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Assessing the accumulation of carbon in peatlands

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Introduction

An assessment of the integrated *amount* of carbon accumulated in peatlands requires two sorts of information: the area of peatland; and profiles of its depth both in linear measure (cm, for example) and as cumulative dry mass (kg m^{-2} for example).

It is difficult to estimate the area of peatlands. They interdigitate with other sorts of ecosystem; many peatlands are difficult to identify from the air, particularly when tree-covered; and many peatlands are remote from roads and inaccessible on the ground. Some of the uncertainties in the estimation of peatland area in the former USSR are discussed by Botch *et al.* (1995).

Area is difficult, but depth and bulk density are more so as they cannot, yet, be estimated reliably from the air and, on the ground, must be measured rather than simply recorded from visual inspection.

The statement that northern peatlands cover about 2.3 % of the Earth's land surface and contain about 450 Pg (Gt) of carbon (Gorham 1991) is, therefore, indicative only. It serves to establish that there is about the same amount of carbon in these peatlands as in the atmosphere: 600 Pg (Houghton, Jenkins & Ephraums 1990).

Improvements in estimates of area, depth and dry bulk density require more work or technical improvements in remote sensing or both, but what is needed is clear enough in principle and I consider it no further here.

An assessment of the *rate* of accumulation may be made in two main ways: using measurements of gas fluxes at the surface and of losses of organic matter in runoff; or by using some model of the accumulation process based on historical performance (coupled with bulk density profiles and knowledge of the age of the peat), or on some belief about the detailed functioning of the peatland ecosystem.

These approaches are complementary: each has strengths and weaknesses. It is with these methods that this article is concerned.

Gas flux measurements

The simplest method of measuring effluxes is the flux-box. This is a closable container placed over a part of the peatland, typically about 50-100 cm across. A collar remains permanently in the peat and the flux-box is put in a shallow trough around the top of the collar. Water in the trough seals the gap between flux-box and collar. When temperature differences alter the pressure inside relatively small amounts of gas bubble into or out from the chamber. This prevents the build up of substantial pressure differences. The earliest such measurements on peatlands are those of Clymo & Reddaway (1971) but there have recently been numerous better and more extensive measurements, with values ranged around the early ones (Bartlett & Harriss 1993 review them). One may follow the accumulation, or loss, of carbon containing gases (CH_4 and CO_2) in the static enclosed volume and calculate flux from the slope of the concentration line, the chamber gas volume, and the area. Portable infrared gas analysers now allow rates to be measured in no more than a few minutes. The instruments are sensitive enough for it to be possible to use a second approach: measure the difference in concentration between inlet and outlet with a gas stream flowing slowly through the chamber. There are many technical problems including heating by the sun and release of gas bubbles by the disturbance caused by a person approaching the site to make measurements. A large number of flux-box estimates have been made, especially of fluxes of CH_4, and relationships have been shown with temperature, watertable, abundance and nature of rooted plants (that provide a low resistance path to the atmosphere), light and so on. A recent review is by Bubier & Moore (1994). Peatland surfaces are usually a mosaic of wet hollows, less wet lawns, and drier hollows. The rates of gas flux with these microhabitats differs by a factor of perhaps 3-30, and they vary much in time as well (Bartlett & Harriss 1993, Bubier & Moore 1994).

Flux-boxes average over an area of about 0.1-1.0 m^2. Scaling measurements to average annual values for a whole peatland is therefore fraught with problems. One needs methods that will do this scaling automatically.

Suitable methods based on micrometeorology are now being applied. In the oldest of these, the flux gradient technique, profiles up to a few metres height of temperature, humidity, windspeed and gas concentration are measured and from these the flux of water vapour, momentum, and carbon-containing gas can be calculated. More recent is the technique of eddy correlation which uses the fact that transport away from the surface is by the vertical component of the wind and there must be similar fluctuations in vertical windspeed and gas concentration. Measurements must be made at a rate of about 10 s^{-1}, so expensive equipment is necessary. A third method also uses the correlated changes in vertical windspeed and gas concentration but it does so by using rapid-acting valves to collect upcurrent air and downcurrent air into two separate bags for later analysis by a cheaper method than is necessary for eddy correlation. Averaging is performed here by the valves.

All these micrometeorological methods integrate automatically though not equally to a distance perhaps 100-500 m upwind from the sampling point and over an area of 10^3-10^5 m^2. But they are technically more expensive and demanding than are flux-boxes, and are difficult to run continuously for long periods. From long runs the effects of temperature can be distilled, and if the peatland to one side of the sampling point is dry and to the other wet then with favourable wind directions some of the effects of watertable may also be inferred (Fowler 1995).

Similar principles may be applied from aircraft, and then the result is an average over 10^8-10^9 m^2.

Assessment of carbon losses in water seeping through the catotelm is only just beginning.

One or more of these methods has been used successfully for CH_4 flux with peatlands in Minnesota (Verma *et al.* 1992), in North America (Crill, Bartlett & Roulet 1992, Fan *et al.* 1992), and in Britain (Clymo & Pearce 1995, Fowler *et al.* 1995). Where comparisons of estimates for whole peatlands have been made using different types of method they have usually agreed within a factor of two and often to within 20 %. There are no obvious reasons why one should not use the micrometeorological methods, at least, for CO_2 as well.

Peatland processes

It is convenient to distinguish a surface layer, the acrotelm (Ingram 1978) which extends down to the depth reached by the watertable in a dry summer, from the underlying catotelm. Processes within the acrotelm are quite complex (Clymo 1992) but the overall effects, with the acrotelm considered as a black box, are these.

- The watertable moves steadily downward during a dry summer to perhaps 50 cm below the surface but its upward movement is limited, as it is in a V-notch weir, by the porous structure of the acrotelm.

- Carbon is fixed from atmospheric CO_2 by photosynthesis. Some is returned to the atmosphere by respiration as CO_2, some is converted to CH_4 and returned to the atmosphere, and some is passed down to the catotelm as peat. Overall the effect is to convert some atmospheric CO_2 to CH_4 and to remove some for a few millennia as peat. Whether the warming potential of the conversion of CO_2 to CH_4 is less than or more than the cooling potential of the removal of CO_2 as peat is not clear.

- Some plant materials (leaves of *Rubus chamaemorus* for example) decay rapidly while *Sphagnum* decays slowly. The slower the decay the greater the increase in the proportion that survives to pass into the catotelm.

- Once established the acrotelm remains of approximately constant thickness. It is not itself a peat accumulator but acts as a selective preprocessor of the plant material before passing it on as peat to the *catotelm: the true site of peat accumulation.*

It is difficult to get accurate dates for layers in the acrotelm, but Malmer & Wallén (1993) show that nitrogen is conserved in the acrotelm and its cumulative total may be used as a surrogate for the passage of time. They show that in hyperoceanic regions the rate of addition of dry mass and the rate of loss by decay, both on an area basis, are both higher than they are in less oceanic peatlands. But the net effect, seen in the rate at which dry mass enters the catotelm (*p* below) is much the same in both sorts of peatland.

The catotelm is permanently waterlogged - it has a much lower hydraulic conductivity then the acrotelm does - and, because O_2 diffuses through water more slowly than it is used up by micoorganisms, the catotelm is permanently anoxic. Decay is anaerobic and, for reasons that are unclear, is much slower than in the acrotelm. But decay does continue (Clymo & Pearce 1995) and this has consequences for age *vs* standard dry mass curves.

The sorts of 'rate' of peat accumulation

The accumulated dry mass, [dimension M], in one peatland may be much greater than in another simply because the first peatland is of much greater area. Comparisons of processes almost always require, therefore, that the accumulated dry mass be expressed on a unit area basis. There is no accepted way of making this distinction. Here I will call accumulated dry mass on an area basis the 'standard accumulated dry mass' [M L^{-2}]. Neither the accumulated dry mass nor the standard accumulated dry mass are rates. They have no element of time in their definition or value of time in their calculation. Sometimes there is an unspecified assumption that two peatlands whose standard accumulated dry mass is being compared have been growing for the same length of time. If that is true then the one with the greater standard accumulated dry mass must, on average, have had the greater rate of accumulation. But one cannot say what that rate was.

Rates involve time in their definition. There are three sorts of standard rate in common use. They have the same dimensions [M L^{-2} T^{-1}] and, therefore, may have the same units (kg m^{-2} a^{-1} for example) but for any one site each of the three has very different values and meanings. They should not, usually, be compared. Suppose we have a graph of the standard accumulated dry mass, *M*, plotted against time, *T*, since peat growth began. In general this curve rises rapidly but then turns over and rises ever less steeply. Any slope in this space will be *M*/*T* and therefore have dimensions [M L^{-2} T^{-1}] i.e slopes on this graph are standard rates.

When peat began to accumulate there was nothing to decay so the rate of accumulation was the same as the standard rate of addition of dry mass to the catotelm i.e. what survives passage through the acrotelm. Call it *p*, for productivity [M L^{-2} T^{-1}]. Implicit in this section is that we are considering timescales of centuries and millennia. On such scales *p* may be approximately constant. That is not to say that it does not fluctuate greatly during a single day and with the seasons.

Now suppose that several thousand years have passed, but *p* remains the same. The peat is decaying very slowly while new plant matter is added at rate *p* to the top of the catotelm from the base of the acrotelm. To get the true rate of peat accumulation now we must subtract the rate of loss from *p*. The result, graphically, is the slope of the *M vs T* graph at the present time, i.e. d*M*/d*T*. To evaluate this algebraically requires assumptions about the decay process (Clymo 1992), but all such models show that this true rate is less than *p*, and that it diminishes still further as time passes. In the context of carbon accumulation this rate has been called TRACA, the true rate of carbon accumulation.

The third sort of rate is used when the standard dry mass and a single basal date are known. This allows the long term average (or apparent) rate of accumulation to be calculated. In the context of carbon accumulation this rate is known as LARCA or LORCA. On the *M vs T* plot LARCA is the chord between the origin and the present.

In summary, when a peatland starts to grow all three rates are the same. But as time passes, even if *p* remains the same, the other two decrease. If *p* is constant then TRACA < LARCA < *p*.

Models of accumulation

The rate of accumulation of dry mass in the catotelm is the standard rate of addition (*p*) minus the total losses at all depths. In the simplest model *p* is assumed constant and the rate of decay is assumed to be a constant proportion, α, of what has accumulated so far (Clymo 1984). The relation between standard accumulated dry mass and time is that described above: it rises steeply at first then levels off toward an asymptote at $M = p/\alpha$. Many, but not all, peatlands where there is sufficient evidence to test the fit to this model do have a gently convex curve (concave if plotted as standard dry mass below the surface against age of the peat). The slope at the origin is *p* and the convexity (or concavity) measures α. But this is not the only possible model. Clymo (1992) shows that models in which the proportional rate of decay of a mass of peat decreases as decay proceeds (and the residue becomes more refractory) fit the data as well as the constant rate model. The value of *M* in these models does not reach an asymptotic upper limit but continues indefinitely upward, though at an ever decreasing rate. The fitted values of *p* differ, though the fits are equally good. At present we do not know which value of *p* to believe. Until we do it is not possible to use this long term approach to make an independent comparison with the flux based snapshots. When that does become possible we will be able to see whether there have been recent changes.

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