings, *C. compactum* produces a new mineralized layer each year, and layer thicknesses have been shown to respond to sea ice cover, making them useful to record long-term sea ice variability. However, a recent study showed that records had replicability problems, maybe due to dating mistakes. Our study applies tree-ring dating methods (dendrochronology) to match annual algal growth layers across algal specimens. Results showed that these new methods reduced dating errors, allowing for more precise past sea ice cover reconstructions.

Keywords: Coralline red algae, Sea ice proxy, crossdating, sclerochronology, growth increments, dendrochronology, Mg/Ca ratios, LA-ICP-MS.

1 INTRODUCTION

1.1 Dating Methods for Biogenic Environmental Proxies

Sclerochronology – the study of physical and chemical variability in the incremental structures of invertebrates, fish otoliths and non-geniculate coralline red algae – plays an important role in the field of paleo-environmental reconstructions due to the significant environmental controls on chemical variations, growth rates and on the cyclicity of growth band formation (Prendergast et al., 2017). Growth increment (or growth band) widths often have a strong relationship with one environmental parameter, but in many cases growth mechanisms are complex due to various controls on growth (Weymouth, 1922; Ansell, 1968; Schöne et al., 2003; Witbaard et al., 2003; Hippler et al., 2009; Butler et al., 2010; Ballesta-Artero et al., 2017). When growth increments are strongly related to a single environmental variable, this variable is often the dominant variable changing interannually. For example, growth increments from the coralline red alga *Clathromorphum compactum* have been shown to strongly correlate with sea ice cover but only in high Arctic regions where sea ice is likely to be the dominant interannual variable (Leclerc et al., 2021).

When validated by multiple samples overlapping in age, sclerochronological timeseries can be used to reconstruct paleo-environmental variables going back centuries (Butler et al., 2009; Butler et al., 2013; DeLong et al., 2014; Reynolds et al., 2016; Reynolds et al., 2017). To properly judge rates of change and natural ranges of variability to include in model simulations, proxy dating must be reliable. In the case of individual, live-collected samples, the date of collection is known and can be used as an initial anchor point to count back in time. However, measurement timeseries that are dated by increment count alone have inherent temporal uncertainty due to locally absent or unresolvable (e.g., extremely narrow) growth increments that can be heterogeneous between samples and within different cross-sections of individual samples.

For instance, corals, which typically rely on a single core sample, are reported to have ± 1 to 5 years of uncertainty per century (Swart et al., 1996; Felis et al., 2000; DeLong et al., 2007; Shen et al., 2008; DeLong et al., 2013). These uncertainties are due to complex and sometimes irregular structural growth across the coral colony (DeLong et al., 2013). Errors can propagate back through time, which even at a rate of 1-5% can complicate reconstructions of interannual and decadal climate variability such as the El Niño-Southern Oscillation (DeLong et al., 2013; Black et al., 2016). Temporal measurement errors in individual sample timeseries, however, can be effectively identified and corrected by crossdating. Crossdating is a hypothesis-driven method first established in dendrochronology – the study of tree rings (Glock, 1937; Fritts, 1976) – to scrutinize and validate age models of individual samples by comparing measurement timeseries (e.g., growth or other geochemical variables) with those of other independently validated samples from a given species and collection site, or to a master chronology (i.e., the averaged timeseries of several crossdated samples also from the same species and site). The crossdating method is an iterative and retrospective process that seeks to identify synchronous patterns in width, anatomy, or geochemical data among multiple samples, information that is used to diagnose dating errors (i.e., missed, false or locally absent increments) (Fritts, 1976). Accordingly, crossdating has increasingly been used in sclerochronology, matching widths of growth increments among live-collected individuals with dead-collected samples to create chronologies that extend farther back in time (Butler et al., 2013).

Radiometric dating is often used to verify absolute dating of long-term crossdated chronologies (Linge et al., 2008; Butler et al., 2009; DeLong et al., 2013; Marali and Schöne, 2015; Reynolds et al., 2016). However, radiometric dating techniques (i.e., accelerator mass spectrometry radiocarbon (^{14}C) or uranium-thorium (^{230}Th) dating) should not be used exclusively without prior crossdating. This is due to error margins and time-averaging of multiple decades resulting from

collecting carbonate material from multiple thin increments needed to fulfill analytical weight requirements; 10–15 years of growth in slow growing organisms (DeLong et al., 2013; Rasher et al., 2020). However, in cases where sample replication is high, growth coherence is strong between individual samples, and overlap among samples spans multiple decades, the chances of spurious crossdating, as can be a concern with dead-collected individuals, is very low and additional verification by radiometric dating is less critical.

1.2 Benefits and Limitations of Crossdating

Crossdating is critical to extract environmental signals within proxy data. In the event of dating errors, owing to locally absent or false increments, patterns among samples become offset relative to one another. Then when these misaligned samples are averaged, the final chronology and underlying environmental signals are muted (Black et al., 2016). Crossdating ensures that all samples are correctly aligned in time before a mean chronology is calculated, so that the underlying environmental signal can be isolated and studied. To ensure annual resolution, crossdating focuses on interannual timescales, comparing each increment to its immediate neighbors. Crossdating methods identify synchrony by comparing interannual patterns of relatively wide or narrow increments (or relatively high or low values in the case of geochemical indicators). If an increment is missed or falsely added, the pattern in that individual will appear offset relative to the pattern in the other samples, indicating that an error has occurred. Crossdating is first and foremost a visual technique, but dating should also be statistically verified using software tools like COFECHA (Holmes, 1983). These programs attempt to statistically mimic the process of visual crossdating by removing long-term trends (low-frequency variability) to isolate the interannual variability, and cross-correlate among individuals to quantify synchrony. Long-term trends, as could be induced by the 20th century decline of sea ice or increase in glacial runoff (Hetzinger et al., 2019; Hetzinger et al., 2021), or ontogenetic trends, increase the chances of spurious correlations and are therefore eliminated (i.e., detrended). COFECHA flags unusually insignificant correlations as possible errors, prompting the analyst to visually reinvestigate the original samples and/or geochemical data to determine if a true dating error occurred. Critically, all data must be visually crossdated before statistical verification, since the statistical analysis assesses the correlation between individual samples and the mean dating series defined by all other specimens. If the quality of the mean dating series is lessened by crossdating errors present in individual series, the power of the analysis to detect errors will also be compromised.

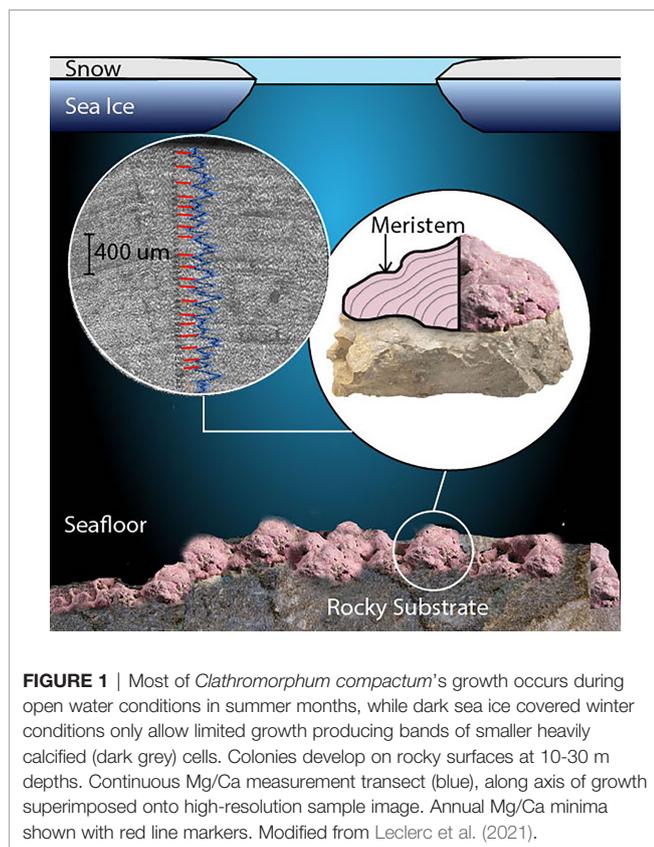
Once data have been crossdated, ontogenetic low-frequency trends (if present), as are commonly observed in tree ring growth records, can be detrended using data-adaptive curve fitting methods, a process called standardization (Fritts, 1976). Mathematically, the standardized series are typically calculated as the ratio of observed growth over expected growth (i.e., the ontogenetic growth trend), which renders the standardized timeseries unitless with a stationary mean value and variance

(Cook, 1987). In tree-ring studies, the standardized timeseries are often then averaged by individual to attenuate intra-sample noise (i.e., in cases where more than one radii has been measured from an given sample) and then by site to create a mean site chronology which attenuates inter-sample noise and enhances the common signal (Fritts, 1976). In turn, well-crossdated chronologies can be used to hindcast past environmental variability, feedbacks and mechanisms, and the frequency of extreme events (Butler et al., 2013; DeLong et al., 2014).

While crossdating can be used to build robust annually resolved timeseries, it becomes impractical or impossible if the data (e.g., sample images or instrumental output) are of low quality or if there is no synchrony among samples. In addition, there will always be some degree of asynchrony among samples, and the challenge of crossdating is identifying the underlying synchronous patterns through this individual-level “noise.” Indeed, non-synchronous increment patterns that could affect some individuals but not all can result from: 1) pollution (Turekian et al., 1982); 2) extreme variation in water salinity, temperature and turbidity over fine spatial scales (Epplé et al., 2006); 3) disturbed habitats (Stott et al., 2010); 4) injury (Fritts, 1976); and; 5) disease or predation (Marali and Schöne, 2015). If no environmental variable affects growth, as could occur at sites with very favorable growing conditions, then growth will not be synchronous and crossdating will be impossible. Likewise, increments must be clearly formed and samples well prepared to delineate increment boundaries and identify synchronous growth patterns. Finally, individuals must be sufficiently long-lived that patterns can be robustly matched among individuals (Black et al., 2016).

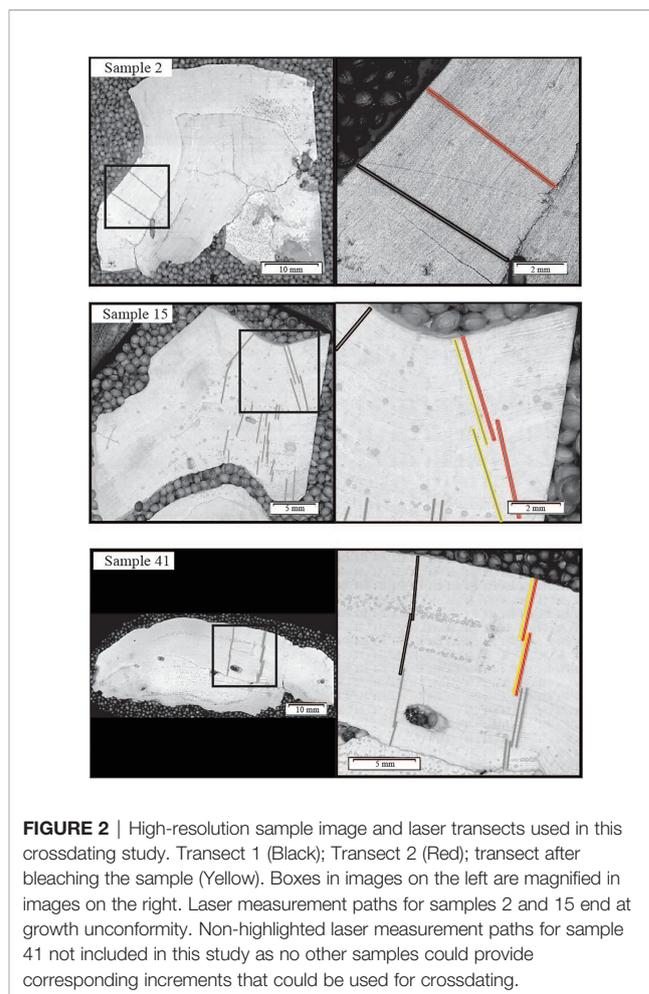
1.3 Application of Crossdating to Coralline Red Algae

Historical climate records are rare in remote regions, such as the Arctic, and climate monitoring stations are sparsely distributed. Therefore, reliable highly resolved baseline environmental data required to understand Arctic environments of the past can only be provided by proxy records. The arctic and subarctic coralline red algae species, *Clathromorphum compactum*, has been used to produce multi-century, annually resolved proxy timeseries of temperature, sea ice, runoff, primary productivity, and multi-decadal climate oscillations (Halfar et al., 2008; Halfar et al., 2011; Hetzinger et al., 2011; Halfar et al., 2013; Chan et al., 2017; Hou et al., 2018; Hetzinger et al., 2019; Hetzinger et al., 2021; Leclerc et al., 2021). This species' high-magnesium calcium carbonate skeleton consists of annual calcified growth increments produced at a rate relative to surrounding sea surface temperature (SST) and sunlight access (Williams et al., 2018a) (**Figure 1**). When continuous magnesium to calcium ratios (Mg/Ca) are measured either with laser ablation inductively coupled mass spectrometry (LA-ICP-MS) or electron microprobe, the annual cyclicity of Mg/Ca ratios can be graphically observed. Cycles of Mg/Ca are produced by the alga preferentially incorporating magnesium during the warm season (summer), and less so in the cold season (winter), enabling their use to date specimens and growth increments



(e.g., Caragnano et al., 2017). This dating methodology enabled the use of *Clathromorphum compactum* growth increments and sub-annual sampling of isotopes and trace elements to further understandings of temperate and Arctic environments.

Many previous coralline algae proxy studies have relied on an individual sample per site (Halfar et al., 2013; Fietzke et al., 2015; Chan et al., 2017; Hou et al., 2018). In cases where multiple samples were involved, annual dates (i.e., age models) of staggered samples were determined by what placement produced the best cross-correlation with segments overlapping in ^{14}C or ^{230}Th ages (e.g., (Kamenos, 2010; Williams et al., 2017). However, formal crossdating of growth increments has not yet been applied (Black et al., 2019). Alternatively, a common method involves identifying winter Mg/Ca values (i.e., annual Mg/Ca minima) (Figure 1) as anchor points for annual Mg/Ca cycles, validated by the presence of a visual increment in high-resolution images, and counting the annual cycles back in time (Figure 1). Often multiple overlapping measurements are necessary to avoid the reproductive cavities (i.e., conceptacles) and ensure intra-sample replicability (Figure 2). Finally, researchers average annual width and/or trace element values between samples to produce a non-crossdated mean dating series (e.g., Hetzinger et al., 2019). In instances where climate records are available, climate records can be used to justify final increment widths. Though there are justifications for this technique (Stoica et al., 2000), it remains controversial. It can



elicit subjective age model determinations based on what fits better with environmental records especially when not corroborated by other samples. Furthermore, without crossdating, one cannot be sure that growth or geochemical data are truly being driven by a shared environmental signal required for paleo-environmental reconstructions.

There is conflicting evidence for whether researchers can use individual algal samples without crossdating for paleo-climatic studies. A study on monthly resolved Mg/Ca ratios of non-crossdated *C. compactum* samples in the Gulf of Maine found high reproducibility (Hetzinger et al., 2018). Another study near the French islands of St. Pierre and Miquelon used stains and visual identification of non-crossdated *C. compactum* growth increments and showed high intra- and inter-sample replicability of Mg/Ca and Ba/Ca (Siebert et al., 2020). However, the latter study also showed insignificant inter-sample correlations of growth increment widths, stating that potentially chiton predation pressure and other variables can have a larger impact on inter-sample growth variability. This may be more common in warmer subarctic sites due to the relationship between warmer temperatures and predation (Adey and Steneck, 2001; Williams et al., 2018a; Leclerc et al., 2021).

Further, the Siebert et al. (2020) and Hetzinger et al. (2018) studies downsampled Mg/Ca ratio data to a 12-value/year resolution that follows a cyclical pattern every year. Hence, such a timeseries suffers from autocorrelation and inevitably correlates even in the presence of dating errors. Therefore, these findings are insufficient to demonstrate that Mg/Ca data were synchronous between specimens without crossdating. On the other hand, high arctic sites have produced algal growth increments that correspond strongly to sea ice conditions (Leclerc et al., 2021), suggesting that growth is being controlled by a common variable and that growth should be synchronous. Nevertheless, low inter-sample replicability has been found at many high arctic sites (Hetzinger et al., 2019; Leclerc et al., 2021). This may be due to the narrower increments produced in the high Arctic, which may be more likely to be missed and cause dating errors, as has been demonstrated in other biogenic proxies (Black et al., 2016). While accurate identification of growth bands and Mg/Ca cycles depend on experience and sample quality (Black et al., 2016), unconvincing and non-synchronous Mg/Ca and growth increment records of *C. compactum* support the importance of crossdating methodologies for coralline algal records.

This study compares the replicability of *C. compactum* annual growth increments before and after crossdating for three samples from Beechey Island, Nunavut, Canada (Figure 3). For the non-crossdated samples, we first report the findings of an inter-observer study to demonstrate the embedded subjectivity in non-crossdated age models. We then determine which preliminary dating methods best prepare timeseries for crossdating (i.e., increment identification or annual Mg/Ca cycles corroborated by visual increments). We report intra- and inter-sample replicability before and after crossdating, in addition to a brief comparison to instrumental and historical sea ice-related records. Results demonstrate that crossdating improves inter- and intra-sample replicability and increases correlations to sea ice records.

2 METHODS

2.1 Collection, Preparation, and Geochemical Analysis

Clathromorphum compactum crusts were collected in 2016 via SCUBA (19–20 meters depth) at a site near Beechey Island in Lancaster Sound, Nunavut, Canada (Figure 3). The three samples used throughout this study (identified throughout as 2, 15, and 41; Figure 3) were prepared into polished thick sections exposing a cross-section of annual growth increments that were then digitally imaged with an Olympus VS-BX reflected light microscope and automated stage using Geo.TS software (Olympus Soft Imaging Systems) and automatically stitched into a photo mosaic. Images were used to digitize laser ablation paths along the growth axis on the Geo.TS software, which were then transferred to a NWR 193 UC laser ablation inductively coupled plasma mass spectrometer (LA-ICP-MS) system coupled with an Agilent 7900 quadrupole mass spectrometer at the University of Toronto's Earth Science Centre. Measurements of Mg/Ca were obtained by conducting continuous laser ablation line scans at 5 $\mu\text{m}/\text{sec}$ speed, a slit size of 10 by 70 μm and 10 Hz pulse rate (for more details see Leclerc et al., 2021). In all samples, Mg/Ca outliers appeared as Mg/Ca spikes when plotted. Outliers were removed outside the lower and upper quartiles of Mg/Ca data (first quartile minus 2 standard deviations and third quartile plus 2 standard deviations, respectively).

For intra-specimen replicability purposes, two laser ablation transects were measured for each sample. Visual increments were difficult to identify on two of the samples (15 and 41) and Mg/Ca cycles from the first two transects running through the entire sample did not resemble one another (Supplementary Figures 1.2a, 1.3a). Accordingly, we applied a previously

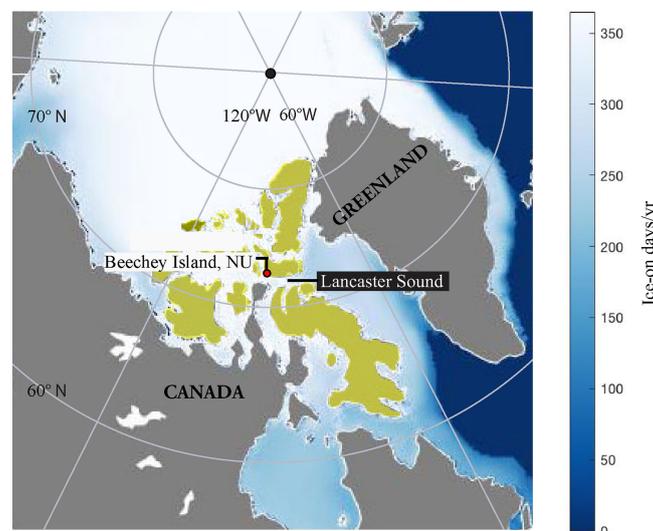


FIGURE 3 | Map of *Clathromorphum compactum* sampling site (Beechey Island; 74°42'54.46"N 91°47'29.35"W) used for this study. Highlighted yellow region comprises Canadian Arctic Archipelago. Gradient of blue indicates duration of ice cover (ice-on days; <15% SIC) per year (average between 1979–2015). Data sourced from NSIDC daily SIC dataset (25 km² resolution).

established bleaching protocol (see **Supplement Materials** in (Fietzke et al., 2015) to the above two samples to remove organics and test if bleaching would improve the identification of Mg/Ca cycles. Annual Mg/Ca cycles were clearer and visual increments were more visible after bleaching for these samples. Bleached samples 15 and 41 were re-imaged and re-analyzed with LA-ICP-MS following the previously outlined methods, and accordingly, had a total of three measured transects. For our purposes, the bleached samples' Mg/Ca output was helpful as the calibrated Mg/Ca cycles were synchronous with one of the non-bleached transects and could be used for crossdating. We therefore removed one transect from each sample with low resemblance to the average of the other two transects that had high replicability between them for the rest of analysis (see **Supplementary Text 2.1, Supplementary Figures 1.2, 1.3**). Low resemblance may be related to growth disturbances from predators (Adey et al., 2013) or *C. compactum*'s hemispherical shape that allows for distinct areas of the sample to have different access to sunlight (Adey, 1965). As an additional note, Mg/Ca cycles were clearer and visual increments were more visible after bleaching for these samples.

2.2 Inter-Observer Study

In 2019, four of the co-authors (hereafter named *observers*), who are all experienced in coralline red algae age model construction, were asked to provide age models for two *C. compactum* samples (2 and 15) to determine the variability of ages assigned to each transect without crossdating. They were provided detailed instructions and calibrated Mg/Ca ratios taken along two transects of samples 2 and 15. The first step of instructions asked them to identify perceived annual Mg/Ca minima. They were allowed to look at Mg/Ca ratios from both transects to determine minima. Second, observers were provided Mg/Ca ratios superimposed on top of high-resolution microscopic images of the samples' increments and asked to make determinations on the correct position of minima (i.e., a Mg/Ca-visual method). Finally, as a third and last step, observers were given regional satellite sea ice concentration records (1979–2015; 75 km² resolution) to compare with their age models from the previous step. They were allowed to refine their age models based on this data and the assumption that Mg/Ca ratios and increment widths negatively correlated with sea ice concentrations (SIC), as this variable had been shown to have a strong correlation with growth increments and Mg/Ca at this site (Leclerc et al., 2021). Based on the “confirmation” of cycles by SIC data, this changed their interpretation of other cycles that date prior to the satellite era (pre-1979). Minima were counted for each transect and compared between observers.

2.3 Visual and Mg/Ca-Visual Methods for Intra-Sample Comparison

Two methods used to assess intra-sample coherence were initially tested prior to crossdating (between-sample) to evaluate which was most efficient and effective at producing low intra-sample variability of timeseries. These methods were evaluated for all three specimens (samples 2, 15, 41). We then

also evaluated which method, produced the best starting point for inter-sample crossdating by running timeseries through COFECHA. The first method, visual, consisted of matching growth increment widths identified in high-resolution microscopic images of samples from transects (see section 2.1). The second method, Mg/Ca-visual, involved cross-matching growth increments measured based on the distance between two sequential Mg/Ca minima identified through annual LA-ICP-MS-gathered Mg/Ca ratio cycles from the two transects. Increments identified by Mg/Ca cycles were then also cross-referenced to visual growth increments. Finally, for each method, a single timeseries for each sample was produced by averaging annual growth increment timeseries from both transects. For inter-specimen comparison, growth increments were standardized into unitless anomalies by subtracting each increment width measurement by the sample average and dividing the difference by the standard deviation.

2.4 Crossdating

Pointer years (Schweingruber et al., 1990a) – years with particularly thick or narrow increments, or particularly high or low Mg/Ca annual maxima – were identified in each transect of samples 2, 15, and 41. Subsequently, measurement timeseries were cross-matched first within and then between samples. Once these prominent pointer years had been identified, more subtle patterns of synchrony were compared to further refine crossdating. Both annual growth increment widths and Mg/Ca maxima were used for crossdating. This process allowed for the identification of false, locally absent and missed rings (see **Supplementary Text 2.2 for lexicon for dendrochronology terms and definitions**). After all specimens were crossdated and statistically validated (see section 2.5), the original annual growth increment timeseries (standardized as anomalies) were averaged to reduce individual noise and isolate the climate signal (Fritts, 1976; Schweingruber et al., 1990b).

2.5 Crossdating Validation and Assessment

COFECHA dendrochronology software provided statistical verification of the crossdating among measurement timeseries. Inter-series correlations were calculated for increment widths and Mg/Ca annual maxima, respectively. Prior to calculating these statistics, COFECHA removes low-frequency variability from each measurement timeseries to isolate high-frequency variability suitable for correlation analysis (Holmes, 1983). It also identifies outlier measurements in the output that lie in the outer tails of the distribution of all rings to help identify possible measurement errors due to the misidentification of Mg/Ca minima. Unlike tree rings and bivalves (e.g., Marali and Schöne, 2015), the coralline alga *C. compactum* does not experience ontogenetic decrease in growth, as it retains stable growth solely driven by environmental variability (Halfar et al., 2007). However, detrending was used here to remove low-frequency variation caused by multi-decadal and centennial environmental trends such as the 20th century reduction of sea ice (Hetzinger et al., 2021). For detrending, a 32-year cubic spline

with a 50% frequency response (default setting in COFECHA) was applied to annual growth increment measurements for each of the transects, and growth increments or Mg/Ca values were divided by the value predicted by the spline to yield dimensionless indices. Any remaining autocorrelation was removed using low-order autoregressive models to ensure that all standardized measurement time series were serially independent and thus meet the assumptions of correlation analysis (Holmes, 1983). Correlations between each standardized set of measurements and the average of all others were broken into 50-year segments overlapping by 25 years. If a dating error had occurred, correlations would drop noticeably in the years preceding the error. Thus, dividing measurements into segments provides a way to narrow the location of dating errors in the dataset. Non-significant correlations ($p > 0.01$) flagged by COFECHA as possible dating errors (e.g., locally absent or false ring) were manually re-evaluated using the sample images and Mg/Ca measurement series and corrected (e.g., by adding or removing a ring boundary) where a dating error could be confirmed.

2.6 Master Chronology and Two-Sample Master Chronologies

Once all three samples' (i.e., 2, 15, and 41) chronologies ($n=6$ transects) were crossdated and validated with COFECHA, raw growth increment and calibrated annual Mg/Ca maxima for each transect ($n=2$ transects per sample) were individually averaged to produce samples averages ($n=3$ sample averages). Sample averages were converted into anomalies (see section 2.1) and averaged between samples to produce a Master chronology (Figures 8, 9).

The strength of crossdating was assessed with 49-year running correlations (Figures 6, 7). Each detrended sample timeseries was evaluated in comparison to the average of the two other crossdated specimens (identified as two-sample master chronology). For example, crossdated timeseries of sample 2 was correlated to the two-sample master chronology of samples 15 and 41 in Figures 6D, 7D.

2.7 Sea Ice-Related Records

Non-crossdated timeseries and the crossdated chronology were compared to different sea ice-related records. Records used include: 1) Atlantic Multi-decadal Oscillation (AMO) 10-year running mean smoothed from the Kaplan SST V2, calculated at NOAA PSL1 (<http://www.psl.noaa.gov/data/timeseries/AMO/>); 2) Annual sea ice concentrations (SIC) for summer averages (May-Oct) were extracted from the gridded National Snow & Ice Data Center (NSIDC) Sea ice Concentration Data Set (Version 3) (<https://nsidc.org/data/g02202>; (Peng et al., 2013; Meier et al., 2017) for a 75 km² area around the Beechey Island algal collection site (for more information on procedure see (Leclerc et al., 2021); 3) Long-term annual summer (May-Oct) sea ice concentration were extracted from the HadISST record (1° resolution) from KNMI Climate Explorer tool (<https://climexp.knmi.nl>) and; 4) Winter (Jan-Apr) Labrador Sea Ice Export record was extracted from Hill and Jones (1990).

3 RESULTS

3.1 Inter-Observer Study

When given the same data (high-resolution sample images and Mg/Ca ratios), individual observers provided estimates of differing timeseries lengths. The range of years identified by each observer diminished with each step of age model construction (Table 1). After reviewing calibrated Mg/Ca ratios, the difference in record length reported among observers was 18-62 years; equivalent to 8-29% of the entire record length. This difference reduced to 15-22 years after adding the visual interpretation of increments in high-resolution images, accounting for 7-14% of the entire record length. Finally, after refining age models based on regional satellite sea ice concentration records, the difference in length was further reduced to 8-19 years, corresponding to 5-9% of the entire length of records. The results of the inter-observer study highlight that a degree of subjectivity is imbedded in non-crossdated age model interpretation.

TABLE 1 | Results of inter-observer study reporting number of years identified in each transect after each step outlined in methods section 2.2.

| | Sample | Transect | Observer ID & corresponding age determinations (yrs) | | | | Range (yrs) | Crossdated age (yrs) |
|--------|--------|----------|--|-----|-----|-----|-------------|----------------------|
| | | | #1 | #2 | #3 | #4 | | |
| Step 1 | 2 | 1 | 109 | 95 | 113 | 107 | 18 | 102 |
| | | 2 | 135 | 109 | 132 | 105 | 30 | 120 |
| | 15 | 1 | 134 | 72 | 101 | 117 | 62 | 74 |
| | | 2 | 92 | 64 | 81 | 74 | 28 | 75 |
| Step 2 | 2 | 1 | 109 | 96 | 111 | | 15 | 102 |
| | | 2 | 134 | 112 | 130 | | 22 | 120 |
| | 15 | 1 | 100 | 76 | 78 | | 24 | 74 |
| | | 2 | 91 | 72 | 75 | | 19 | 75 |
| Step 3 | 2 | 1 | 105 | 96 | 110 | 103 | 14 | 102 |
| | | 2 | 125 | 110 | 129 | 118 | 19 | 120 |
| | 15 | 1 | 76 | 69 | 77 | | 8 | 74 |
| | | 2 | 82 | 68 | 74 | | 14 | 75 |

*An incomplete timeseries (only 1 laser ablation path per transect) for sample 15 was used for the inter-observer study owing to the shorter length.

3.2 Intra- and Inter-Sample Replicability of Growth Increments Prior to Crossdating

Inter-series correlations were positive and statistically significant within samples, indicating strong transect agreement for both methods (visual and Mg/Ca-visual) (Table 2). Inter-series correlations were much lower when calculated among samples for both methods. However, the Mg/Ca-visual method produced generally higher intra- and inter-sample inter-series correlations. (Table 2 and Figure 4) Further, the correlation between satellite Sea Ice Concentrations (SIC) and the visual mean chronology was less strong than that between SIC and the Mg/Ca-visual mean chronology (Table 2). Accordingly, the subsequent crossdating process was continued solely with the Mg/Ca-visual chronologies.

3.3 After Crossdating

Intra-sample and inter-sample inter-series correlations remained positive and significant throughout the length of the growth increment record ($p < 0.05$; 49-year windows) and were consistently higher compared to non-crossdated timeseries

(Table 2; Figures 5, 6). Each specimen correlated significantly to the two-sample master chronologies (the average of the two other samples) (Figures 6D–F). However, steep drops in inter-sample correlation were observed around 1946 (window: 1921–1970) and 1931 (window 1917–1956), suggesting two brief periods of reduced growth synchrony among samples (Figures 6E–G). Annual Mg/Ca maxima contain much more individual-level variability than increment widths and yielded lower inter-series correlations (Table 2; Figures 7D–F). The positive inter-series correlations (Table 2), while weak, hint at a common environmental signal affecting interannual variability, but more samples may be required to isolate that common Mg/Ca signal (Figures 7A–C). Further, detrended Mg/Ca maxima and increment widths (averages between transects) significantly correlate to one another within each sample (2: $r = 0.55$, $p < 0.00001$; 15: $r = 0.45$, $p < 0.00001$; and 41: $r = 0.60$, $p < 0.00001$), showing that some environmental drivers of growth and Mg/Ca variability are shared.

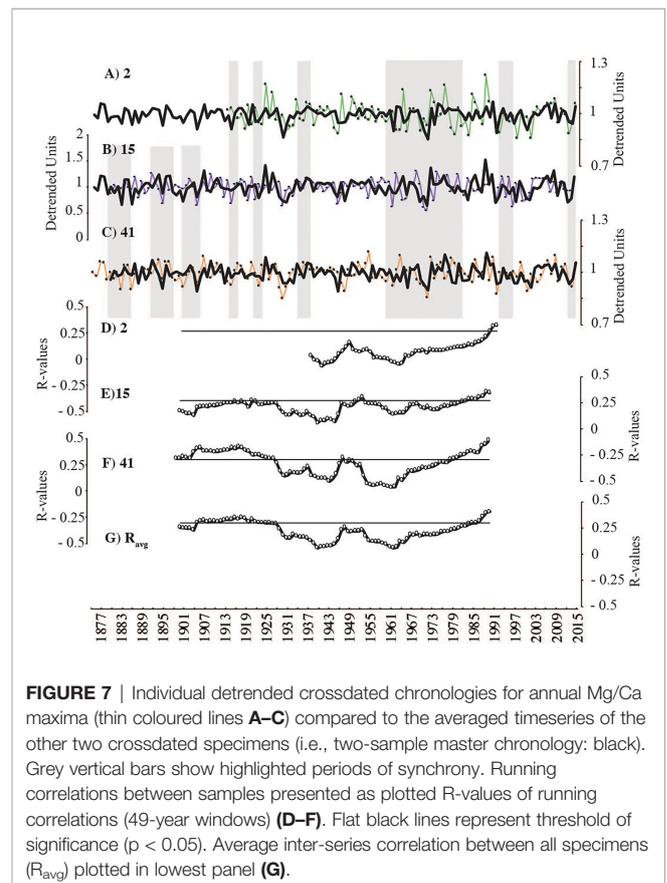
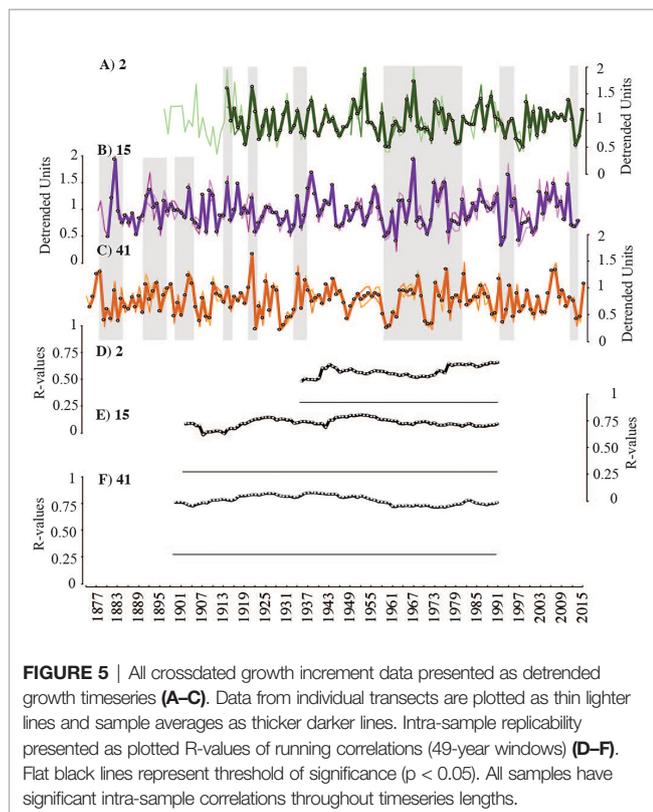
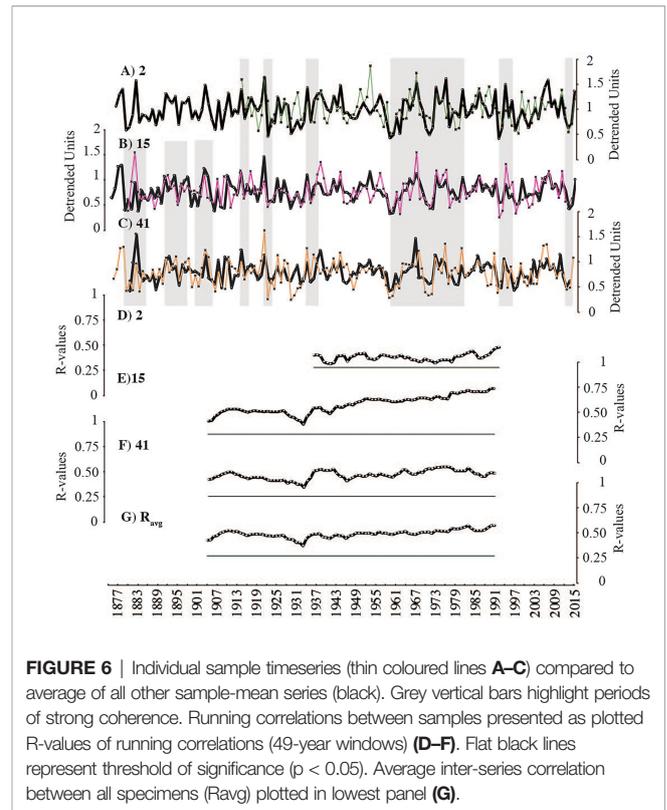
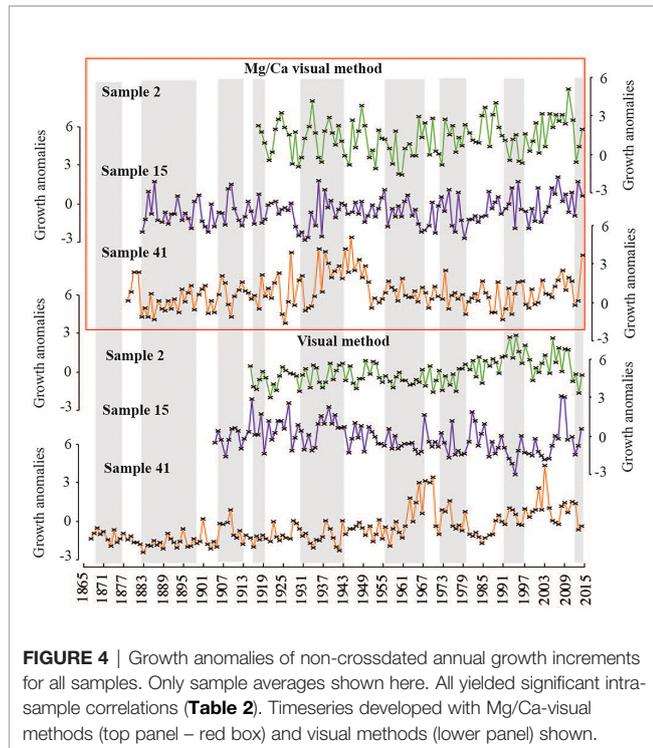
Correlation coefficients between sample averages and summer sea ice concentrations were significant for only 2 specimens prior to

TABLE 2 | Comparison of intra- and inter-sample COFECHA calculated inter-series correlation (i.e., ISC: 50-year windows) of annual growth increment widths.

| Sample | Intra-sample variability | | Inter-sample variability | | | SIC relationship | |
|--|--------------------------|--------------------------|--------------------------|--------|----------------------------|----------------------|--------|
| | ISC R-values | Overlapping length (yrs) | ISC R-values (n=2) | | ISC of all transects (n=6) | Correlation R-values | |
| | | | 15 | 41 | | | |
| Mg/Ca-visual method | | | | | | | |
| 2 | 0.510 $p < 0.00001$ | 98* | -0.054 | -0.019 | 98 | 0.150 | -0.60 |
| 15 | 0.439 $p < 0.00001$ | 133**** | | -0.085 | 133 | | |
| 41 | 0.628 $p < 0.00001$ | 137 | | | | | |
| Visual method | | | | | | | |
| 2 | 0.434 $p < 0.00001$ | 101 | -0.110 | -0.051 | 101 | 0.133 | -0.4 |
| 15 | 0.556 $p < 0.00001$ | 111 | | -0.163 | 111 | | |
| 41 | 0.445 $p < 0.00001$ | 149 | | | | | |
| Crossdating method (growth) | | | | | | | |
| 2 | 0.604 $p < 0.00001$ | 102**** | 0.419 | 0.272 | 101 (2-15) 102 (2-41) | 0.592 [†] | -0.71 |
| 15 | 0.703 $p < 0.00001$ | 135 | | 0.543 | 135 | | |
| 41 | 0.749 $p < 0.00001$ | 141 | | | | | |
| Crossdating method (Mg/Ca maxima) | | | | | | | |
| 2 | 0.549 $p < 0.00001$ | 102**** | 0.154 | 0.105 | 101 (2-15) 102 (2-41) | 0.35 [†] | -0.685 |
| 15 | 0.403 $p < 0.00001$ | 135 | | 0.299 | 135 | | |
| 41 | 0.320 $p = 0.0001$ | 141 | | | | | |

Because COFECHA has difficulty reading timeseries with gaps, when calculating intra-sample ISC and ISC for all transects, the values for the missing increments were interpolated as the average of the previous and following increments bordering the missing increment. [†]Mean sensitivity of 0.361. [‡]Mean sensitivity of 0.074.

Intra- and inter-sample inter-series correlations are also provided for crossdated annual Mg/Ca maxima. Correlations with sea ice records (75 km² resolution – NSIDC) are with averaged anomalies of *C. compactum* measurement timeseries (calculated for 1979–2015 period). For COFECHA outputs of inter-series of all transects (n=6), longer transects within samples were shorted to be the same length as the shorter transect. Number of asterisks (*) indicates the number of possible locally absent rings, however, all years are covered by at least one transect per sample.



crossdating (**Figure 8**; left panel), but significant for all 3 specimens following crossdating. Crossdating also produced a stronger correlation between sea ice concentrations and the master chronology (**Figure 8D**). Notably, crossdating improved correlations between individual timeseries and SIC for all samples except sample 2, where correlations remained similar (non-crossdated: $r = -0.63$; crossdated: $r = -0.62$). Averaging two samples slightly improved correlations to SIC_{SUMMER} . Average correlation of sea ice concentrations correlated with individual timeseries: $r = -0.591$; and correlated with the averaged timeseries of two specimens: $r = -0.599$. The highest correlation between the average of two samples and SIC was achieved with the average of sample 2 and 41 ($r = -0.701$) but was still marginally lower than the correlation coefficient yielded with three combined sample averages ($r = -0.716$).

The master chronology was downsampled to a 10-year running mean to test correlation to AMO; a smoothed 10-year resolution record; and showed a significant correlation of $r=0.4$ ($n=130$ years, $p < 0.00001$; **Figure 9**). At an annual resolution, correlations with winter Labrador Sea Ice Export (LSIE) and HadISST sea ice concentration records were significant but low ($p < 0.01$) (**Figure 9**). However, when downsampled to a 5-year running mean, correlations became much more significant ($p < 0.00001$). Notably, correlations with LSIE were strongest in

the early record, especially if a 1-year lag was imposed to LSIE) and less so after 1958.

4 DISCUSSION

Our inter-observer study showed that non-crossdating methods are prone to integrating dating errors. Observers given the same high-resolution sample images and Mg/Ca ratios produced records with varying lengths for samples 2 and 15 between ± 5 years/century and ± 9.3 years/century, respectively. Further, comparison of two non-crossdating age model methods (i.e., Mg/Ca-visual, or visual methods) showed that both methods had a degree of replicability within samples, but correlations between algal specimens were weak and not statistically significant. A previous study found significant correlation between growth increments and satellite sea ice concentrations at 7 arctic sites (Leclerc et al., 2021), suggesting a common driver of growth and that crossdating methods may therefore be helpful to reduce inter-sample variability. The aforementioned study produced short chronologies ($n = 37$ years), that likely suffered from some age model misinterpretation, which was addressed by down-sampling data to a 5-year average resolution to reduce the effect of

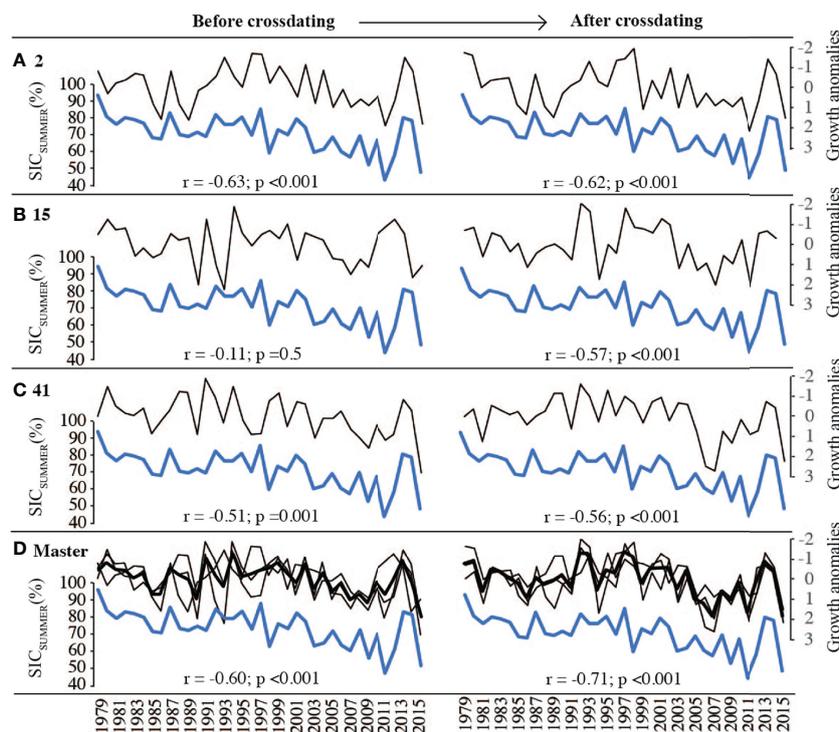
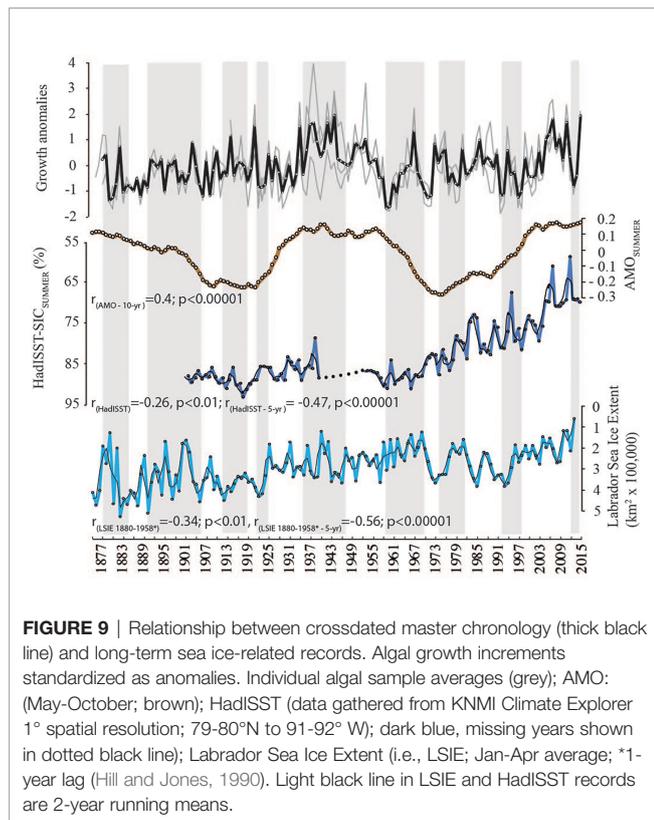


FIGURE 8 | Relationship between regional summer sea ice concentrations (SIC; blue) and standardized algal growth anomalies (averaged transects for each sample; **A–C** black) before (left) and after (right) crossdating. Growth anomalies inverted on y-axis due to hypothesized negative relationship between growth and sea ice cover. Master chronology of all averaged timeseries presented in black (**D**). All correlation coefficients between individual timeseries/master chronology and SIC reported as R-values.



misidentified or incorrectly measured increments. However, smoothing filters dampen interannual patterns of growth variability, add autocorrelation, and thus hamper the ability to produce annually resolved timeseries, limiting their usefulness for climate model calibration and reconstruction. A considerable concern for confident and accurate dating of longer algal timeseries is that errors rates propagate with time. When producing multi-century timeseries, an error rate of ± 5 years/century could compound to a total error of ± 10 years after 200 years, and ± 30 years after 600 years. Crossdated timeseries are not limited by propagating errors, have greater intra- and inter-sample replicability, and produce master chronologies that better isolate the climate signal, especially at interannual timescales.

Crossdating was also helpful in diagnosing locally absent years and lags, and in interpreting reasons for lower intra-sample replicability. Several locally absent years were identified in the crossdated timeseries of sample 2. Sample 2 does not have any gaps in the averaged timeseries from its two transects, but crossdating of Mg/Ca cycles against other samples showed that both transects had locally absent year(s), some of which were present in one transect and not the other (**Supplementary Figure 1.1**). Furthermore, sample 15 had a locally absent increment for the most recent year of the record (2015), and therefore the entire timeseries was ‘lagged’ by one year. This 1-year lag was caused by a growth unconformity (i.e., growth gaps) mistaken initially for the meristem, made clear when

crossdating and by superimposing Mg/Ca cycles over the high-resolution image. Accordingly, lags between coralline algae records and environmental variables in previous studies using one sample per site or without crossdating, may be spurious due to a missed or falsely added ring (e.g., (Hou et al., 2018; Hetzinger et al., 2019; Leclerc et al., 2021). Additionally, we found noticeably lower running correlation values for transects within sample 2, and excluded measurement timeseries in samples 15 and 41 (see section 2.1, **Figure 3**). We excluded these two measurement timeseries from subsequent crossdating analyses due to their poor coherence to the broader sample set. Like the transects from sample 2, removed transects were spatially further apart than the two transects retained for crossdating, had more neighboring conceptacles and bioerosion, followed a slightly different growth axis, and thus may have had disparate access to sunlight perhaps due to irregular shading from macroalgae overgrowth (Williams et al., 2018b). Accordingly, crossdating was able to identify: 1) transects with non-synchronized growth, likely due to transects that tracked periods of irregular or interrupted growth patterns, to eliminate from the master chronology; 2) locally absent increments difficult to interpret when only working with one sample, and; 3) periods of lower intra-sample covariability.

Our findings mirror results of other crossdated proxies that showed that non-crossdated mean dating series with interpretation errors correlated less strongly with environmental variables than crossdated chronologies (Black et al., 2016). Our crossdated and pre-crossdated age models were not refined, biased or forced to correlate to environmental data. On the contrary, a published non-crossdated mean dating series ($n = 37$ years) of the same Beechey samples presented slightly higher correlations to SIC (Leclerc et al., 2021: $r = -0.74$); $r = -0.716$: this study) however, low inter-series correlations demonstrated that growth was not synchronized between samples likely due to age model construction being biased towards satellite SIC records. The results of our study showed that high and significant relationships between growth and SIC can still be achieved without validating age models through environmental record comparison.

The Beechey Island master chronology shows a correlation (decadal resolution) with Atlantic Multi-decadal Oscillation Index a climate pattern that controls sea surface temperature and sea ice variability (Miles et al., 2014). This correlation is particularly strong in the mid-record when the positive phase of AMO is equivalent to warmer temperatures, longer growing seasons, and thus, larger growth increments (**Figure 9**). Our results are similar to previous findings that showed that growth increments (Halfar et al., 2011) and Ba/Ca ratios (Chan et al., 2017) in *C. compactum* samples collected from the coast of Newfoundland and the Gulf of St. Lawrence also correlated to AMO. Furthermore, the crossdated Beechey Island record had significant correlations to the HadISST sea ice concentration record and the early sections of the historical Labrador Sea Ice Export record (1880–1958 at a 1-year lag). The loss of correlation in recent decades may be due to the rapid decline

of Labrador's sea ice extent compared to the Canadian Arctic Archipelago's, which has had a slower decline (Cavalieri and Parkinson, 2012) (Figure 9). These findings suggest long-term algal growth responds to seasonal sea ice conditions, and limited dating errors of the Beechey Island crossdated master chronology, as propagating dating errors would significantly skew correlations.

An important consideration is that the number of replicates crossdated here is relatively low. For tree-ring crossdating, typically at least 2 replicate cores from 20 trees (40 cores total) are crossdated to ensure that all locally absent and false rings are identified (Fritts, 1976). For *C. compactum*-based crossdating, the high analytical and acquisition costs and low yields of high-quality specimens from collection sites (i.e., samples with uninterrupted regular growth layers, spared of predator grazing, and with a low concentration of conceptacles) are significant limitations to acquiring a large sample size for crossdating. However, if effective crossdating can be achieved with a few analyzed algal samples, this approach represents a great opportunity to improve the quality and reliability of algal paleo-environmental records. Furthermore, in the case of the oldest sample (sample 41), the earliest increments did not overlap in time with any of the other samples, and only had intra-sample replicates. Accordingly, these un-crossdated early sections should cautiously be used for paleo-environmental reconstruction. While a high-quality older specimen is highly valuable for reconstruction purposes, it is also rarer, and unlikely to have external replicates. We recognize this to be a limitation of all long-term chronologies.

Inter-series correlations between *C. compactum* growth timeseries (n=6) are comparable to those attained from other crossdated biogenic proxies but remain lower than timeseries from some trees, fish otoliths, and bivalves (Tables 2, 3). A possible reason for *C. compactum*'s lower replicability is its very narrow increments (20-30 μm) formed in the high arctic during years with a lot of sea ice. Most modifications to chronologies during the crossdating process were made on ambiguous sections of growth or Mg/Ca cycles and tended to be thinner increments easily missed, a feature that may be common among all *C. compactum* chronologies in the high Arctic. We see a similar

issue with Pacific geoduck bivalves that are systematically underaged due to narrow increments difficult to identify during slow growing periods, especially in older specimens (Black et al., 2008b). Therefore, it is important to acknowledge that narrow increments from high arctic *C. compactum* specimens may introduce some uncertainty to records.

4.1 Outlooks and Recommendations

As a summarizing recommendation for future studies, crossdating should continue to be incorporated so algal growth data can accurately be used to reconstruct past sea ice conditions and other environmental variables. Doing so will increase accuracy and reliability of algal chronologies and enhance signal-to-noise ratio, enabling well-dated paleo-environmental reconstructions. For annual algal records of carbon isotopes ($\delta^{13}\text{C}$), magnesium to calcium ratios (Mg/Ca), barium to calcium ratios (Ba/Ca), and annual algal growth increments, crossdating at least two *C. compactum* specimens can reduce dating errors. In southern regions of the species distribution, where individual growth is more variable, Mg/Ca ratios may be more suitable for crossdating if more than three specimens are analyzed. If a single specimen produces visibly distinct growth boundaries and Mg/Ca cycles, while others are less defined, the clear specimens can be utilized as the base for the iterative crossdating process. When interpreting poorly defined growth increments and Mg/Ca cycles, analysts can crossdate sections before and after poorly defined increments against the master chronology to determine the presence of any missing or false rings. Analysts can also detrend data to extract intra- and inter-sample variability and reduce the potentially spurious effect of long-term trends on correlations. Once samples are crossdated, original or normalized growth increment widths (i.e., anomalies) can be averaged, and this master chronology used to assess the relationship with environmental variables. Given the difficulty of visually identifying narrow increments in some samples, optical improvements would be another significant methodological advancement. The future application of visual increment enhancements, such as Mutvei solution staining (Siebert et al., 2020) applied to high arctic specimens in conjunction with crossdating, could be considered for future study.

TABLE 3 | Inter-series correlations (ISC) of inter-sample growth replicability compared between other crossdated biogenic proxies.

| Source material | Species | ISC | Reference: |
|-----------------|---|-------------|-------------------------------------|
| Bivalves | <i>Arctica Islandica</i> | ~ 0.4-0.6 | (Butler et al., 2009) |
| | Geoduck clams | 0.735 | (Black et al., 2008b) |
| Trees | Douglas-fir | 0.48 - 0.65 | (Black et al., 2010) |
| | Western hemlock | 0.35 - 0.43 | |
| | <i>Pinus sylvestris</i> | 0.4-0.42 | (Kirchhefer, 2001) |
| | <i>Larix decidua</i> & <i>Pinus cembra</i> L. | 0.47 | (Büntgen et al., 2005) |
| | <i>Pinus ponderosa</i> | 0.55 | (Pohl et al., 2013) |
| | <i>Abies procera</i> | 0.65 | Referenced in (Black et al., 2008a) |
| | <i>Picea glauca</i> | 0.50-0.62 | (Porter et al., 2013) |
| Fish otoliths | Yelloweye rockfish | 0.54-0.68 | (Black et al., 2008a) |
| | Splitnose rockfish | 0.52 | (Black et al., 2005) |
| Coralline algae | <i>C. compactum</i> | 0.592 | This study |

5 CONCLUSION

Joining a growing body of sclerochronologists (Helama et al., 2006; Black et al., 2016), we advocate for crossdating in age model construction of biogenic increment-yielding paleo-environmental archives. This proof-of-concept study reveals human bias in non-crossdated *C. compactum* timeseries and highlights the value of crossdating. Here we demonstrate that crossdating improves intra- and inter-sample replicability and enhances the relationship between algal growth and sea ice records. Growth synchrony between samples, and strong correlations to regional sea ice conditions highlights the strong and shared environmental control of sea ice on algal growth. While the application of crossdating methods to algal data is a lengthy process, it is also necessary to form a network of well-dated proxy records in order to understand the spatial and temporal variability of sea ice behavior, which can also be incorporated into modelling predictions.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**. Further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Data Curation: NL and AT. Formal Analysis: NL, JH, SH, and MZ. Funding acquisition: JH and NL. Methodology: NL, TP and BB. Project administration: NL and JH. Supervision: JH.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2022.923088/full#supplementary-material>

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