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High resolution record of carbon accumulation rates during boreal peatland initiation

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Abstract

Boreal peatlands are a major global C sink, thus having important feedbacks to climate. A decreased concentration in atmospheric CO_2 7000–10 000 years ago has been linked to variations in peatland C accumulation rates attributed to warm climate change and increased productivity. Yet, this period also corresponds to early stages of peatland development (as peatland was expanding) following retreat of ice sheets and increases in C storage could be associated with wetland evolution via lake filling or following marine shoreline emergence. Unravelling past links amongst peatland dynamics, C storage, and climate will help us assess potential feedbacks from future changes in these systems, but most studies are hampered by low temporal resolution. Here we provide a decadal scale C accumulation record for a fen that has transformed from salt marsh within the last 70 yr on the isostatically rebounding coast of James Bay, Québec. We determined time frames for wetland stages using palynological analyses to reconstruct ecological change and ^{210}Pb and ^{137}Cs to date the deposit. The C accumulation rates during the tidal marsh and fen stage (87 and 182 g C m^{-2} yr^{-1}, respectively), were as much as six times higher than the global average for northern peatlands. We suggest that the atmospheric CO_2 flux during the early Holocene could be attributed, in part, to wetland evolution associated with isostatic rebound which makes land for new wetland formation. Future climate warming will increase eustatic sea level, decrease rates of land emergence and formation of new coastal wetlands, ultimately decreasing rates of C storage of wetlands on rebounding coastlines.

1 Introduction

Boreal and arctic peatlands constitute a major global C resevoir of 400–500 Gt (Roulet, 2000), but also release CH_4 to the atmosphere – thus can have important feedbacks to climate (e.g. Yu et al., 2011). Post-glacial development of these boreal wetlands has played a key role in shifts of atmospheric concentrations of CO_2 and CH_4. Carbon

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sequestration histories in peat deposits have shown variations in peatland C accumulation rates over the Holocene that have been linked with a decreased concentration in atmospheric CO_2 7000–10 000 years ago. This increased C storage has been attributed to climate change and increased productivity (MacDonald et al., 2006; Yu et al., 2011). However, this period also would have corresponded to early stages of peatland development following retreat of ice sheets and substantial increases in storage could be associated with wetland evolution via lake filling (e.g. Kubiw et al. 1989) or following marine shoreline emergence (e.g. Shennan et al., 1999, 2000; Pendea et al., 2010).

Some northern peatlands originated as marine shorelines emerged from the sea isostatically recovering from crustal depression caused by ice sheets (e.g. Shennan et al. 2000; Pendea et al., 2010). Immediately after emergence tidal marsh deposits formed and with continued crustal uplift, marshes were isolated from tidal influence and transformed into freshwater minerotrophic fens. Continued accumulation of peat eventually isolates the ecosystem from groundwater, making possible a shift from a fen to ombrotrophic bog. As wetland transition occurs, the rates of C storage in soils and greenhouse gas flux could change significantly. Modern tidal marshes globally store an average of $210\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Chmura et al., 2003), and northern freshwater peatlands considerably less, 20 to $30\,\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Roulet, 2000). Thus wetland evolution associated with marine emergence could explain, at least in part, high C accumulation rates in the early Holocene.

Unravelling past links amongst peatland dynamics, C storage and climate will help us assess potential feedbacks from future changes in these ecosystems. Although immensely useful, most paleoecological studies have been limited to, at best, a centennial resolution in dating of ecosystem change. Deposits are dated with ^{14}C, which commonly has an analytical error of 20 to 60 ^{14}C years, and uncertainties in calendar years ranging from 100 to 300 years (Guilderson et al., 2005). In addition, peat deposits are subject to autocompaction that increases with time, further decreasing potential temporal resolution of a sample of buried peat. Yet, decadal to centennial

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change in C balance are the most relevant to climate change impact assessments and mitigation policies; a research theme that Yu et al. (2011) noted requires urgent attention.

Decadal scale C accumulation rates can be determined by dating surface deposits with the short lived radioisotopes ^{210}Pb and ^{137}Cs which have been used to determine rates in wetlands, such as freshwater fens (Ali et al., 2008; Craft et al., 2008) and tidal salt marshes (Chmura and Hung, 2004) which are easily located on the landscape. However, determination of high resolution C accumulation rates associated with early wetland evolution requires location of a fen that has transformed from salt marsh during a period within the limitation of ^{210}Pb-dating, the last 100–200 yr, a condition not readily visible on the landscape. Boreal coastal regions presently undergoing isostatic rebound can provide such analogues and we located a site in early stages of peatland formation on the coast of James Bay, Quebec. We used palynological analyses to reconstruct ecological changes, measured sediment C density, dated the deposits with ^{210}Pb and ^{137}Cs, and thus were able to document C accumulation rates at a subdecadal scale.

2 Materials and methods

2.1 Study area and sediment sampling

Our site is located in the high boreal zone of eastern James Bay, northwestern Québec at 52.78° N 78.76° W. The region was covered by the last remnants of the Laurentide Ice Sheet until the early Holocene when marine waters invaded the newly deglaciated surface (Dyke et al., 2003). The marine transgression was brief and followed by shoreline regression under the influence of glacio-isostatic rebound. Over the last ~7000 years landscape emergence has been underway at a rate ranging from 6.5 m/100 yr between 7000 and 6500 cal yr BP to 1.4–2 m/100 yr during the late Holocene (Pendea et al., 2010).

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The sampled wetland is bordering by steep slopes (∼20–30°) vegetated with spruce trees (*Picea mariana* and *Picea glauca*). The basin holding the wetland is a former marine channel ∼150 m-wide and 800 m-long. A 1971 topographic map published by Department of Energy, Mines, and Resources confirms that the site was then a tidal channel. During our field work in 2006 the channel was filled with emergent tidal wetland vegetation dominated by *Carex paleacea, Juncus balticus* and *Schoenoplectus maritimus*. However, salt-intolerant brown mosses were evident in small areas of the wetland. In one such area we collected a 33 cm-long sediment slab, retrieving all peat without compaction, by cutting it from the side of a pit. The soil slab was sectioned into 1 cm thick layers. A subsample was cut from each slice for pollen analysis with 1.5 cm-diameter metal cylinder, and the remaining sediment in each layer was dried, weighed to determine dry bulk density, then ground for radionuclide and carbon analysis.

2.2 Paleo-wetland analysis

Pollen samples were processed as detailed by Pendea and Chmura (2012) and resulting assemblages were used to assess shifts in wetland environments over time by comparing them to a suite of modern analogues Pendea and Chmura (2012) developed for this region. The advantage of using pollen to reconstruct ecosystems is that it reflects a broader area than the small section of peat sampled and vegetation contemporaneous to the level sampled. Macrofossil analyses, in contrast, was not practical for this study which required processing of contiguous layers to develop a high resolution, sub-decadal record. Roots and rhizomes penetrate older layers while stems are buried by younger sediment. Isolation of seeds or leaves characteristic of various wetland types would address this problem, but it would have required washing our samples over a sieve – an action that would result in loss of dissolved carbon and small particulate matter, compromising our carbon calculations. Using Discriminant Analysis we identified the highest similarity between a fossil sample and one of the a priori sample groups within the suite of modern analogues: low marsh, high marsh, fen, and bog. All Discriminant Analysis calculations and regression analyses were performed using IBM

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SPSS 19.0 (IBM Inc., 2011).

2.3 Rates of sediment and carbon accumulation

The radionuclides ^{210}Pb, ^{241}Am, and ^{137}Cs were analysed by direct gamma assay in the Liverpool University Environmental Radioactivity Laboratory using Ortec HPGe GWL series well-type coaxial low background intrinsic germanium detectors (Appleby et al., 1986). Enough slices (19 within the 31 cm) were analysed for radionuclides to isolate a ^{137}Cs-peak and apply the CRS model (Appleby and Oldfield, 1978) to calculate ^{210}Pb dates. The ^{210}Pb dates were adjusted with the 1963 peak in ^{137}Cs activity that occurred at 13.5 cm.

The % sedimentary organic C was determined either by loss-on-ignition (LOI) or on a Carlo Erba Na-1500 CNS Elemental Analyzer with a precision of <0.2 µg. The latter method enabled us to determine and subtract the proportion of inorganic carbon from our calculations. For samples classified as tidal marsh the LOI was converted to C using the formula developed by Craft et al. (1991). We performed LOI on all samples classified as fen. Fen samples that were analyzed by both methods were used to produce an equation to estimate % C (% organic C = 0.512 × % LOI − 1.524) for the remaining fen samples. The linear regression of % LOI as a predictor for % C produced an adjusted R^2 of 0.996 with $p = 0.03$. Carbon density was calculated as a product of % organic C and bulk density. From these parameters and sediment accumulation rates we calculated C accumulation rates.

3 Results and discussion

3.1 Rate of paleo-wetland evolution

Our age model is derived by interpretation of ^{210}Pb, ^{241}Am, and ^{137}Cs profiles together (Fig. 1). Cesium-137 concentrations have a well resolved peak at 13.5 cm depth which

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we date at 1963, the year that coincides with maximum atmospheric fallout due to production of this artificial radionuclide during the peak in above testing of nuclear weapons (Pennington et al., 1973; Patrick and DeLaune, 1990). This interpretation is supported by the presence of significant concentrations of ^{241}Am at the same depth (Appleby et al., 1991). Lead-210 concentrations show a subsurface maxima at 2.5 to 4.5 cm depth. Below this depth concentrations continuously decrease to 22.5 cm where they again increase within the tidal marsh phase (see below). The shallow subsurface increase is likely due to influx of Pb in runoff from adjacent slopes following a local fire in 1989.

Palynological analyses reveal shifts from sub-tidal marine sediments to low elevation tidal marsh, then high elevation tidal marsh and eventually freshwater fen within the upper 25 cm (Fig. 2). Samples from 25 to 21 cm were classified as low marsh and from 21 to 5 cm were classified as high marsh, with the uppermost deposit classified as fen in our discriminant analysis of the palynological assemblages. The stratigraphic context constrains the 21–22 cm-section as the transition from low to high marsh, but it was classified as fen. However, the modern pollen analogues upon which our discriminant analysis was based does not include transitional communities, thus the 21–22 cm-section has a low probability (11%) that an analogue was in our data set.

Tidal marsh formation dates to ~1920 A.D. and the system existed as low elevation tidal marsh for ~10 yr when elevation further increased relative to local sea level, tidal flooding decreased, and vegetation characteristic of high marsh became dominant. After another ~60 yr, tidal influences became negligible and the system shifted from high tidal marsh to freshwater fen in ~1997 A.D. This paleoecological interpretation fits with oral history which records the channel was still navigable by canoe during high tides in the early 1960s (F. Asquabaneskum, personal communication, 2006).

3.2 Organic C accumulation rates

Carbon accumulation rates are dependent upon soil bulk density, the %C, and vertical soil accumulation rates (Fig. 3). Bulk density is highest in the early phase of the

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tidal marsh and decreases, with the exception of one fen sample, towards the surface. Carbon density is highest towards the middle of the high marsh phase. In contrast, soil accumulation rates are highest in the fen stage. These high accumulation rates largely drive the pattern of C accumulation. which averaged 42 g m^{-2} yr^{-1} in the low marsh, 87 g m^{-2} yr^{-1} in the high marsh and 182 g m^{-2} yr^{-1} in the fen. The total organic C accumulated over the short history of the wetland is 8 187 g m^{-2} with 593, 5555, and 2039 g m^{-2} accumulated in the low marsh, high marsh, and fen, respectively.

There are few rates of recent C accumulation in minerotrophic fens available for comparison. Craft et al. (2008) used ^{137}Cs to examine peat accumulation rates along a latitudinal gradient in the United States and reported C accumulation rates of 28–47 g C m^{-2} yr^{-1} in a Minnesota fen and 19–56 g m^{-2} yr^{-1} in two Florida fens. Both of these rates are roughly comparable to the global average for northern freshwater peatlands, 20–30 g C m^{-2} yr^{-1} reported by Roulet (2000). Ali et al. (2008) used Pb to examine fens exposed to hydrological changes associated with a hydro-electric complex in the La Grande Rivière watershed of James Bay and reported peat accumulation rates of 50 to 380 g m^{-2} yr^{-1}. They did not calculate C accumulation rates, but applying the average % C determined for the fen deposit in our study (32%), we estimate that C may be stored in fens of the La Grande Rivière watershed at rates ranging from 16–122 g C m^{-2} yr^{-1}. This is a broader range than reported for global peatlands, but still 33 % lower than documented in our recently developed fen. The inland fens are older than the developing coastal fen in our site where isostatic rebound is still occurring. Those examined by Craft et al. (2008) were 30 to 37 yrs old and the fens dated by Ali et al. (2008) were 100 to 150 yr old, thus subject to longer periods of decomposition. Besides reflecting reduced periods available for decomposition, higher C accumulation rates also may be characteristic of young fens, a situation which merits considerably more research. Young fens are likely to have a higher nutrient status as they still can be affected by nutrients in ground and surfaces waters, whereas bogs are hydrologically isolated from these nutrient sources. The nutrient status of fens could accelerate rates of peat production.

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4 Conclusions

Our study indicates that rapid rebound could correspond to rates six times higher than global averages reported for C accumulation in northern peatlands. Thus, the high rates of C accumulation reported for the early Holocene might, in part, be due simply to geomorphic changes without invoking climate drivers.

Rates of fen formation are dependent upon both rates of isostatic rebound and eustatic sea level rise. With no change in eustatic rise, slower rates of rebound would slow transition from tidal marsh to fen, reducing C accumulation rates, while continued peat accumulation in many fens would isolate them from nutrient bearing groundwater, transform them to bogs and further reduce the rate of C storage. Increased rates of eustatic rise will have the same effect. Climate warming increases eustatic sea level in two ways, by increasing meltwater input to oceans and through thermal expansion of ocean water. Thus, we can expect global warming to result in decreased rates of C storage of coastal wetlands on James Bay and other rebounding coastlines.

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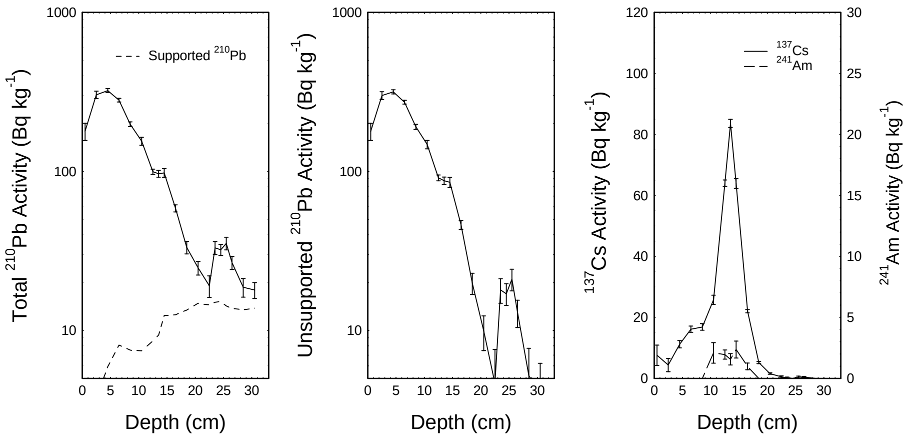

Fig. 1. Profiles of ^{210}Pb, ^{137}Cs, and ^{241}Am, concentrations versus depth in a young fen from James Bay, Quebec.

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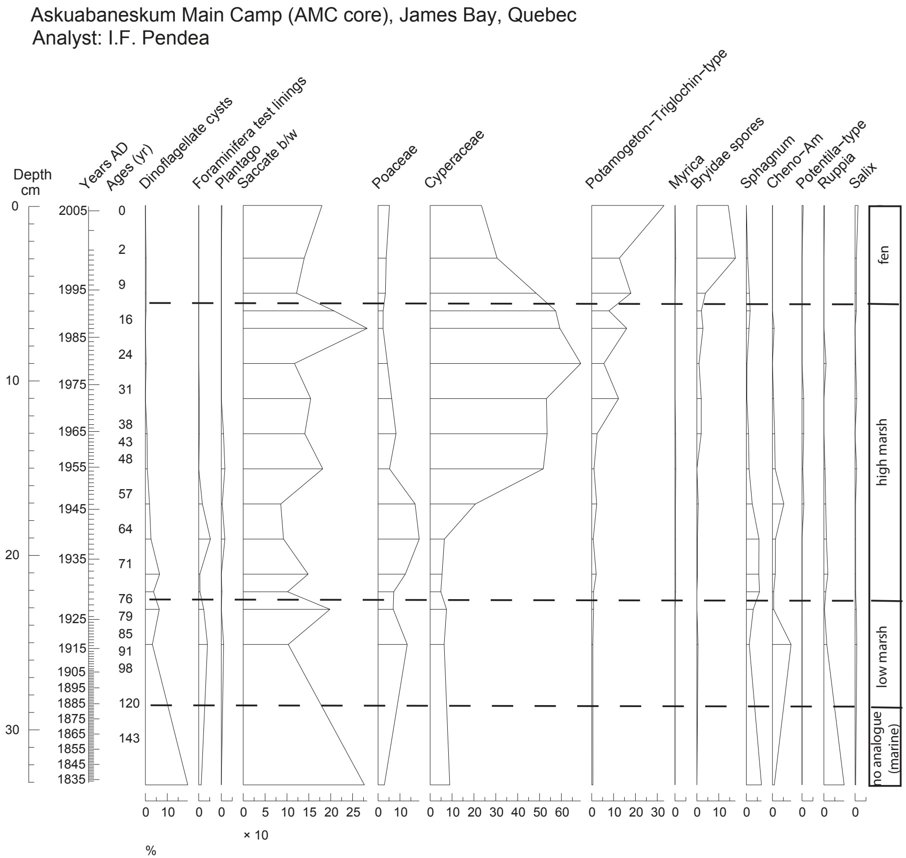

Fig. 2. Percentages of plant pollen, spores and dinoflagellate cysts used in the discriminant analysis classifying paleo-wetland communities. Percentages are based on a sum of all plant pollen and spores, excluding *Sphagnum*. The % Saccate b/w, representing broken conifer pollen prevalent in tidal sediments, is multiplied by 10 for clarity.

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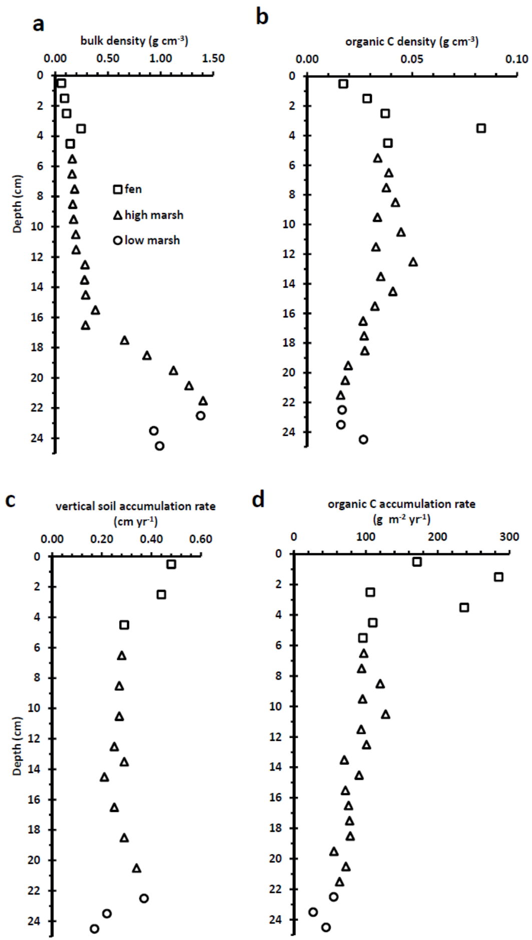

Fig. 3. Profiles of soil bulk density, carbon density, rates of vertical soil accumulation, and rates of C accumulation with depth in wetland deposits from James Bay, Quebec.