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

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ABSTRACT

Seabirds in the Canadian Arctic congregate in large colonies producing oases of biological productivity and diversity in coastal regions. Here we examine sterols, stanols, and stable isotopes ($\delta^{15}N$, and $\delta^{13}C$) in three ^{14}C-dated pond sediment cores near a large seabird colony and archeological site on Devon Island, showing historical occupation by the seabirds and an ancient human (Thule or Norse) settlement over ~1,100 years. Coprostanol in the sediment records captures the presence of humans at ca. 1150 CE, followed by their abandonment of the site by ca. 1300 CE. Seabird presence at this site after ca.1200 CE is indicated by increases in $\delta^{15}N$ and cholesterol/sitosterol. Seabird population expansion is observed after ca. 1600 CE in $\delta^{15}N$ and cholesterol/sitosterol profiles, coinciding with European whaling activities that expanded in the 17th-19th centuries. Our study provides insights to human and seabird occupation in the High Arctic to inform archeological and conservation efforts.

KEYWORDS: Canadian Arctic, seabirds, aboriginal people, sterols and stanols, climate change.

INTRODUCTION

Seabirds are the most abundant terrestrial wildlife in coastal areas of the Canadian Arctic (Mallory and Fontaine, 2004). Most Arctic seabirds spend summers in large colonies principally on low islands or sheer cliffs (Mallory, 2006), where they can be a major source of nutrients and contaminants to nearby ecosystems (Cheng et al., 2016). Several studies have shown that this ornithogenic enrichment may be archived in pond sediments, allowing historical reconstructions of seabird colony establishment, growth, decline, and abandonment (e.g. Hargan et al., 2017; Keatley et al., 2011). Given that extreme weather conditions in polar regions can drastically affect seabird numbers and breeding success (Gaston et al., 2005), archival records in pond sediments may reveal how seabird populations have responded to environmental changes. These may include climate changes (Sun et al., 2013) or human population expansion to the area, whose fishing and whaling practices may have attracted seabirds at that time (Thompson et al., 1995). Various proxies have been developed for investigating modern and historical seabird fertilization in freshwater sediment deposits, including elemental enrichment (Sun et al., 2000), stable isotope composition (Lucassen et al., 2017), and biological microfossils (Keatley et al., 2011). One of the most broadly employed indicators is the stable nitrogen isotope ratio ($\delta^{15}N$), which in seabird guano may be higher than 20‰ (Lucassen et al., 2017). By contrast, other N sources to pond sediments in the Arctic usually have a $\delta^{15}N$ lower than 7‰ (Guo et al., 2004). Likewise, sediment cores adjacent to prehistoric human settlements were shown to be enriched in ^{15}N relative to sites without evidence of past human occupation (D'Anjou et al., 2012; Douglas et al., 2004).

Multi-proxy paleolimnological approaches that include independent tracers add confidence to historical records. Lipid biomarkers have shown potential for tracking seabird and human enrichment to lake/pond sediments (Ceschim et al., 2016).. In addition, previous research showed that pond sediments adjacent to bird colonies were greatly enriched in cholesterol relative to the plant-derived sitosterol (Cheng et al., 2016). In contrast, coprostanol, the dominant stanol in human feces, has been shown to track the arrival of prehistoric humans (D'Anjou et al., 2012). Sterols and stanols may therefore discriminate between seabird and human influences, which may coincide in Arctic coastal environments. In addition to the indicators mentioned above, the stable carbon isotopic ratio $\delta^{13}C$ can be used to track terrestrial and marine carbon in freshwater sediments (Guo et al., 2004), including ornithogenic carbon from seabirds (Lucassen et al., 2017). In Arctic seabird waste, $\delta^{13}C$ shows a relatively narrow range between -21‰ and -17‰ (Dahl et al., 2003), much higher than $\delta^{13}C$ in terrestrial plants and freshwater primary producers of -29‰ to -22‰ (Choy et al., 2010), making $\delta^{13}C$ a potential marker for marine-derived fertilization in Arctic pond sediments.

Here we investigate the impact of a seabird colony and a historic human settlement on freshwater ecosystems using a multi-proxy approach in three freshwater sediment cores dated with ^{14}C and ^{210}Pb from Cape Vera, a High Arctic site on Devon Island, Nunavut, Canada (Figure 1).

GEOLOGICAL SETTINGS AND SAMPLING

Detailed sampling and other methods are available in the Supporting Information.

Three sediment cores were collected during the summer field seasons at Cape Vera, Devon Island, Nunavut, Canada (Figure 1). Pond numbering follows that of our previous publications (Cheng et al., 2016). Ponds CV9 and CV30 are near the base of the cliff, where a large northern fulmar (*Fulmarus glacialis*) colony is located. Previous human occupation is clearly evident at Cape Vera, as a series of at least seven ‘tent rings’ (i.e. stones had been placed in a circular arrangement approximately 2-2.5 meters in diameter) were observed near pond CV13 and the remains of a butchered bowhead whale (*Balaena mysticetus*) cervical vertebrae (Figure S1).

EARLY HUMAN HISTORY AT CAPE VERA

Early records documented artefacts linked to past occupation by Paleo-Inuit and Norse on northern Devon Island and the surrounding region (Sverdrup, 1904), though the timing of occupation in this area is uncertain due to the paucity of artefacts (McGhee, 1984). In the CV30 core, a sharp peak of human-derived coprostanol near the bottom of the core dated to ca. 1150 CE (Figure 2), suggesting human presence at Cape Vera during the Medieval Optimal. The timing of this inferred occupation coincided with the presence of Thule and Norse in the Eastern Canadian Arctic . Longer ice-free summers occurred in this area at that time (Moore et al., 2001; Thomas and Briner, 2009), and bowhead whales also achieved their maximum range in the Canadian Arctic Archipelago (McCartney and Savelle, 1985). The sharp coprostanol decrease observed in core CV30 at ca.1200 CE (Figure 2), suggests abandonment of this settlement, possibly resulting from increased ice-cover and ice extent after ca. 1200 CE in the Canadian Arctic Archipelagoes (Moore et al., 2001), which might have resulted in declining marine mammal populations thus making the region less suitable for Indigenous whalers and Norse ivory hunters (McCartney and Savelle, 1985).

SEABIRD HISTORY AT CAPE VERA RECORDED IN SEDIMENT CORES

The cholesterol/sitosterol ratio ($R_{c/c+s}$), an indicator of ornithogenic enrichment at Cape Vera (Cheng et al., 2016), was low in the bottom of the CV9 core apart for a small increase at ca.1200 CE; thereafter it increased sharply from ca.1700 CE (Figure 3). The $\delta^{15}N$ profile in CV9 core generally tracked the $R_{c/c+s}$ profile, with the exception of a small rise near 1200 CE (Figure 3). $\delta^{15}N$ values and $R_{c/c+s}$ in the CV9 core were significantly correlated (Pearson correlation, r_{45}=0.947, P<0.001). The CV30 core, which is also adjacent to the fulmar colony, had congruent $R_{c/c+s}$ and $\delta^{15}N$ profiles similar to the CV9 core in timing and magnitude (Figure 3). Both indices reached the minimum at ca.1350 CE at 18.25 cm depth, and showed some fluctuation before increasing at ca.1600 CE, then increased to a maximum at the core surface, representing the year of collection (2007 CE, Figure 3). The $\delta^{15}N$ and $R_{c/c+s}$ in the cores CV30 (Pearson correlation, r_{24}=0.870, P<0.001) and CV13 (Pearson correlation, r_{19}=0.892, P<0.001) cores were also significantly correlated.

Likewise, $\delta^{13}C$ values in the CV9 core closely tracked $R_{c/c+s}$ and $\delta^{15}N$ values (Figure 3), and were significantly correlated with $\delta^{15}N$ values (Pearson correlation, r_{23}=0.945, P<0.001). This is not surprising as nutrient subsidies from seabirds or human hunting activities may increase algal productivity, and likewise increase $\delta^{13}C$, because the lighter ^{12}C isotope is removed preferentially from the dissolved inorganic carbon (DIC) pool, leaving the residual DIC enriched in the heavier ^{13}C isotope during periods of rapid photosynthesis, resulting in more positive $\delta^{13}C$ of POM (Schelske and Hodell, 1991). Hence the more positive $\delta^{13}C$ values may suggest increased algal production from fertilization. On the other hand, ^{13}C enrichment could also result from a relative increase in marine carbon that corroborates the influx of marine nitrogen (Lucassen et al., 2017), as determined by measurement of sedimentary $\delta^{15}N$ and sterols (Figure 3). Nevertheless, both scenarios indicate that $\delta^{13}C$ values also track the establishment of the northern fulmar colony in the CV9 core. Likewise, the CV13 core shows a concurrent rise in $\delta^{15}N$ and $R_{c/c+s}$ from ca.1600 CE, and for the CV30 core, the minimum of $\delta^{15}N$ (10.3‰) was at ca. 1300 CE, while the minimum $\delta^{13}C$ (-29.0‰) was observed at ca.1800 CE (Figure 3). Collectively, this multiproxy evidence suggests that all three cores are tracking a growth in the seabird colony at Cape Vera, which was most rapid after ca. 1800 CE, and with ca.1100 CE as the oldest time that the colony would likely have been established (Figure 3).

The $\delta^{15}N$ and $\delta^{13}C$ values of terrestrial modern plants collected at Cape Vera were 4.9±5.0‰ (n=21, SD) and -26.1±2.7‰ (n=21, SD), respectively (Choy et al., 2010). Meanwhile, the $\delta^{15}N$ and $\delta^{13}C$ values of modern aquatic plants were 10.0±7.9‰ (n=19, SD) and -9.5±2.6‰ (n=19, SD), respectively (Choy et al., 2010). Both $\delta^{15}N$ values are close to the values in the earliest sediments in CV9 core, i.e., 8.6‰ pre- 1200 CE. The $\delta^{13}C$ value of -27.6‰ at the same time resembles that found in modern terrestrial plants, suggesting either a dominant terrestrial organic carbon source in pond CV9 at that time, or fecal inputs from herbivorous species like Brant geese (*Branta bernicla*). The slightly more positive $\delta^{13}C$ after that time implies an increase in aquatic organic carbon, confirming the onset of pond fertilization at ca.1200 CE. This result coincides with the previous finding that $\delta^{15}N$ was influenced by human and/or seabird fertilization, whereas $\delta^{13}C$ was dominated by phytogenic input at Cape Vera (Keatley et al., 2011). Interestingly, the CV9 core had the lowest coprostanol concentrations compared to the two adjacent cores (CV30 and CV13), despite having the highest ornithogenic enrichment (Figure 3). Human settlements in the Arctic have been traced in pond sediments using $\delta^{15}N$ and diatom assemblages (Hadley et al., 2010), but sterols appear to provide a more definitive means to differentiate humans from Arctic wildlife. The coprostanol peak extends the human occupation from at least ca. 1050 to 1250 CE, while appearing to be independent of seabird enrichment.

IMPLICATIONS OF SEABIRD OCCUPATION AT CAPE VERA

The basal ^{14}C ages of both CV9 and CV30 cores fall into the early part of the Medieval Optimal. These ages imply that the ecosystem at Cape Vera began a significant development since ca.1000 CE, which may have initiated the accumulation of aquatic sediments in these ponds. This finding coincides with IP_{25} reconstructed spring sea ice in this area, suggesting an extremely low spring ice extent at ca.1000 CE (Vare et al., 2009). Less sea ice extent would increase primary productivity within foraging areas (Mallory et al., 2008), and might be attractive to seabirds like northern fulmars establishing a colony at that time (Fisher, 1952). In addition, these early sediment deposits would have already been in freshwater ponds and separated hydrologically from the ocean, as evidenced by the abundance of freshwater diatoms and absence of marine diatoms in the oldest sediment deposits of these cores, indicating that these ponds would have already been separated from the ocean at that time (Keatley et al., 2011). These observations suggest that isostatic rebound had already lifted the base of these cliffs above sea level and initiated pond formation and the accumulation of freshwater sediments (King, 1991). Interestingly, the $R_{c/c+s}$ values showed no significant difference between the Little Ice Age (ca. 1400 CE to ca. 1700 CE) and the Medieval Optimal (ca. 950 CE to ca.1200 CE), as defined by Mann et al. (2009), in either core CV9 ($t_{25}=2.059$, $P=0.95$, Student's t test) or CV30 ($t_4=2.776$, $P=0.86$, Student's t test). Similarly, the $\delta^{15}N$ values were not significantly different in cores CV9 ($t_{12}=2.179$, $P=0.12$, Student's t test) or CV30 ($t_5=2.571$, $P=0.47$, Student's t test). We consider two ecological possibilities that might be consistent with this pattern. First, fulmars may have inhabited the cliffs at Cape Vera during both of these time periods, but their population remained small and thus guano inputs to the ponds would have remained small. Alternately, the coastal apron below Cape Vera is also an important migratory stopover and feeding area for Brant geese, a small herbivorous goose, which feeds lower in the food web and around the ponds in the spring and summer (Mallory and Gilchrist, 2005). The $R_{c/c+s}$ values in Brant guano (0.603±0.099) are much lower than those of fulmars (0.998±0.001) (Cheng et al., 2016), hence the low $R_{c/c+s}$ values could also reflect inputs from this species in the absence of fulmars. Northern fulmars are sensitive to climate change because their relatively high trophic position requires sustained high marine productivity to support their population

(Mallory, 2006). Hence the absence of an obvious fulmar population decrease during the Little Ice Age, may also suggest a relatively stable climate during this time at Cape Vera. Nevertheless, both CV9 and CV30 cores, as well as the CV13 core, recorded sharp increases of $R_{c/c+s}$ from ca. 1600 CE, suggesting a dramatic shift in the inputs to the ponds from local birds including a much higher marine-derived nutrient input. This suggests that fulmar activities flourished since that time, and this reflects either the dramatic expansion, or more likely the colonization of the cliffs at Cape Vera by fulmars. The timing of this increase matches well with the detailed documentation of the expansion of the population and colony establishment by fulmars across the North Atlantic over the last 200+ years (Fisher, 1952). Also, fulmars are ravenous consumers of fatty waste products (offal, bait, fats) from human whaling, fishing, and hunting practices (Mallory et al., 2012). Thus human activities, especially European whaling, which began in the 1600s and grew in the 18th and 19th centuries in the Labrador Sea and Baffin Bay (Finley, 1990) would have greatly increased food availability for the fulmar. A warming climate in the last two centuries (Thomas and Briner, 2009) could also have contributed to higher marine productivity and potentially supported a growing fulmar population (Brown, 1970). Other proxies in dated sediments from the same ponds at Cape Vera, for example chironomid head capsule counts, diatom community shifts, and sedimentary chlorophyll *a*, also tracked increased pond productivity in the past ~200 years (Michelutti et al., 2011). However, the absence of a coprostanol peak during the last two centuries suggests that seabirds, not humans, were the main drivers of freshwater productivity at Cape Vera.

CONCLUSIONS

We used sterols, stanols, δ^{13}C and δ^{15}N to reconstruct seabird ecology and Indigenous peoples' history at Cape Vera, Devon Island, NU, Canada. Our results suggest human occupation at this site as early as ca.1050 CE to ca. 1100 CE based on a sharp coprostanol rise in CV30 core. A likely seabird population expansion after ca. 1600 CE is observed in all three cores based on δ^{15}N and the $R_{c/c+s}$ ratio, possibly due to increasing summer temperatures and/or increased human fishing or whaling activities in the region after the Little Ice Age. Collectively, our results show a pattern of climate-human-seabird ecological history reconstructed in the Arctic by multiple and complimentary proxies.

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FIGURE CAPTIONS

Figure 1. Map of the study site. Location of the study site in Canada shown in the inserted section. The fulmar colony is located on the cliff. Ponds CV9 and CV30 are at the base of the cliff. Pond CV13 is ~1 km away from CV9, and close to seven tent remains.

Figure 2. Coprostanol profiles in the three sediment cores. The scales of the horizontal axis are set to the same to show the high coprostanol spike in CV30 core. The inserted line in the right panel indicates the ^{14}C age and error range of the coprostanol peak in CV30 core.

Figure 3. Sterol ratios and stable isotopic ratios in the three sediment core profiles at Cape Vera. The $R_{c/c+s}$ value is the ratio of cholesterol : (cholesterol + sitosterol) in the sediment samples. $R_{c/c+s}$ (red triangles) and $\delta^{15}N$ (blue circles) track the seabird impact on the ponds, higher proxy values indicate higher impact of seabird. $\delta^{13}C$ (magenta circles) track organic carbon source; lower (more negative) values indicate more terrestrial organic carbon. The cyan shaded area indicates the Little Ice Age (ca. 1400 CE to ca. 1700 CE), and the yellow shaded area indicates the Medieval Optimal (ca. 950 CE to ca. 1200 CE), respectively.

Table 1. Radiocarbon results of sediment cores. Ages were obtained from macrofossils isolated from sediment core sections. Raw ages were calibrated with the calibration curve IntCal13. 'Modern' in the calibrated age column refers to a sample from >1950 (in the era of nuclear weapons testing). 'Mix' in the macrofossil type column refers to a mix of terrestrial and aquatic macrofossils. A mix of both macrofossils were used for dating unless the terrestrial ones were enough for analysis. Ages from mixed macrofossils were corrected with a reservoir age of 400 years. See Supporting Information for detailed chronology.

Core	**Middle Depth (cm)**	**Sample Size (mgC)**	**$\delta^{14}C$ (‰)**	**Raw ^{14}C Age (BP)**	**Calibrated Age (BP)**	**Macrofossil Type**	**Calibrated Age (CE)**	**Species**
CV13	3.25	0.16	86.5±2.0	-660±15	Modern	Mix	Modern	*Daphnia* ephippia
	8.75	0.019	-92.8±15.1	780±140	454±199	Mix	1496±199	*Daphnia*, larvae midge, moss.
CV9	4.25	0.12	-49.7±2.2	410±20	9±14	Mix	1941±14	trace amounts of organic matter
	12.25	0.085	-142.2±3.4	1230±35	734±59	Mix	1216±59	trace amounts of organic matter
	14.25	0.077	-146.1±3.8	1270±40	765±68	Mix	1185±68	trace amounts of organic matter, plant tissue, midge.
CV30	2.25	0.027	132.9±12.8	-990±100	Modern	Terrestrial	Modern	*Saxifraga oppositifolia*
	10.25	0.040	-21.5±7.7	170±70	153±157	Terrestrial	1797±157	*Saxifraga oppositifolia*
	22.0	0.069	-146.8±3.9	1275±40	778±57	Mix	1172±57	*Saxifraga oppositifolia*, *Papaver* sp., *Silene uralensis*

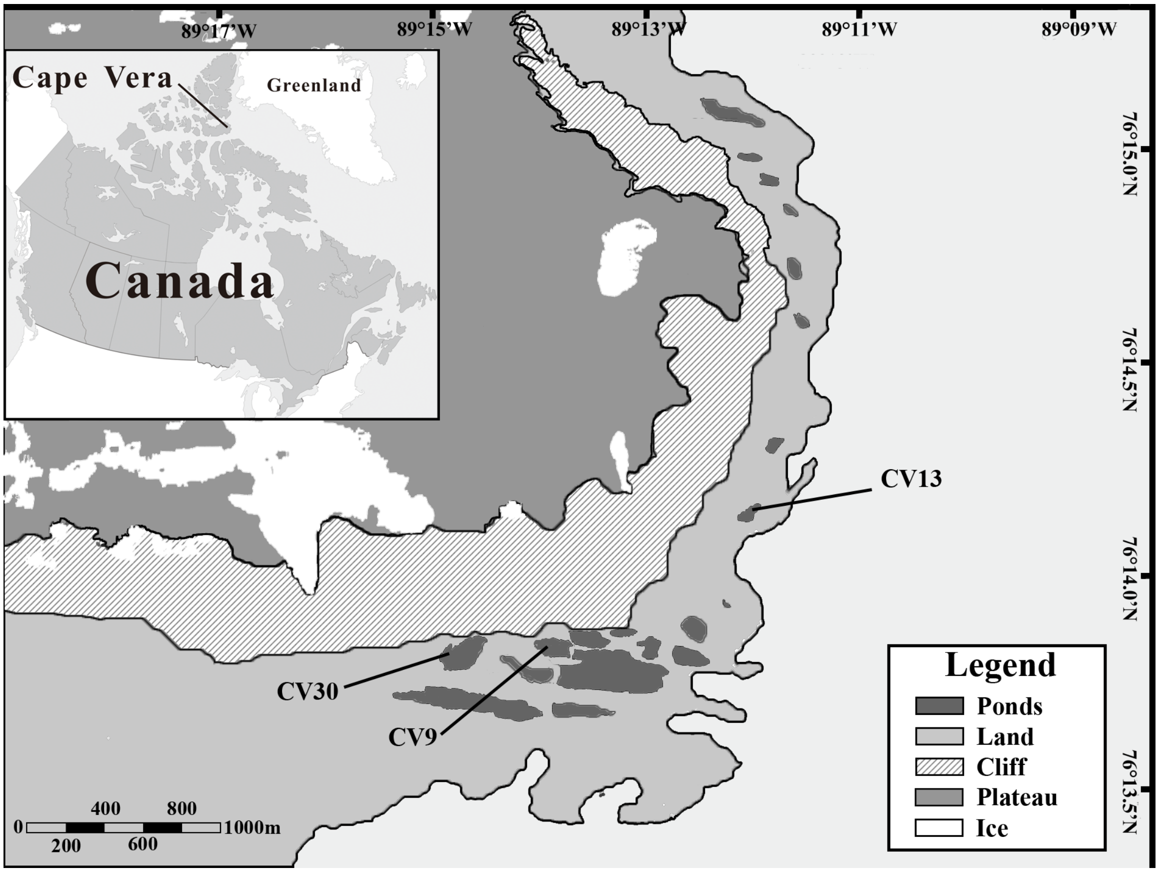
89°17'W
89°15'W
89°13'W
89°11'W
89°09'W
76°15.0'N
76°14.5'N
76°14.0'N
76°13.5'N
Cape Vera
Greenland
Canada
CV13
CV30
CV9
Legend
Ponds
Land
Cliff
Plateau
Ice
0
200
400
600
800
1000m

Figure 1

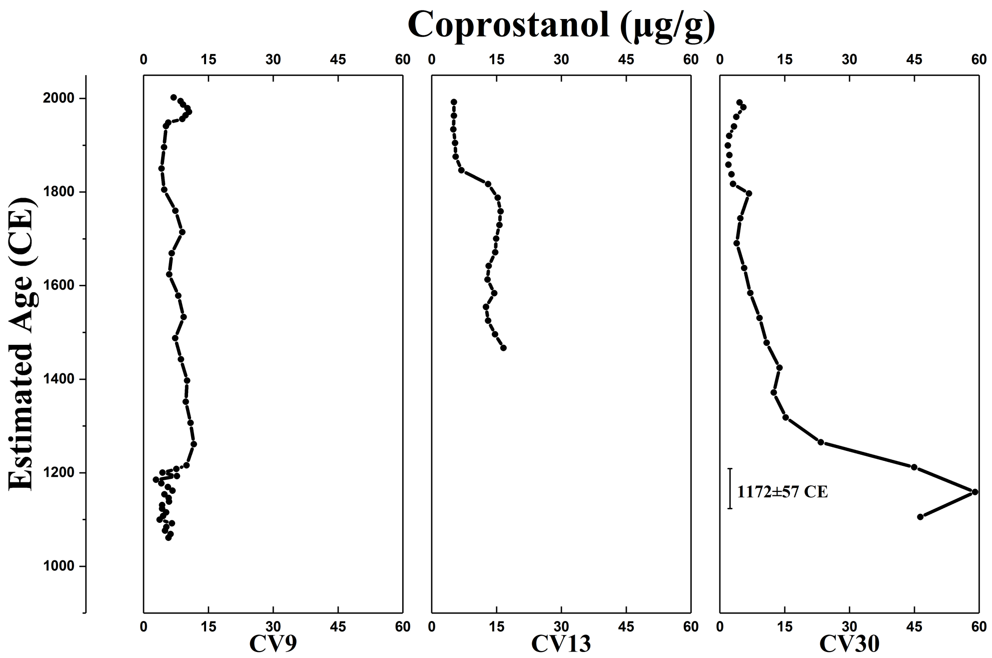
Coprostanol (µg/g)
Estimated Age (CE)
2000
1800
1600
1400
1200
1000
0
15
30
45
60
CV9
CV13
CV30
1172±57 CE

Figure 2

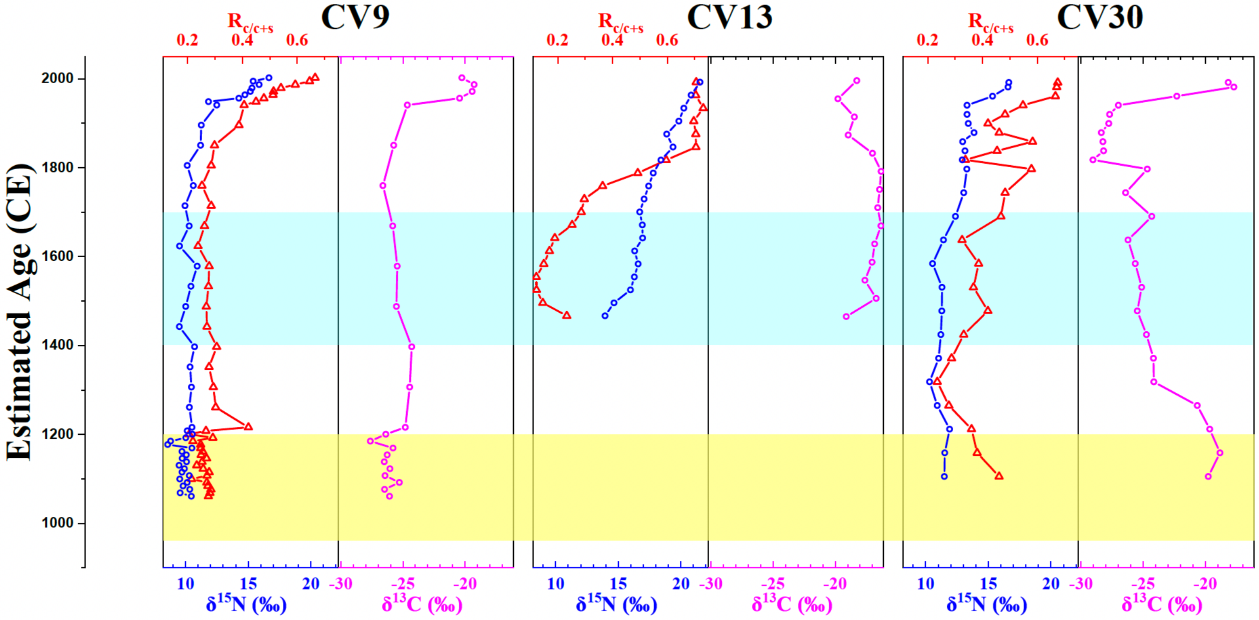
CV9
CV13
CV30
$R_{c/c+s}$
0.2
0.4
0.6
Estimated Age (CE)
2000
1800
1600
1400
1200
1000
10
15
20
-30
-25
-20
$\delta^{15}N$ (‰)
$\delta^{13}C$ (‰)

Figure 3