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SHORT PAPER

Millennial-Scale Rhythms in Peatlands in the Western Interior of Canada and in the Global Carbon Cycle

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A[1] natural ~1450-yr global Holocene climate periodicity underlies a portion of the present global warming trend. Calibrated basal radiocarbon dates from 71 paludified peatlands across the western interior of Canada demonstrate that this periodicity regulated western Canadian peatland initiation. Peatlands, the largest terrestrial carbon pool, and their carbon-budgets are sensitive to hydrological fluctuations. The global atmospheric carbon-budget experienced corresponding fluctuations, as recorded in the Holocene atmospheric CO_2 record from Taylor Dome, Antarctica. While the climate changes following this ~1450-yr periodicity were sufficient to affect the global carbon-budget, the resultant atmospheric CO_2 fluctuations did not cause a runaway climate–CO_2 feedback loop. This demonstrates that global carbon-budgets are sensitive to small climatic fluctuations; thus international agreements on greenhouse gasses need to take into account the natural carbon-budget imbalance of regions with large climatically sensitive carbon pools.

Key Words: **peat; carbon; Holocene; cycles; periodicities; CO_2; Canada.**

A global postglacial ~1450-yr climatic periodicity has recently been recognized (Pestiaux *et al.*, 1988; Sirocko *et al.*, 1996; Bond *et al.*, 1997; Mayewski *et al.*, 1997; Campbell *et al.*, 1998; Bianchi and McCave, 1999). The cause of this periodicity is, as yet, unknown, but is not believed to be solar variation (Stuiver *et al.*, 1997), and the exact length of this period varies by ±50 years from study to study, depending on the quality of dating control and proxy methods used. This periodicity is superimposed on longer Milankovitch-scale orbitally induced trends (Berger and Loutre, 1991) and may have been responsible for globally recognized millennial-scale postglacial climatic events such as the Little Ice Age, the Medieval Warm Period, and the Younger Dryas (Campbell *et al.*, 1998). In continental western Canada, the ~1450-yr periodicity has been identified as wet and dry cycles in late Holocene sediments (Campbell *et al.*, 1998; Campbell, 1998). Postglacial basal peat dates from continental western Canada (Fig. 1a) show cycles of peatland initiation, demonstrating that the ~1450-yr climatic periodicity had a significant impact on the carbon sequestration potential of the landscape. Correlative cycles are found in the rate of change of atmospheric CO_2 concentration measured on air bubbles in an ice core from Taylor

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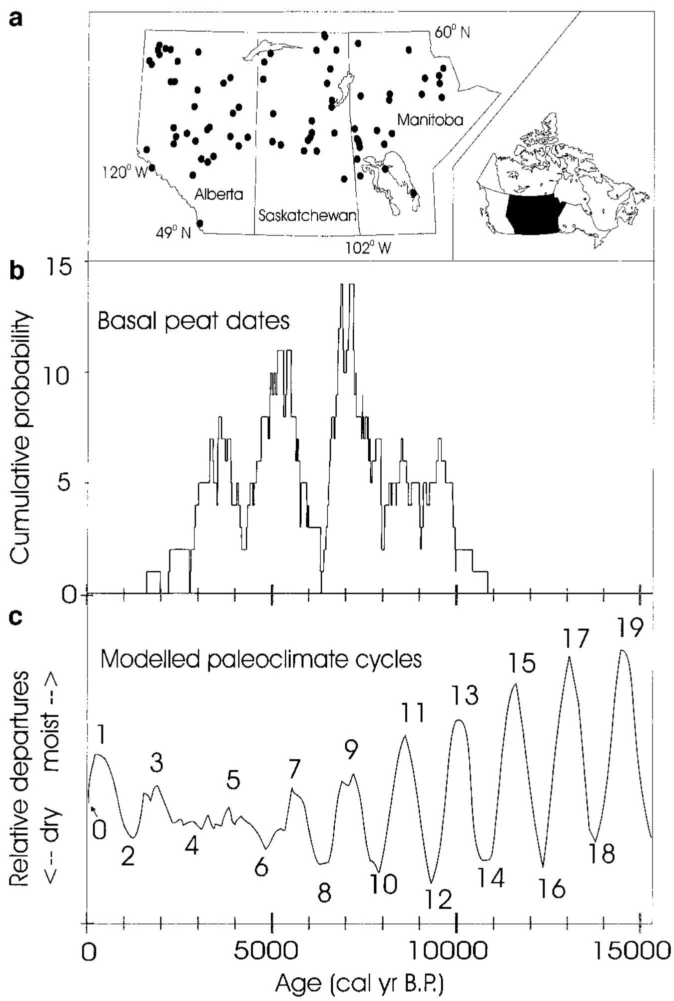

FIG. 1. (a) Locations of western Canadian peatlands used in this study. (b) Cumulated probability histogram of all available calibrated (Stuiver and Reimer, 1993) radiocarbon basal peat dates (with calibrated ranges of less than 1000 yr) in western continental Canada (Halsey *et al.*, 1998), constructed by summing the number of calibrated date ranges including any given year. Based on basal dates from 71 sites in Alberta, Saskatchewan, and Manitoba. Only paludified sites are included, and the material dated was the basal peat, not underlying materials. (c) Paleoclimate model for southern Alberta (Campbell *et al.*, 1998), with numbered wet (odd) and dry (even) intervals.

Dome, Antarctica (Indermühle *et al.*, 1999), indicating that this climatic periodicity affects the global carbon cycle.

Peatlands are the result of a long-term excess of biological production over decomposition and form mainly in environments where precipitation exceeds evapotranspiration. The western interior of Canada has a continental climate with long, relatively dry, cold winters and moist, warm summers. Much of the southern portion of the region is too dry to support forest or peatlands, but boreal forest and peatlands dominate the landscape in the northern part. The regional vegetation is thus sensitive to fluctuations in the precipitation–evapotranspiration balance (Hogg, 1997). Most of the study area was deglaciated between ca. 20,000 and 15,000 cal yr B.P. (Campbell and Campbell, 1997; Dyke and Prest, 1987; all ^{14}C dates in this paper are calibrated using Calib 4.1, Stuiver and Reimer, 1993). The southern margin of the boreal forest in Alberta, Saskatchewan, and Manitoba is limited by drought. Peatlands are found almost exclusively within the forested zone, where they occupy 406,000 km^2, representing 23% of the land base (Halsey *et al.*, 1998).

Boreal peatlands are the most important terrestrial global carbon stock and play an important role in the global carbon cycle (Gorham, 1991). At short time scales, peatland carbon accumulation is controlled predominantly by seasonal water levels, and peatland initiation is similarly controlled by regional climate and site-specific factors (Halsey *et al.*, 1998). That millennial-scale climate fluctuations occurred through the Holocene is well established. A model of paleoclimate fluctuations based on spectral and non-linear regression analysis of a high-resolution late-Holocene lake sediment record from southern Alberta has been proposed (Campbell *et al.*, 1998). While the relative magnitudes of wet/dry cycles suggested by this model are not likely to be accurate, the model does adequately predict the timing of postglacial climate events. Here, we number the climate phases of that model starting with 0 (present), 1 (Little Ice Age), 2 (Medieval Warm Period), etc., for discussion purposes, with odd numbers indicating wet periods and even numbers indicating dry periods (Fig. 1c).

A cumulative probability histogram of calibrated basal radiocarbon dates from 71 paludified peatlands in western continental Canada (Fig. 1b) shows distinct peaks in peat initiation coincident with wet periods 5, 7, 9, and 11. A comparison of the peat dates with the model of paleoclimate cycles indicates that the majority of basal dates are contemporaneous with cold/wet periods. The relative absence of dates younger than ca. 3000 cal yr B.P. is primarily due to a sampling bias, with few shallow peat sites having been sampled and dated.

The slight lag between wet interval 13 and a subsequent peak in peat initiation may relate to the general use of bulk radiocarbon dates, which require a relatively large volume of peat. As the oldest peat can be expected to be most decomposed and most compacted, the material dated at the base of the oldest cores is likely to have incorporated some peat younger than the initiation of the peatland, producing a lag between peat initiation and the date obtained. There is a conspicuous absence of peatland initiation dates prior to ca. 10,000 cal yr B.P. despite the fact that much of the landscape was deglaciated and thus available for peat growth by ca. 15,000 cal yr B.P. (Campbell and Campbell, 1997; Dyke and Prest, 1987). Palynological evidence at one central Alberta lake site indicates that *Sphagnum* did occur during cold/wet period 15 (ca. 11,500 cal yr B.P., coeval with the Younger Dryas) but disappeared during the subsequent warm/dry period 14 (Hutton *et al.*, 1994). It is not known if this *Sphagnum* occurrence represents an adjacent peatland, but the percentage of *Sphagnum* spores (nearly 10% of upland pollen) is high enough for that to be a plausible interpretation. The lake is surrounded today by a

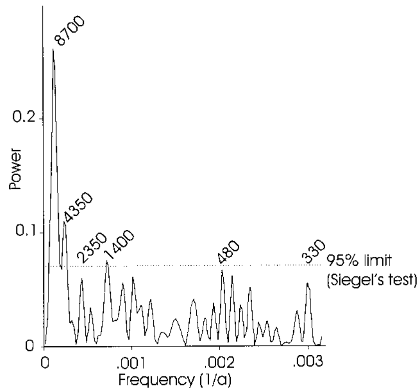

FIG. 2. Spectral analysis of the Taylor Dome CO_2 record (Indermühle *et al.*, 1999). Analysis was performed on the rate of change of the CO_2 record using SPECTRUM (Schulz and Stattegger, 1997). Peaks are numbered with the length of the period in years. Any peak above Siegel's limit is statistically significant.

large peatland complex, and the percentage of *Sphagnum* spores is lower (less than 5% of upland pollen). If a peatland occurred near this site, the absence of basal dates from across the region prior to 10,000 cal yr B.P. may be explained by the occurrence of a pronounced warm/dry period ca. 11,000 cal yr B.P. during which previously formed peat may have been oxidized. If peat is in fact as labile as this suggests, future natural warming/drying coupled with greenhouse-gas-induced warming/drying may result not only in a cessation of formation of new peatlands but also in the conversion of extant peatlands from carbon sinks to carbon sources, resulting in a positive feedback to the global warming trend. Similarly, the peat initiation cycles shown here should have had a significant impact on the global carbon cycle, particularly if this phenomenon was not restricted to the western interior of Canada.

The first high-resolution Holocene atmospheric CO_2 record, derived from air bubbles in the Antarctic Taylor Dome ice core (Indermühle *et al.*, 1999), can be inspected for an indication of matching cyclicities in global atmospheric CO_2. The record shows a 25-ppmv rising trend through the later Holocene, attributed mainly to land-cover changes, which released ca. 195 Gt carbon (Indermühle *et al.*, 1999), related to Milankovitch cycles. There are, however, a number of millenial-scale fluctuations superimposed on this trend. Spectral analysis (Fig. 2) reveals a number of important frequencies, dominated by several periods in the 400- to 500-yr range and periods of $\sim$1400 and $\sim$2350 yr. The $\sim$2350-yr period may correspond with Heinrich-like events, whereas the $\sim$1400-yr period likely corresponds to the $\sim$1450-yr period found by Campbell *et al.* (1998) and to the peat initiation dates. The inexactitude of the wavelength matches for the $\sim$1450-yr cycles is well within the error range of the available dates, estimated at $\pm$4% in Campbell *et al.* (1998) and at $\pm$8% in Indermühle *et al.* (1999). The amplitude of the $\sim$1400-yr CO_2 cycle is in most intervals $<$3 ppmv, which is close to the limits of reproducibility of the data of 1 ppmv (Indermühle *et al.*, 1999). The spectral peat is, however, significant at the 95% level according to Siegel's test (Schulz and Stattegger, 1997). Furthermore, the record shows a decrease in the slope of the rising CO_2 trend at those times when the peatlands were initiating (i.e., cool, moist periods in the climate model) and an increase in the slope of the rising trend at times when the peatlands were not initiating (i.e., warm, dry periods in the climate model), as would be expected if the peatlands were affecting the global carbon cycle.

Western Canadian peatland initiations might not by themselves be sufficient to account for the periodicity in atmospheric CO_2. It seems likely, however, that the $\sim$1450-yr climate cycle would not influence peatland initiations alone but would influence other terrestrial carbon pools as well. Certainly, several of the climate events associated with the climate cycle, including the Younger Dryas and the Little Ice Age, are well known to have affected vegetation in various parts of the globe (Ladurie, 1971; Shane, 1987; Grove, 1988; Campbell and McAndrews, 1993; Mathewes *et al.*, 1993).

The currently available information/evidence does not allow the development of an empirical model of CO_2 concentrations that fits the data well enough to show what fraction of the present CO_2 rise is natural rather than anthropogenic. It is likely, however, to be $<$5 ppmv, or $<$6% of the $\sim$80 ppmv rise since A.D. 1900 (Houghton *et al.*, 1990). This linkage of climate cycles with global atmospheric CO_2 then provides a paleo-analog (and therefore long-term) answer to the question "will the warming feed the warming?" (Woodwell and MacKenzie, 1995), and the answer is, "yes, but not much." While the postglacial thermal maximum appears to have resulted in decreased atmospheric greenhouse gas concentrations (Indermühle *et al.*, 1999), it should be noted that the postglacial thermal maximum was in part caused by an orbitally induced increase in seasonality of insolation, and so it is in many ways a poor analog for future warming. Similarly, the correlation of CO_2 and temperature at the scale of ice ages may involve processes not likely to operate in the near future. The periodicity discussed here does not appear to be caused by variations in seasonality of insolation, and it may provide more reasonable proxies of the impact of anthropogenic greenhouse-gas-induced warming on the natural components of the global carbon cycle.

If changing land cover is also responsible for the $\sim$1450-yr cycle in global CO_2, then those regions where the greatest change in land cover is occurring may be faced with natural as well as anthropogenic changes in biospheric carbon stocks. Distinguishing between these may be difficult if not impossible, as anthropogenic processes may be affecting the same land base. Current international agreements on atmospheric carbon do not recognize these natural climate-driven changes in carbon stocks. If the natural processes are focused in particular regions (such as the boreal forest or desert margins) as might be expected, then international agreements should recognize this natural process.

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