

A fine-scale record of 130 years of organic carbon deposition in an anoxic fjord, Saanich Inlet, British Columbia

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Abstract

A varved sediment sequence from an anoxic temperate fjord is examined for a 130-yr record of organic carbon content and stable carbon isotope composition. Saanich Inlet, British Columbia, receives most detrital input from a logged and reforested watershed. Winter and summer laminae differences are significant and are isotopically depleted with respect to water column organic carbon. Within the core, organic carbon content increased from 2.5% in the 1860s to 3.3% in the 1990s, whereas carbon isotopes become depleted by 1.2‰ toward the late 1990s. Homogenization of large sample volumes yields the most repeatable carbon results. Overlaid on the trends are cycles of roughly a 38-yr period for both records. River outflow has not changed, but logging rates that peaked midcentury in the watershed match the organic carbon shifts. This influence, plus the interdecadal Pacific-climate oscillation, likely explain the periodicity observed.

The stable carbon isotopic composition of organic matter reflects carbon pathways in extant ecosystems. To the extent that this signal is preserved in aquatic sediments, it may be used to trace variation in sources of carbon with sediment depth, thus giving the investigator some insight into past carbon-flux variations (Meyers 1997). Sedimentary carbon isotope values are determined by the mix of carbon entering the water from several sources and by the fate of that carbon in the water column and after deposition on the bottom. It should be possible to discern relative contributions from terrestrial and marine sources (Westerhausen et al. 1993), bearing in mind that many characters of both the subaerial and marine habitats influence the nature of that signal. Martinelli et al. (1999) successfully used bulk isotopic composition of particulate organic carbon in a riverine system to identify vegetation changes in the watershed.

My study explores input shifts on relatively short time frames in the sedimentary record. Use of a high-resolution sediment record that is well dated can allow one to test the concept that small changes in organic carbon character are reflected in the preserved sequence in a marine basin. Further, laminated sediments provide a history of environmental change that may be reflected in primary productivity changes. Instrumental records provide a short data series on climate-related parameters that, in the North Pacific, identify several potential oscillators (Ware 1995). Recent changes in marine productivity in the northeast Pacific have focused attention on the role of atmospheric and sea-surface phenom-

ena (Beamish 1993; Gargett 1997). For longer records, other well-dated series are usable, such as tree rings, coral bands, and varved sediments. Although particulate carbon accumulation in sediments results from a myriad of factors, it may provide an indicator of the patterns of forced production changes in the vicinity.

Saanich Inlet is a temperate marine fjord on Vancouver Island, British Columbia, Canada (Fig. 1). A shallow sill restricts inflow to the 230-m-deep basin. Dissolved oxygen at depth is quickly depleted by respiration, and the deep water in Saanich Inlet typically is dysaerobic for most of the year. During the summer, complete anoxia can develop below 130 m (Anderson and Devol 1973). An undisturbed sedimentary record accumulates where no macrofauna inhabits the inlet floor. The nature of the sediment reflects input changes throughout the year. Distinct layers, or varves, form by alternations in plankton deposition between growing and nongrowing seasons (Gucleur and Gross 1964; Blais-Stevens et al. 1997). Dark laminae have fewer diatom tests and coincide with times of greater terrestrial runoff from late summer through winter (Dean et al. 1999). The resultant laminae in Saanich Inlet sediments are clear enough to derive a precise annual chronology in short cores. Saanich experiences a reverse estuarine circulation, with strong freshwater input from the north. Although there is no major freshwater outflow directly into Saanich Inlet (Ministry of Environment 1996), there is extensive incursion into the inlet mouth from Cowichan River (Fig. 1) flows, which peak during the winter. This river delivers most of the terrigenous sediments (Blais-Stevens et al. 1997). The land around the inlet, including the Cowichan River Valley, experienced extensive deforestation at the turn of the century as forest and agriculture industries developed (Lyons 1958).

Saanich Inlet has stimulated many studies that exploit the fine sedimentary record. Examination of the physical characters of the exceptional laminations has yielded sedimentation and seismic histories (Blais-Stevens et al. 1997). Excellent preservation of diatoms, pollen, and fish remains allow for fine-scale interpretations of past changes (i.e.,

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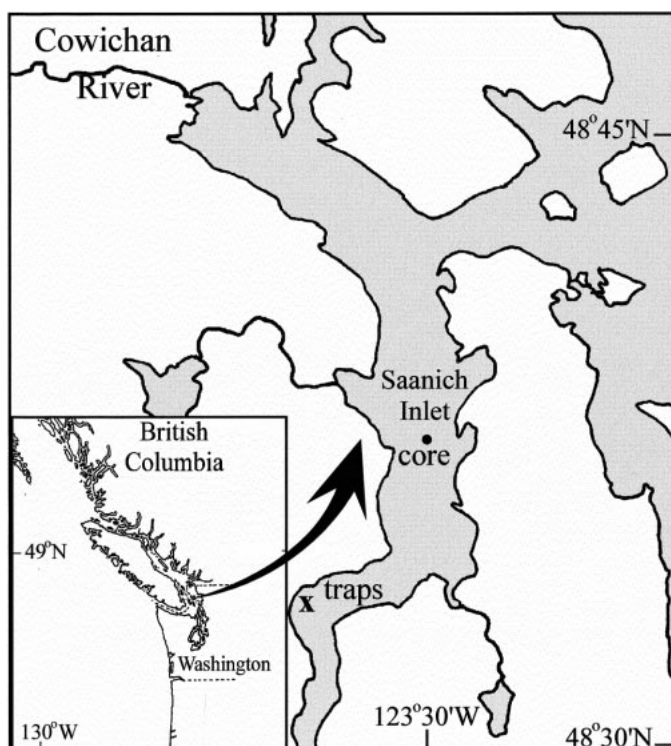


Fig. 1. Saanich Inlet, British Columbia, Canada. Note location of the Cowichan River, the major freshwater input to the inlet. Maximum inlet depth is 230 m.

Heusser 1983; McQuoid and Hobson 1997; O'Connell and Tunnicliffe 2000). Several geochemical studies have examined the behavior of organic compounds in the sediments (Nissenbaum et al. 1972; Hamilton and Hedges 1988; Cowie et al. 1992). The Ocean Drilling Program (ODP) included Saanich in a short drilling leg (169S) to extract a complete Holocene record. In their study of the 120-m core, McQuoid et al. (2000) recorded a marked shift in organic carbon character through the Holocene. As organic carbon content increased to its present level, the terrestrial component decreased, and the marine signature became stronger, suggesting greater marine production. This study extends the work of McQuoid et al. (2000) to examine the nature of the sedimentary carbon on a seasonal basis in the upper laminae of Saanich Inlet. A major boon to this study is the presence of a well-resolved absolute time scale. I explore the methods required to discern changes in the isotopic character of the organic carbon and the possible causes of the observed shifts in a time of changing land use and climate conditions.

Two overlapping box cores were taken midinlet (48°37.9'N, 123°30.0'W) from 230 m water in June 1995. This station was also sampled for in situ freeze cores (McQuoid and Hobson 1997) and ODP cores (McQuoid et al. 2000). The box-cored sediments were frozen using a dry-ice/methanol slurry once on deck, and these sediments were maintained in a freezer. Varve counts, distinctive laminae, and diatom markers were used to align and date cores. Absolute dating was confirmed by reference to a midinlet core, in which the 1963 cesium-137 peak was determined and counting from the surface was possible (Collins 1997;

McQuoid and Hobson 1997). The box cores spanned the years 1861 to 1958 and 1933 to 1991 and contained distinctive diatom horizons: 1919, 1935 (peak years of *Chaetoceros didymus* resting spore abundance), and 1940 (first *Rhizosolenia* appearance). The best sections of the two cores were selected to form a single complete sequence of laminated couplets totaling 176 cm in length. This composite became the sample source. Core alignment and absolute dating is not likely to be perfect. Other unpublished studies on these sequences indicate maximum error that is on the order of 2–3 yr. Further characteristics of these cores are described in O'Connell and Tunnicliffe (2000).

Core surfaces were cleaned prior to sampling. Laminae were highly visible: each annual couplet was ca. 1 cm thick, except in the top uncompressed layers. Every light and dark layer in the 130-yr sequence was sampled and maintained in a frozen state until analyzed. In this study, a "year" consists of a lower light lamina and the overlying dark lamina. Sample handling was a major concern, as initial isotope results were not replicable. Numerous trials were run with a variety of washing times, acidification techniques, and sterile procedures. The one factor that strongly influenced reproducibility of results was homogenization of the sediments. For final analyses, about 2 to 3 cm³ of wet sediment was extracted for each sample. Sediments were rinsed twice to remove salt by centrifugation. To remove the inorganic carbon fraction, the sample was digested in 2 ml 10% HCl for 24 h. Subsequent rinsing and centrifugation further neutralized the sample and removed salt.

Samples were then freeze-dried and pulverized, first by hand (using a glass pestle) and then further using a ball mill until a homogeneous consistency was reached. A 10–15-mg aliquot was weighed to aluminum carriers and stored in a desiccator until combustion and analysis using Elemental Analyzer–Isotope Ratio Mass Spectrometry (Geochemistry Lab, University of Victoria). Several plant remains extracted from the core were also combusted. Isotope values were measured relative to a working standard and were calibrated against the international PDB reference scale. Results are expressed in the following notation: $\delta^{13}\text{C}_{\text{carbon}} (\text{‰}) = \left(\frac{R_s}{R_{st}} - 1 \right) \times 1,000$, where R_s and R_{st} represent the $^{13}\text{C}:^{12}\text{C}$ ratio in the CO_2 of the sample and the Pee Dee Belemnite (PDB) standard, respectively.

Overall organic carbon values are relatively low: around 2.8% dry weight (Table 1). Organic carbon ranged from a low of 2.20% to 3.68%. Three samples from the 1948 laminae yielded values of over 5%, implicating detritus such as leaf litter; the light isotopic values (to -23.8‰) were similar to those of seedpods picked from the cores (-22.01 , -27.44 , -27.74 , and -29.01). The outliers from 1948 were discarded.

Replicates—Paired replicates, each extracted from the same lamina, were run for both organic carbon content and $\delta^{13}\text{C}$. The variability within pairs was compared to the variability between the summer and winter layers of the same years to be sure that it was possible to discern seasonality. Variances between replicates were significantly lower than variances between the seasons for both organic carbon and $\delta^{13}\text{C}$ ($P < 0.05$ for both values in Levene's test). A simple

Table 1. Average seasonal values of carbon content and stable isotope composition for carbon in Saanich Inlet sediments. "Summer" refers to light bands and "winter" to dark bands. Pairwise differences between seasons were tested using the Wilcoxon matched-pairs signed-rank test (two-tailed).

	Organic carbon (% dry weight)		$\delta^{13}\text{C}$ (‰ PDB)	
	Mean	SD	Mean	SD
Summer	2.7946	.322	-22.0033	.556
Winter	2.8453	.322	-22.0868	.515
Pairwise significance	$P = 0.0053$		$P = 0.0024$	

correlation between replicates 1 and 2 for the $\delta^{13}\text{C}$ values was highly significant at $r^2 = 0.89$ (Fig. 2). Samples that were run without the pulverization and homogenization steps could not distinguish between summer and winter differences. This preparation technique and sample data were discarded. Very small sample volumes caused a variability that masked the increase in organic carbon content and the depletion in stable carbon isotope values upcore. Replicable values with apparent pattern were obtained using large sediment sample volumes that were mechanically homogenized before subsampling for analysis.

Seasonality—There were no significant differences between the overall summer and winter values of organic carbon content or $\delta^{13}\text{C}$. However, a pairwise test that compares summer with succeeding winter in each year found significant differences, with winter values being richer in organic carbon content and lighter in isotopic character. When a paired season test was attempted using the preceding winter and the summer of the overlying year, no significant differences were found. Systematic seasonal differences in sedimentary organic carbon within a year (but not with the next year) indicate a coordinated response in marine and terrestrial production in any year. That response does not extend to the next production year. Sampling took the spring–summer diatom-dominated band first; terrestrial production from that summer would wash into the inlet in the dark fall–winter band that was labeled as the same year. The link was likely made much stronger by the fall plankton blooms that appeared in the dark layers (McQuoid and Hobson 1997); the marine productivity within one calendar year probably shifts together more strongly than it does within the fall of one year and the spring of the next.

Figure 3 compares organic carbon character in particulate traps moored at a 50-m depth with the corresponding years in the sediments at a 230-m depth. Variability is much higher in the trapped particles, with ranges from -23.0 to -19.2 ‰ (Calvert unpubl. data). Much of the heavier portion is not represented in the sediments. Note the different locations of traps and cores depicted in Fig. 1. The availability of carbon dioxide affects isotopic composition: in the warmer temperatures of summer, pCO_2 decreases, and thus, less discrimination by marine plankton occurs (Meyers 1997). The seasonal trap values recorded here and in Cowie et al. (1992) are greater in the summer, as would be expected. However,

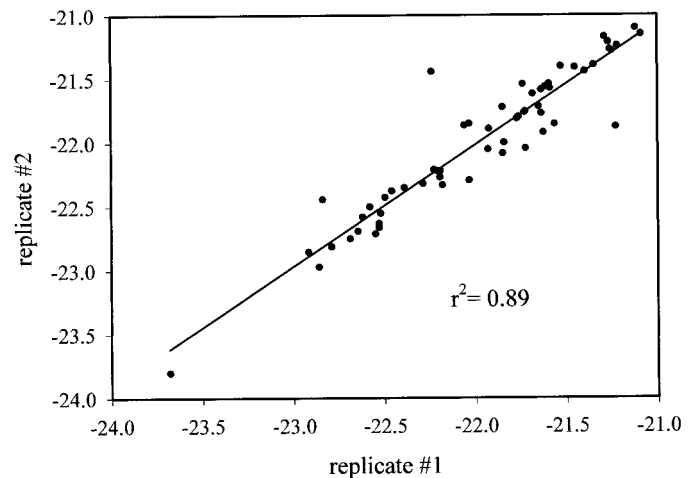


Fig. 2. Test of reproducibility of carbon isotope data. Replicate pairs of sediment from the same laminae are plotted. Correlation is highly significant at $P \ll 0.05$, and the variances of the pairs data set is significantly lower than variances of seasonal pairs from the same data years (see text).

it is not possible to discern the cause of the shift to the winter values. Winter is the time of greater runoff and terrestrial carbon delivery, which also lightens the isotope signature. Water column variation is reflected in the pairwise seasonal differences in organic carbon content and isotopic character from sediment laminae.

Trends—Figure 4 presents the history of organic carbon character in Saanich sediments over 130 yr. Organic carbon rises from values of around 2.5% dry weight in the 1860s

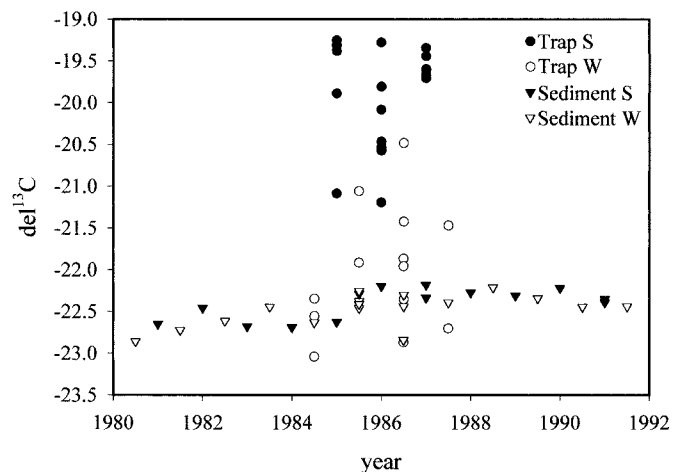


Fig. 3. Comparison of carbon isotope composition from particles captured at 50-m water depth and sediments of the corresponding year. Replicate samples were taken for some laminae in the sediment cores. Trapped particles were poisoned and recovered within months, whereas carbon in the sediments degraded over several years until core recovery in 1995. Details of the moored traps are published in Sancetta and Calvert (1988). The traps were moored further up-inlet (Fig. 1) than the cores. Trap data used here are partly published in Cowie et al. (1992) and are partly courtesy of S. E. Calvert.

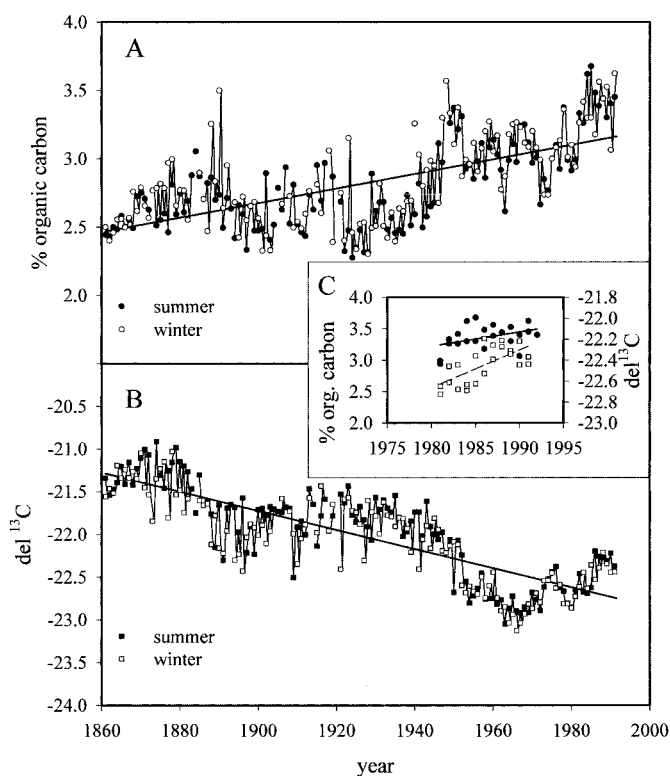


Fig. 4. Carbon characteristics in laminated cores of Saanich Inlet. Replicate samples for any given year are averaged to a single value. "Summer" values come from the light laminae, "winter" from the dark. (A) Percent organic carbon by sediment dry weight. (B) Stable carbon isotope composition. (C) Carbon character in the upper 11 yr. Filled circles are organic carbon, and hollow squares are $\delta^{13}\text{C}$. Core collection date was 1995; thus, the upper 4 yr were lost in sampling. The fitted lines represent linear relationships.

to values of 3.3% in the 1990s, whereas the isotope character changes from -21.3 to -22.5% PDB. A notable shift occurs in the late 1940s. Higher organic carbon values tended to associate with more negative $\delta^{13}\text{C}$ values (Figure 5). The correlation is only barely significant ($r = 0.58$; $P < 0.05$, with 10 degrees of freedom where the data sets are autocorrelated over 26 lags).

Interpretation of organic carbon change within a core is not without difficulties as a result of transport and diagenetic processes. Organic carbon levels in Saanich fall in the ranges previously reported. Murray et al. (1978) and Hamilton and Hedges (1988) recorded an abrupt upcore increase of organic content in the upper layers of Saanich sediments. Figure 4A illustrates a notably higher organic carbon content in the upper 10 yr (top 25 cm of sediment). However, the logarithmic increase toward the surface described by these authors is not present in these 10 yr (Fig. 4C); the top 4 yr are missing; they were likely blown away by the corer.

Shifts in isotopic signatures of detrital carbon relative to source occur during transit and residence in the sediment (Meyers 1997). The fine Saanich record reveals a progressively enriched (heavier) carbon isotope signal with depth as relatively greater amounts of ^{13}C are represented in the organic carbon. Diagenesis is likely to change the isotope sig-

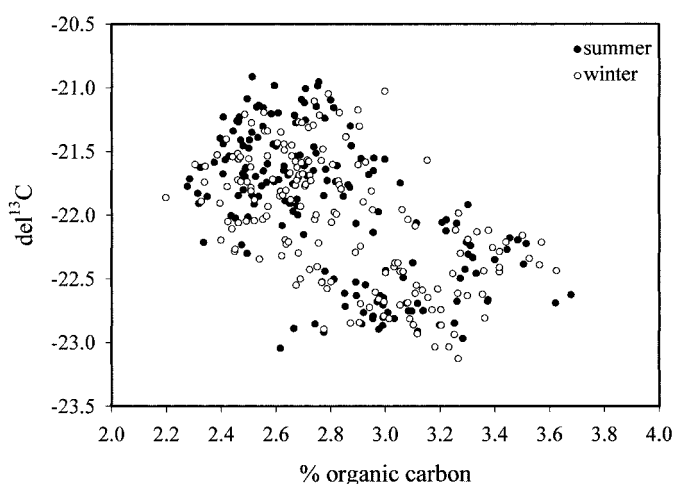


Fig. 5. Scatterplot of the relationship between organic carbon and isotope character. As the data are strongly autocorrelated, no regression is given, but there is a tendency for sediments with increasing carbon content to have a lighter isotopic character. No overall difference between summer and winter values is evident, although seasonal pairs are different (see text).

nature, as organic compounds degrade at different rates (Macko et al. 1994). Studies that show little or no change can be found (i.e., Emerson and Hedges 1988), but most examples in short-term records indicate a relative depletion of carbon isotopic composition with time or depth (Nissenbaum et al. 1972; Macko et al. 1993; Westerhausen et al. 1993). One example of downcore enrichment occurs in a high-organic algal sediment in which ^{12}C -enriched lipids were lost first (Macko et al. 1993). However, carbohydrates and amino acids usually are released in the first stages of decomposition/diagenesis, resulting in relative ^{13}C loss (Macko et al. 1993, 1994). Most commonly, diagenesis causes a reverse effect to that seen here. In addition to differential loss of select organic compounds, marine organic material tends to degrade first, leaving the more refractory lignins (Hamilton and Hedges 1988; Macko et al. 1994) and a depleted (=more terrestrial) signal deeper in the core. It is reasonable to interpret the shift in the Saanich core as a change from greater marine input in the late 1800s to greater terrestrial input in the mid-1900s; if anything, the signal is likely dampened by diagenetic changes.

The organic carbon collected in Saanich traps has a notably different isotopic signature than the corresponding sediments. Hamilton and Hedges (1988) and Cowie et al. (1992) noted preferential degradation of the marine organic fraction with depth. Although water column losses may explain this phenomenon, it is possible that suspended traps do not capture terrestrial organic material carried into the inlet by the influx of cold bottom waters in the fall. This water mass is responsible for deep-water renewal and turnover in Saanich (Anderson and Devol 1973). The location of the traps near the head of the inlet likely means that Cowichan River-derived terrestrial material was missed. Macko et al. (1994) found a rapid isotopic shift in macroalgal material mixed with sediments over several weeks: the shift to values that were lighter by 2.8‰ is attributed to differential organic

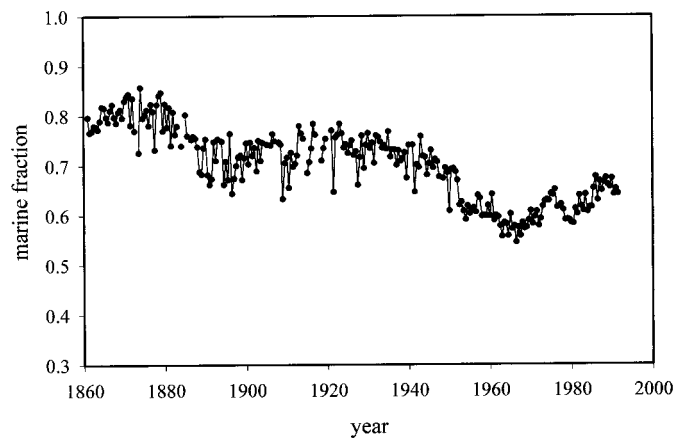


Fig. 6. Marine fraction of $\delta^{13}\text{C}$ showing summer and winter values. Calculation follows the linear equation $\delta^{13}\text{C} = m_1(\delta \text{ terrestrial}) + m_2(\delta \text{ marine})$, where m_1 and m_2 are fractions of terrestrial and marine input, respectively. Marine end-member is the average of the summer trapped carbon values (Fig. 3); terrestrial end-member is the average of pollen analyses presented in McQuoid et al. (2000).

compound loss and microbial fractionation. The average difference in trapped organic carbon and the upper 5 yr of sediments of my study is -1.5% . Some of the trapped organic carbon may have undergone degradation while in the traps; this difference is less than that observed in the controlled study of Macko et al. (1994). There is a greater difference in the summer values of trap and sediment carbon than in the winter values (Fig. 3); degradation of summer marine carbon may occur more rapidly than degradation of winter terrestrial carbon.

Organic carbon sources—In the Saanich Holocene sequence, upper core samples (about 400–1,500 yr before present) yielded $\delta^{13}\text{C}$ values of between -20 and -22% , with a progressive shift toward the less negative values toward the present (McQuoid et al. 2000). These authors interpret a gradual increase in marine production through the Holocene. My study uses similar methods and the same instrument, yet I recorded the opposite trend; the difference is that this study examines the most recent sediments of the basin, which the ODP cores did not sample. McQuoid et al. (2000) explore several mixing models. For the uppermost part of the core, they use observed values of end-members to determine a marine component of between 78 and 86%. In my study, the last 130 yr of Saanich record averages at a marine value of 71%. This calculation uses end-member values of -19.9% (average summer value of trapped carbon in Fig. 3) for marine and of -27.0% (average value of pollen samples taken from eight plant species around Saanich, as presented in McQuoid et al. [2000]) for terrestrial. The seedpods picked from the sediments averaged -26.4% , although the range of values was too large to use as terrestrial end-member. The marine component decreases from around 80% at core base to a low of 57% in the early 1960s. Cowie et al. (1992) used a variety of organic compounds to identify the predominant component of organic carbon in Saanich to be of marine

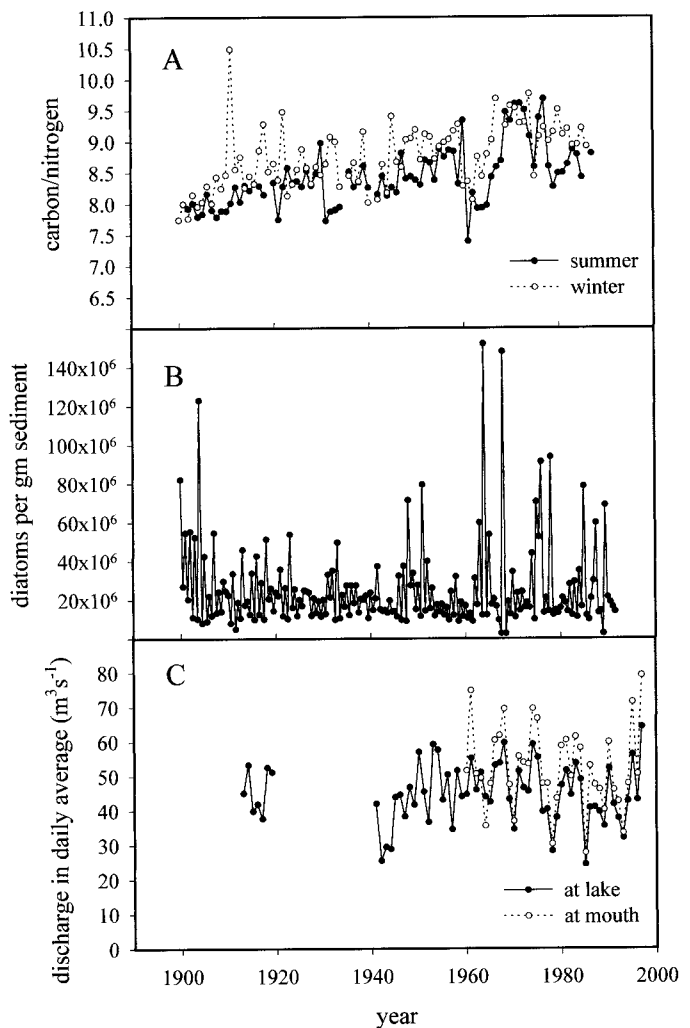


Fig. 7. Information on marine and terrestrial influences on Saanich sediments. (A) Bulk carbon:nitrogen ratios measured on laminae in the core used to establish the date sequence shown in Fig. 2. Data are extracted from Collins (1997). (B) Total diatom counts from the same reference core. Data from McQuoid (1995). (C) Average daily Cowichan River outflow measured at lake outlet and near river mouth. Data from Pacific Region, Environment Canada.

origin. Both Cowie et al. and Hamilton and Hedges (1988) model vascular plant contribution to upper Saanich sediments (sampled in 1983) as 20–30%.

Phytoplankton samples from Saanich Inlet yield carbon/nitrogen (C/N) values of between 4.2 and 5.3, whereas higher values in sediments are attributed to mixing with terrestrial organics (Hamilton and Hedges 1988). Collins (1997) presented data for organic carbon and nitrogen in a well-laminated core that was used as the temporal reference datum for my study. Mean C/N for the winter bands was significantly higher (8.75) than it was for the summer (8.43). The overall increasing trend of these data (Fig. 7A) supports the increase of terrestrial input through the 1900s. This C/N trend is also opposite the diagenetic trend: the more labile amino acids usually degrade first, causing depletion in nitro-

gen at depth in sediments (Cowie and Hedges 1991; Macko et al. 1993). For example, Martens et al. (1992) illustrated marked upcore decreases of C/N in shallow cores from anoxic sediments.

The change in organic carbon input does not seem to relate to plankton production, at least as recorded by the diatoms that dominate phytoplankton in Saanich. Figure 7B presents total diatom abundance in the reference core; McQuoid and Hobson (1997) presented the species breakout and seasonal data. The diatom record remained flat through the 1900s; although there was a hint of greater production at the turn of the century, there was no noticeable decrease that explained the isotopic shift seen in later years. McQuoid and Hobson (1997) find that sea-surface characteristics and a climate indicator (Pacific North American Index) are significant variables explaining diatom variability.

The major detrital input to Saanich comes from the Cowichan River, although some input is delivered from streams that issue directly into the inlet; less than 2% of Saanich suspended solid input derives from local streams (Ministry of Environment 1996). The large Fraser River flow from the mainland carries little sediment to the inlet. Average monthly outflow of the Cowichan River in winter months is more than twice that observed during the summer months, and winter outflow peaks in December and January. There have been no large shifts in Cowichan flow during the course of the recorded history (Fig. 7C); thus, volume delivery to Saanich has not changed. Unlike Burrell (1988), I find no correlation between river outflow and the amount of organic carbon in the sediments.

If changes in organic carbon signal are of minor diagenetic or nonplanktonic origin, then terrestrial input has changed. Martinelli et al. (1999) were able to detect changes in vegetation cover in a Brazilian watershed from $\delta^{13}\text{C}$ composition in river sediments. Saanich Inlet sediments also appear to record changes in land use around the inlet. The Cowichan watershed delivers most of that record. Whereas areas to the east of the inlet were settled and cleared beginning in the 1850s, the Cowichan Valley first saw settlers in the 1880s. Logging by ox team began 10 yr later, and logging by steam donkeys began in 1900. Rajala (1993) described the growth of the lumber industry in the valley, giving some estimates of timber extraction from the area (Fig. 8). With the railway came many laborers who were participating in a burgeoning industry; by the 1940s, most of the accessible slopes were stripped, and three sawmills were in operation. In 1958, the combined output of the three mills was 1.1 million cubic meters (Rajala 1993). Despite recommendations by the National Forester in the 1930s to encourage replanting in the region, the first tree farm was not established until 1961. The only consistent post-1940 records I could find are from Western Forest Products archives, and these records document output from one mill (Fig. 8). The final mill closure was attributable to lack of available lumber to sustain production of this and all local mills. Today, the Cowichan outflow drains about 1,100 km² in a basin with about 60,000 people in a dozen towns and rural areas. Forest products, agriculture, and tourism are the major industries.

The cleared slopes of the Cowichan Valley in the late

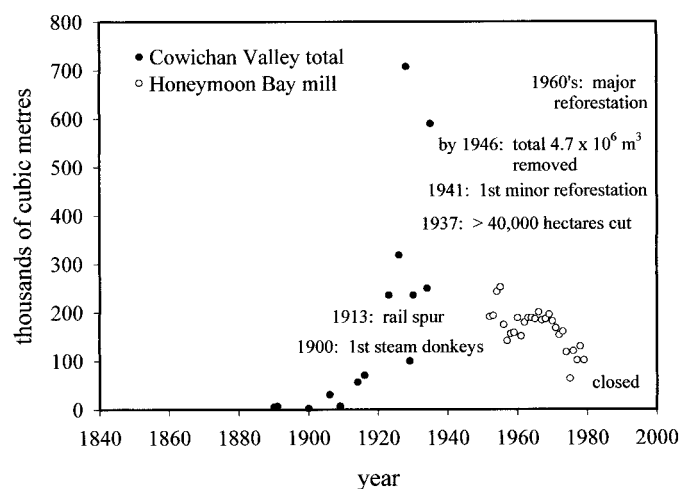


Fig. 8. Approximate volumes of timber removed from the Cowichan River watershed region. Total values given by, or interpreted from, Rajala (1993); post-1940 values are from one mill (data from Western Forest files in British Columbia Provincial Archives).

1930s to 1940s are likely responsible for the large shift that occurs in the organic carbon content and isotopic values shown in Fig. 4; organic carbon content in the sediments increased by 15–20% from the turn-of-the-century values. Although most detritus remains caught in rivers and deltas (Burrell 1988), erosional floods in the winter likely carry suspended detritus further, to Saanich basin. Griffin and Goldberg (1975) recorded the steady increase of charcoal in Saanich sediments over the twentieth century, which reflected fire incidence in surrounding woodlands. Heusser (1983) noted changes in pollen input from the cedar, western hemlock, and Douglas fir that had dominated the previous 2000 yr. Alder presence in pollen counts in Heusser's Saanich cores doubles between 1900 and 1970, and she also noted corresponding increases in grasses, plantain, and charcoal. A few observations on sediments processed for pollen analysis are available for my core: in 1865 and 1918, cedar: alder pollen ratios were around 3:2, but by 1935, a radical shift had occurred, as indicated by the 1:4 ratio (Hebda pers. comm.). Cedar was a major constituent of the Cowichan Valley, and alder is the first colonist in riparian habitats. Throughout the core, organics were present as pollen and wood fibers. Many organics were amorphous and apparently complexed to minerals, making it difficult to visually discern the dominant source of organic change in this core.

The reforested slopes of the Cowichan Valley probably retain more detritus in the woodland system (now in second-growth stands) than in the cleared areas of the midcentury. Figure 6 indicates that the terrestrial component of the sediments of Saanich has decreased since the mid-1960s. Hamilton and Hedges (1988) record a change in vascular plant input to Saanich. I recalculated their dates by equating their core depths to the well-dated reference core in this study: nonwoody angiosperm tracers are most common in the 1940s (their core base); in the late 1960s, gymnosperm tracers predominated.

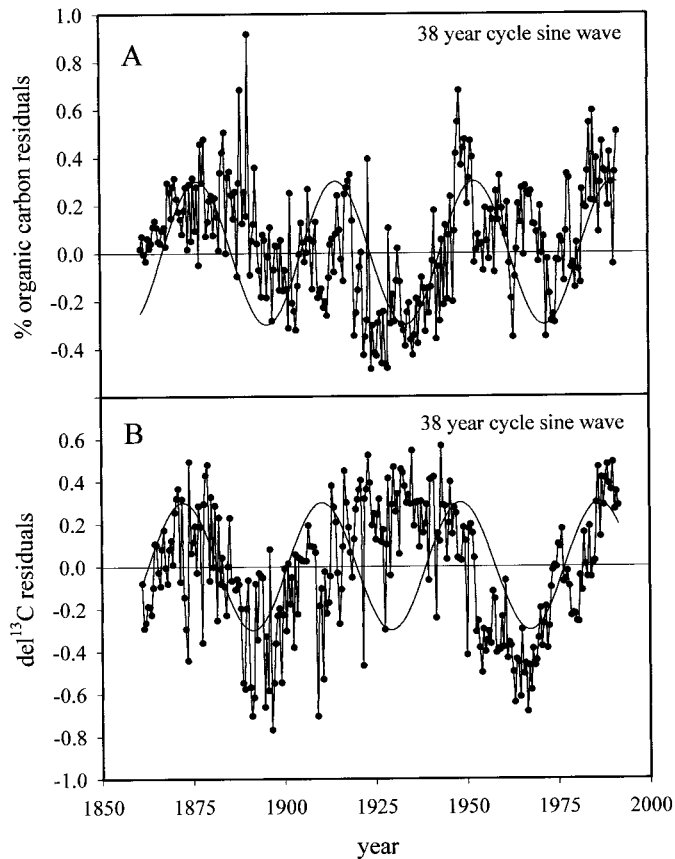


Fig. 9. (A) Detrended and demeaned time series of organic carbon and (B) carbon isotope fractions in Saanich Inlet cores. The sine waves were fit by hand-trying increasing period lengths until the period and lag with the largest correlation coefficients were found. Coincidentally, the same cycle was selected for each data set, although they are offset by 4 yr (first zero crossings are 1863 in A and 1867 in B).

Cycles—Both the organic carbon and $\delta^{13}\text{C}$ signals have long-term cycles, but they are not in phase. The strongest Tukey spectral peaks in both data sets appear at 38 yr, yielding a single high-density peak in the cross spectrum. Figure 9 represents the best fit of that 38-yr cycle to the organic carbon signals after demeaning and detrending. The fit is imperfect, but it is interesting that the same cycle dominates both data sets. The cross correlation is significant at a lag of about 4 yr. The periodograms have considerable energy at the 19-yr (organic content) and 20-yr ($\delta^{13}\text{C}$) frequencies; the 38 yr could be a harmonic reinforced by other frequencies. The Cowichan outflow has a strongly significant cycle at 7 yr, but it is the 19-yr frequency that yields a strong co-spectral peak with organic carbon only. Interestingly, that significant cross correlation is lagged (led by river outflow) by 6 yr; although 1–3 yr may be reasonable for residence/transport, the remaining lag may be caused by dating imperfections in our cores. There is no significant peak in cross-spectral plots of carbon with diatom numbers.

Sedimentary records provide a long time series to examine environmental conditions prior to measurement history. The Cowichan River outflow shows the strong El Niño-Southern

Oscillation (ENSO) periodicity that is present in the major North Pacific pressure cells (Beamish 1993). In Saanich sediments, this 4–7-yr cycle is present in the numbers of herring scales deposited in the same cores studied here (O’Connell and Tunncliffe 2000). Although Saanich organic carbon is predominately of marine origin, diatom variability is not directly reflected in the organic carbon history. The organic carbon record shows a 38-yr cycle, a frequency that does not dominate climate records (Ware 1995). The Cowichan outflow data series is too short to detect this cycle but does show the 19–20-yr cycle that Ware identifies as a bi-decadal oscillation related to sea-surface temperatures and wind gyres in the Pacific. Atmospheric behavior cycles at this frequency (whatever the fundamental cause) influence precipitation and runoff. This frequency was recently identified in a 227-yr tree-ring series around the Gulf of Alaska (Wiles et al. 1998). The most parsimonious interpretation of the 38-yr cycle is that the interdecadal climate signal of 19 yr is reinforced at twice the frequency by the logging and re-growth history in the Cowichan Valley.

Short sediment cores can provide useful information on fine-scale organic carbon variations of the recent past. This study on Saanich Inlet finds that (1) it is important to process larger samples to homogenize the particulates; (2) organic carbon content and stable isotope values differ between laminae deposited in summer and winter; (3) organic carbon increases from 2.5 to 3.3% in 130 yr, whereas $\delta^{13}\text{C}$ shifts from -21.3 to -22.5‰ ; (4) a 38-yr cycle fits both data sets the best, although they are offset by 4 yr; (5) the only factor examined that could explain the organic carbon trends is logging in the watershed of the river delivering the most detrital material; and (6) a bi-decadal climate oscillator likely influences the 38-yr cycle. Additional work on diagenesis of organic matter would augment interpretation of fine-scale changes. As further work on biotic signals and climate oscillations in the North Pacific develops, the information presented here may enhance the historical time series. Despite the complex processes that affect the journey of organic carbon from source to sink, it appears possible to discern the impact of land-use changes in an adjacent marine basin. In the case of Saanich Inlet, anthropogenic activity has markedly increased the amount and character of organic carbon sequestered in the sediments.

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