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Implications of Peat Accumulation at Point Escuminac, New Brunswick

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The world's peatlands contain about 450 GT of readily decomposeable organic carbon. Peat-forming systems have two main layers, of which the lowest is the thickest and includes the peat proper. The upper layer fixes carbon by photosynthesis, loses it by selective decay, and passes on about 15% to the lower zone; here decay continues, although very slowly. One consequence is that as for Point Escuminac, New Brunswick, the relation of age to depth may be concave. Although the surface of the peatland is as productive as ever, the true rate of carbon accumulation is decreasing; after 10,000 yr it is only 33% as efficient at sequestering carbon as it was when the peatland began to grow. Peatlands are usually thought to represent sinks for carbon, but a warming climate could make some peatlands carbon sources rather than sinks, thus initiating positive feedback. ©1993 University of Washington.

INTRODUCTION

Soils contain the largest pool of readily metabolizable organic carbon in the terrestrial biosphere. An important part of this is in peatlands, although estimates of the amount of carbon in soils and in peatlands differ considerably (i.e., Matthews and Fung, 1987; Clymo, 1987; Gorham, 1991). Peatlands cover about 3% of the Earth's land surface, mostly in Canada and in Russia, and contain about 450 GT of organic carbon. These peatlands have been fixing carbon by photosynthesis and accumulating it as peat for millennia. They are often assumed to be virtually indefinite carbon sinks. We think that this may be decreasingly true and in this article give evidence to support this view.

Peat-forming systems consist of two layers. The term acrotelm is used for everything above the lowest level reached by the water table in a dry summer, and the term catotelm is used for the permanently waterlogged peat below this (Ingram, 1978). The material formed at the top of the acrotelm decays selectively and eventually about 10–20% passes into the catotelm (Clymo, 1984). In reality it is the catotelm that rises at a speed determined by the rate at which the open porous structure of the acrotelm collapses at its base as the load of new material above it increases. In steady conditions, material is added at the top by photosynthesis and is lost at the same rate from the acrotelm to the catotelm, so the acrotelm remains at the same thickness while the catotelm thickens.

The addition of matter from the base of the acrotelm to the top of the catotelm is exactly analogous to the addition by photosynthesis to the top of the acrotelm. If the acrotelm is in a steady state then so is the rate of addition to the catotelm. In the catotelm decay is anaerobic; its main products are carbon dioxide and methane. The rate of anaerobic decay is much less than that of aerobic decay. The concentration of carbon dioxide and of methane increases down into the catotelm (i.e., Clymo, 1984; Dinel *et al.*, 1988; Shotyk, 1989). This implies continued production of these gases in the catotelm; if it were not so, then diffusion would result in the highest concentrations near the place where the rate of production is highest. The semifossil age of the evolved methane is consistent with continued production or dilution of recent gas with older (Wahlen *et al.*, 1989). The possibility that some methane is fossil and comes from underlying rocks or groundwater cannot be excluded (Aravena *et al.*, 1990).

Clymo (1984) has developed a model that considers the long-term productivity, i.e., the addition of organic matter to the top of the acrotelm, and the consequences of the processes of decay. If productivity is constant and there is no decay in the catotelm, the profile of age against depth, plotted as in Figure 2, will be a straight line. If decay continues, however, even at a very slow rate, then the profile will be concave. Specifically, Clymo

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(1984) shows that if M' is the cumulative mass (on an area basis) below some arbitrary datum, T' is the age relative to that of the datum, p' is the rate at which dry mass is added (on an area basis) at the datum level, and α' is the proportional rate of decay, then

$$M' = \frac{p'}{\alpha'}(1 - e^{-\alpha' T'}).$$

We report here the first good opportunity to test this model in North America, where peatland productivity and decay is less well known than in Europe. The results we present raise some important questions concerning the calculation of peat accumulation rates based on radiocarbon dates from two or more depths and the implications to be drawn from these results on the effectiveness of peatlands as carbon sinks.

STUDY SITE

The peatland at Point Escuminac, on the north-central coast of New Brunswick (47° 04′ N, 65° 49′ W; Fig. 1), was covered with ice before 13,500 yr B.P. Isostatic depression during deglaciation maintained low land levels before emergence from the sea by 12,000 yr B.P. (Rampton *et al.*, 1984).

The peatland at Point Escuminac covers >10 km^2 on a flat headland of sandstone. Relief is minimal and drainage is poor owing to the low altitude of the land. The center of the bog is slightly raised and has numerous pools. The surface vegetation includes the dwarf shrubs *Empetrum nigrum, Kalmia angustifolia, Gaylussacia baccata,* and *G. dumosa;* the cotton sedge *Eriophorum spissum;* and the mosses *Sphagnum fuscum* and *S. flavicomans*. The north shore is eroding and has exposed a profile of the accumulated peat in a cliff. At the base are thin layers of sand, silt, and organic mud. Above them, and extending 484 cm to the present surface, is *Sphagnum*–shrub–wood–*Eriophorum* peat. From this cliff 22 samples were dated by radiocarbon. The resulting ages indicate a record of organic sedimentation and peatland formation beginning ca. 11,000 yr B.P. following the isolation of the basin from the sea. Shortly thereafter, a shallow pond supporting aquatic macrophytes existed at the study site. Development of fen through primary peat accumulation continued until ca. 4700 B.P. when transformation into a bog was complete. Thereafter, the bog spread laterally by paludification onto higher parts of the peninsula. The level of the sea gradually transgressed and cut the steep cliffs into the modern bog that covers Point Escuminac today (Warner *et al.*, 1991).

METHODS

Peat samples were collected from the cleaned cliff face for radiocarbon dating. For the calculation of dry bulk

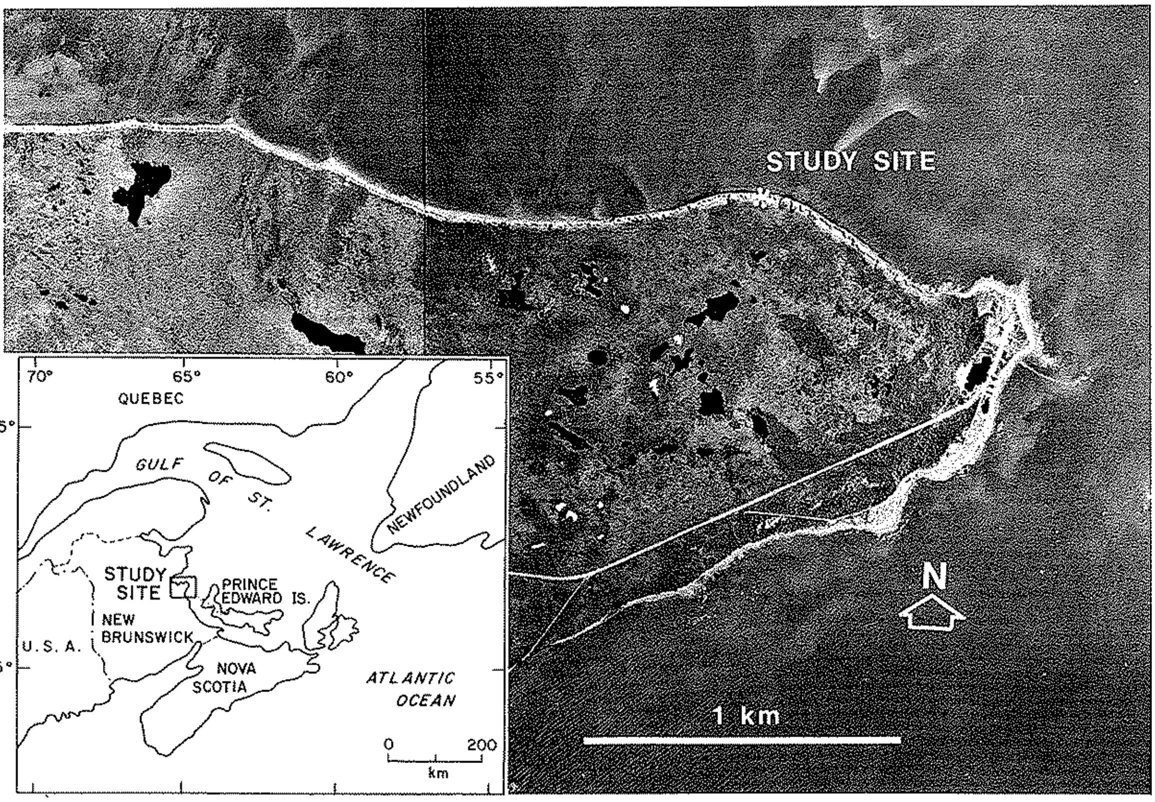

FIG. 1. Aerial photograph of the peatland at Point Escuminac, New Brunswick and the position of the study site on the sharp line of eroded peat cliffs at the north side of the peninsula. (Photographs A22089-80, 82, Department of Energy, Mines and Resources, Canada).

density, samples were taken every 5 cm. The ash-free dry mass was used in calculations, giving a mean value of 0.28 g cm^{-3}. This value is high, perhaps partly due to dewatering and compaction at the peatland edge (however, this does not affect the dry mass calculations) and partly because of the high proportion of wood of dwarf shrubs in the peat.

The 22 radiocarbon ages for the sampled peat were calibrated using the 20-yr data in the CALIB program of Stuiver and Reimer (1986). The oldest five samples were beyond the range of the calibration program. Of the 16 with a radiocarbon age <7250 yr B.P., 4 have three alternative calibrated ages. The depth–age curve was fitted using the simplex procedure of Nelder and Mead (1965). Ages and masses were standardized to unit mean. If the horizontal and vertical differences from the line fitted to these standardized values are designated u and v, respectively, the optimized function is the sum of squares of the nearest distances given by $u^2v^2/(u^2 + v^2)$, weighted by the inverse of the uncertainty in the age and the inverse of the number of alternative dates. This procedure distributes error on both axes, unlike the usual regression procedures.

RESULTS

The radiocarbon ages reveal 10 millennia of continuous peat accumulation (although only those within reach of calibration are shown in Fig. 2) and constitute the most comprehensively dated bog-peat sequence in North America (Tolonen *et al.*, 1985; Warner *et al.*, 1991). The fitted line is significantly concave, and the assumptions of long-term constant p' and α' are sufficient, although there clearly were variations over periods of a few hundred years. This does not imply that the assumptions are correct. The same result could have been obtained with a steadily increasing rate of input p', with a steadily decreasing rate of decay α', with steadily shortening periods of no input to the catotelm, or with some combination of these; however, all would require careful adjusting continuing over 8 millennia by speculative mechanisms. The fitted value of α' is 0.00011 yr^{-1} and is within the range of values for other sites (Clymo, 1984; Lewis Smith and Clymo, 1984; Clymo, 1991). This parameter controls the curvature in Figure 2. Obviously, a period of 5–6 millennia is needed for the curvature to become noticeable, i.e., for the value of α' to be demonstrably greater than zero. This factor and the relatively few dates for any one profile, may partly explain the apparent departure from linearity in many radiocarbon-dated profiles.

The value of p' is 190 g m^{-2} yr^{-1}, which is about four times that in most European examples (Clymo, 1984, 1991) but less than that on Beauchêne Island in the South Atlantic (Lewis Smith and Clymo, 1984). There must be some sites where p' and α' have not been even approximately constant over such long times and where a simple concave curve is a poor fit; however, such sites do not invalidate the insight that comes from sites that do fit the model. The assumptions that p' and α' are constant for several millennia seem to be consistent with most of the 16 observations in Europe and the southern hemisphere (Clymo, 1984; Lewis Smith and Clymo, 1984; Clymo, 1991), as well as the Point Escuminac profile.

DISCUSSION

We think that when the peatland at Point Escuminac began to grow and the catotelm had just begun to form, there was no underlying peat to decay so the true rate of sequestering dry matter was identical to the rate of input, p'. The rate of addition remained constant but the overall rate of loss increased as the accumulated mass of peat increased. The rate of sequestering is given by dm'/dt' =

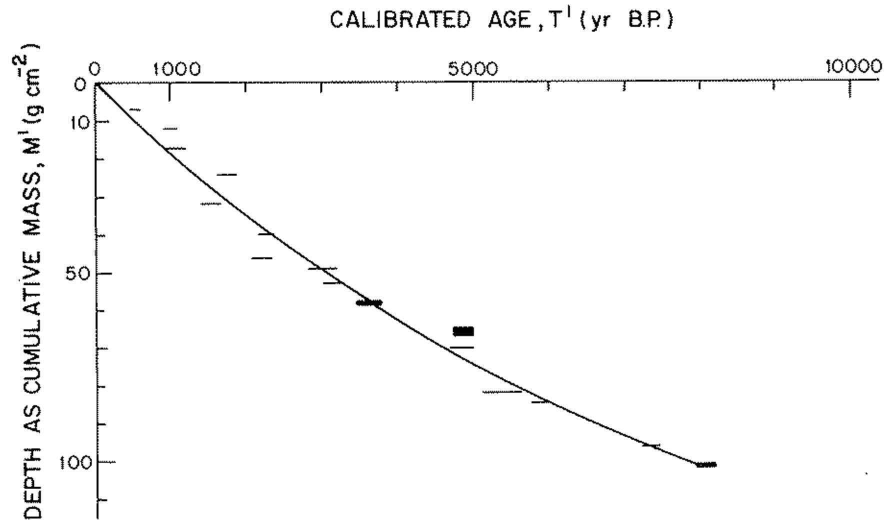

FIG. 2. Age, T' (as calibrated radiocarbon age), and depth, M' (as cumulative ash-free dry mass, on an area basis, below the surface), of a peat profile at Point Escuminac, New Brunswick. The 1 sigma counting bounds are shown. The curve was fitted to $M' = (p'/\alpha')(1 - \exp[-\alpha' T'])$. Fitted parameter values [and standard errors] are $p' = 190$ [5.5] g m^{-2} yr^{-1}; $\alpha' = 0.000109$ [0.000009] yr^{-1}.

$p' \exp(-\alpha' t')$, where m' and t' are the accumulated dry mass on an area basis at a time after the peat began to accumulate (Clymo, 1984). Thus, the sequestering efficiency is $(dm'/dt')/p' = \exp(-\alpha' t')$: *the sequestering efficiency is governed by the decay rate alone*. For Point Escuminac after 10 millennia, the sequestering efficiency is only 33% of its initial value (the time for sequestering efficiency to halve is $0.693/\alpha'$). The same calculation shows the rate at which carbon dioxide and methane are produced in the catotelm. The rate of loss of these gases from the peat must be almost the same as their rate of production by decay. For Point Escuminac after 10,000 yr, the rate is $0.67\,p'$. The potential rate of methane efflux from the catotelm may then be calculated. A typical value for p' in Europe is 50 g m^{-2} yr^{-1}. For $\alpha' = 0.0002\ \mathrm{yr}^{-1}$ and a 5000-yr-old peatland, the rate of conversion to gas is 32 g m^{-2} yr^{-1}. The proportion of carbon in the top 50 cm of a peatland is about 0.54 (R. S. Clymo, mean of 179 unpublished values) and in deeper peat about 0.52 (Gorham, 1988), although the value in carbohydrate is only 0.40. If the mass lost from the peat is 50% carbon (Clymo, 1984; Dinel *et al.*, 1988; Shotyk, 1989), then the potential rate of carbon efflux is about 16 g m^{-2} yr^{-1} and should be nonseasonal. Measured rates are strongly seasonal and are about 3–5 times as great, so there must be a second, probably near-surface source of gases. If some of the catotelm methane is oxidized on its way through the acrotelm (i.e., Clymo and Reddaway, 1981; Harriss *et al.*, 1982; Svensson and Rosswall, 1984; Sebacher *et al.*, 1986; Crill *et al.*, 1988), then there may be a solution to the seasonal but partly semifossil methane efflux puzzle.

If the climate were to become warmer or drier, then the rate of aerobic decay and the depth of the acrotelm might increase. These changes would decrease p' to less than the unchanged $\alpha' m'$ with the consequence that the existing peatland would become a carbon source rather than a sink. Existing peatlands might cease to grow and new peatlands might begin to form in regions of North America with hitherto unsuitable climates (Billings, 1987; Gorham, 1991). The addition of peatland gases would augment greenhouse gas emissions to the atmosphere, further enhancing the greenhouse effect. The whole problem of the carbon balance of peatlands and climate is complex and, we believe, needs detailed investigation.

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