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SPATIAL VARIABILITY OF BOMB ^{14}C IN AN UPLAND PEAT BOG

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ABSTRACT. As part of a study investigating the carbon balance of a blanket bog, we made an assessment of the spatial variation of radiocarbon concentrations in the surface layers of a small area of peatland in the north of England. The peat depth at which bomb-^{14}C content was the highest varied considerably between cores sampled from across the site. At several sampling locations, ^{14}C levels >100% Modern were confined to the surface 8 cm, whereas bomb ^{14}C was evident at 1 site, located only meters away, to a depth of at least 12–16 cm. Using the layer where ^{14}C levels first exceeded 100% Modern as a chronological reference layer, we estimated the carbon accumulation rate over the last 50 yr for the surface peat at each site (range ~20 to ~125 g C m^2 yr^{-1}). Our results show that although carbon accumulation over the last 50 yr was similar across the site, variation in the depth to which bomb ^{14}C was evident implied considerable variation in the vertical peat growth rate.

INTRODUCTION

Globally, soils contain ~1600 Gt of carbon, more than twice the amount currently resident in the atmosphere (Schimel 1995). Despite covering only ~3% of the land surface, peatlands (subarctic and boreal) contain ~455 Gt of carbon and are one of the largest and most important stocks of soil carbon on Earth (Gorham 1991). There is considerable potential for global and local changes in climate, N deposition rates, CO_2 concentrations, invasive species, and land use to alter the net carbon balance of these ecosystems. This could result in the net transfer of large quantities of carbon to the atmosphere, thus contributing further to the current atmospheric CO_2 loading (Houghton et al. 2001). Indeed, it has been suggested that in the UK, organic soils, including peatlands, have already lost as much as 10% C in the past 30 yr (Bellamy et al. 2005). The study of peatland carbon stocks and fluxes is therefore necessary to determine whether they are sequestering or releasing carbon. One of the biggest challenges in terrestrial carbon cycle research is to source and partition net carbon fluxes. Methods are many and varied and have been reviewed in detail by Hanson et al. (2000). Natural abundance isotopic (^{13}C and ^{14}C) techniques, in particular, offer a useful, non-intrusive means of tracing carbon flow through ecosystems.

Thermonuclear weapons testing during the 1950s and 1960s resulted in a rapid injection of radiocarbon to the atmosphere, almost doubling the natural ^{14}C abundance. The incorporation of bomb ^{14}C via photosynthesis into the Earth's biosphere has provided a valuable tool for studies of carbon cycling in the atmosphere and in terrestrial and marine environments (Levin and Hesshaimer 2000). Researchers have used ^{14}C to estimate soil organic matter turnover in forests (Harkness and Harrison 1989), grasslands (Masiello et al. 2004), tropical soils (Trumbore 1993), agricultural soils (Jenkinson et al. 1992), and in peatlands (Borren et al. 2004). More recently, the carbon isotopic signature of ecosystem respiration has been used to investigate the CO_2 "sink-source" function of soils (Wang et al. 2000; Dioumaeva et al. 2002; Schuur and Trumbore 2006; Trumbore et al. 2006). However, one of the issues with using natural abundance or bomb-^{14}C tracers in soils is the spatial variability attributable to differences in both biotic (plant productivity, decomposition rates, inputs, and community structure) and abiotic factors (hydrology, climate, chemical, and physical parameters).

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Few studies of peatland carbon dynamics have investigated the spatial variation in ^{14}C content and accumulation rates in surface organic matter layers (Charman et al. 1999), largely due to the prohibitive costs of ^{14}C analysis. In paleoecological studies, it is common for ^{14}C values of material obtained from a single peat core to be taken as representative of the entire peatland; Barber et al. (1998) provide one of the few investigations of spatial variability in peat paleoecological records. However, peat growth (i.e. rate of depth increase) and carbon accumulation rates in peat are known to be greatly affected by a range of biotic and abiotic factors, which themselves may vary over short distances and in time (Clymo et al. 1998).

Here, we present the results of an investigation into spatial variation in the ^{14}C concentration of peat surface layers in an upland ombrotrophic bog. We also report estimated rates of recent carbon accumulation derived from these ^{14}C values.

METHODS

Site Description

Moor House National Nature Reserve (UK National Grid ref. NY70 30) was chosen as the study site, being an area of blanket bog moorland considered to be representative of British upland terrain. It is an area of high carbon storage (Garnett et al. 2001) and has been intensively studied in the past (http://www.ecn.ac.uk/Publications.htm). Peat cores were taken from an experimental site within the Reserve, Hard Hill (NY735 335), an area characterized by gentle slopes with typical blanket bog/moorland vegetation. This particular site was chosen because plant species cover was homogeneous and because the site had not previously been used for experimental work (although the site has been and continues to be subject to grazing). Plant community composition at this site included *Sphagnum* spp., *Calluna vulgaris*, and *Eriophorum vaginatum*. The average peat depth at this site was approximately 2 m.

Peat Sampling

Samples were taken in September 2005 from a carbon dynamics experiment set up in September 2003 that included plant free plots (SOIL) and vegetated plots (VEG). These treatments were established to examine differences in soil carbon cycling attributable to the presence of vegetation. Plots were circular with a diameter of 30 cm (0.071 m^2 area) and each replicated plot was separated by between 2 to 5 m. A total of 6 plots were investigated in the present study, 3 VEG and 3 SOIL, all of which were contained within an area of 57.5 m^2 (5.0 × 11.5 m). The vegetation in the SOIL plots was removed using secateurs, cutting as close to the peat surface as possible. Roots were left in place in order to minimize soil disturbance. After vegetation removal, the SOIL plots were covered with a black cloth that allowed rain to percolate through but minimal light penetration. The plots were regularly tended and any new vegetation growth was removed. Peat samples were taken using a stainless steel corer (4.7 × 4.9 × 100 cm) designed to minimize compaction (Cuttle and Malcolm 1979). The corer was carefully removed from the peat profile, and the top 16 cm of each core was cut into 4-cm increments. Samples were placed into labeled plastic bags and kept in a cool box until arrival at the NERC Radiocarbon Laboratory. Samples were stored at 4 °C until required for analysis.

Determination of Total Carbon and ^{14}C Content

Each 4-cm increment of peat was placed in an evaporation dish, weighed, and dried at 85 °C to a constant weight. Samples were homogenized by grinding to a powder using a pestle and mortar. Subsamples were combusted with pure oxygen in a high-pressure combustion bomb. The resulting gas was cryogenically purified on a vacuum line until only CO_2 remained, and the total volume recovered was measured (allowing % carbon of the peat to be determined). An aliquot of CO_2 from each sample was prepared as a graphite target via an Fe/Zn reduction reaction (Slota et al. 1987) and analyzed for ^{14}C by accelerator mass spectrometry (AMS) using the 5MV tandem accelerator (Xu et al. 2004) at the AMS facility, Scottish Universities Environmental Research Centre (SUERC), East Kilbride, United Kingdom. A further CO_2 subsample was taken for δ^{13}C measurement by an isotope ratio mass spectrometer (IRMS) (dual inlet, VG Optima, Micromass, United Kingdom). All concentrations for ^{13}C are reported using the delta notation with ^{13}C/^{12}C variations relative to the international standard Vienna Pee Dee belemnite (VPDB) (Craig 1957), as described by the following equation:

$$\delta^{13}C\ (‰) = \frac{(^{13}C/^{12}C)_{Sample} - (^{13}C/^{12}C)_{VPDB}}{(^{13}C/^{12}C)_{VPDB}} \times 1000$$

^{14}C data are expressed as % Modern with samples having been normalized to a δ^{13}C of –25‰ (Stuiver and Polach 1977).

Rates of peat accumulation were calculated for the different cores using the depth in the profiles where levels of ^{14}C first exceeded 100% Modern as a chronological reference point. This fixed point represents the deepest layer that contains unequivocal evidence of bomb ^{14}C. Therefore, we considered that peat formed when atmospheric ^{14}C levels first exceeded 100% Modern (~AD 1955) was contained within this 4-cm layer. Annual peat growth rate (cm/yr) was calculated by dividing the depth of the peat slice containing the 100% Modern layer by 50 (number of years for peat growth between AD 1955 and the sampling date). Carbon accumulation rates (g m^{-2} yr^{-1}) were calculated using the same 100% Modern reference layer, dividing the total carbon accumulated (g) above the reference layer by the 50-yr accumulation period. Since a very coarse sampling resolution was used, only maximum and minimum values for both of these rates were calculated. These were based on the range of depth and carbon mass values represented by the 4-cm slices of peat containing the reference layer.

RESULTS

Our study was limited to the top 16 cm of the peat profile. A total of 6 cores were sampled, and ^{14}C analyses were made on each of the 0–4, 4–8, 8–12, and 12–16 cm sections taken from each core (i.e. a total of 24 AMS ^{14}C analyses). Table 1 provides the carbon content (%), bulk density, and carbon isotope results. Carbon content for all samples was around 45–50%, typical for ombrotrophic blanket peat. Bulk density was also typical of upland peats (Clymo 1983) and ranged from ~0.04 to ~0.14 g cm^{-3}, with the lowest values occurring in surface samples. There were no significant differences in either carbon content (%) or bulk density between SOIL and VEG peat cores.

The profiles of ^{14}C content with depth (Figure 1) showed considerable variation between cores, despite their close proximity in the field. ^{14}C concentrations ranged from ~95 to ~130% Modern (Table 1), with evidence of both pre-bomb and post-bomb levels of ^{14}C in all 16-cm depth cores, except for one (post-bomb ^{14}C was present throughout the entire profile of core VEG 3, see Figure 1). In the other peat cores, the lowest ^{14}C concentrations were found in the deepest (12–16 cm) layer.

The range in ^{14}C content of the peat was depth-dependent. For example, the ^{14}C content in the surface layer varied only between ~110 and ~120% Modern, whereas the 4–8 cm layer ranged from ~105 to ~130% Modern. In the deepest layer, ^{14}C content in 5 of the 6 profiles ranged from ~95 to

Table 1 Carbon isotope, bulk density, and % carbon results. VEG = plots with intact vegetation; SOIL = plots cleared of vegetation.

Sample identifier (Core - depth)	Publication code (SUERC-)	Bulk density (g cm^{-3})	% carbon	$\delta^{13}C_{VPDB}$ (‰)	^{14}C % Modern (±1 σ)
VEG 1 - 0–4 cm	9398	0.050	48.9	–29.8	113.48 ± 0.40
VEG 1 - 4–8 cm	9399	0.106	47.8	–28.5	115.05 ± 0.40
VEG 1 - 8–12 cm	9400	0.114	47.1	–25.9	99.50 ± 0.35
VEG 1 - 12–16 cm	9401	0.094	47.7	–26.6	98.42 ± 0.31
VEG 2 - 0–4 cm	8521	0.080	47.5	–28.8	116.50 ± 0.35
VEG 2 - 4–8 cm	8522	0.132	49.4	–27.8	130.42 ± 0.30
VEG 2 - 8–12 cm	8523	0.106	47.6	–27.0	105.75 ± 0.25
VEG 2 - 12–16 cm	8527	0.143	49.2	–26.4	95.62 ± 0.28
VEG 3 - 0–4 cm	9404	0.045	48.0	–30.2	111.74 ± 0.39
VEG 3 - 4–8 cm	9405	0.065	46.7	–28.6	114.98 ± 0.41
VEG 3 - 8–12 cm	9406	0.087	44.6	–26.9	125.80 ± 0.45
VEG 3 - 12–16 cm	9407	0.076	48.1	–28.0	122.15 ± 0.43
SOIL 1 - 0–4 cm	9408	0.086	48.3	–29.2	113.98 ± 0.40
SOIL 1 - 4–8 cm	9409	0.138	49.6	–28.7	109.37 ± 0.33
SOIL 1 - 8–12 cm	9411	0.101	48.4	–27.6	98.61 ± 0.35
SOIL 1 - 12–16 cm	9414	0.107	49.7	–27.7	96.89 ± 0.34
SOIL 2 - 0–4 cm	9415	0.038	46.2	–28.0	118.40 ± 0.38
SOIL 2 - 4–8 cm	9416	0.079	48.3	–26.9	127.35 ± 0.45
SOIL 2 - 8–12 cm	9417	0.095	46.4	–28.3	114.05 ± 0.40
SOIL 2 - 12–16 cm	9418	0.101	47.8	–25.9	95.22 ± 0.33
SOIL 3 - 0–4 cm	8528	0.084	45.2	–28.3	119.68 ± 0.36
SOIL 3 - 4–8 cm	8529	0.109	46.6	–27.2	104.59 ± 0.31
SOIL 3 - 8–12 cm	8531	0.097	46.2	–27.4	96.41 ± 0.29
SOIL 3 - 12–16 cm	8532	0.096	48.9	–27.2	96.66 ± 0.25

~99% Modern, although again, core VEG 3 was distinct, having a ^{14}C concentration of 122% Modern at this depth. There were no obvious differences in the profile of ^{14}C content under the 2 different treatments (VEG and SOIL).

Table 2 presents the calculated values of peat growth rate (annual rate of depth increase in cm/yr) and carbon accumulation rate (g m^{-2} yr^{-1}). Peat growth rate ranged from ~0.08 to 0.24 cm/yr for most sites, although core VEG 3 had an average growth rate of more than 0.32 cm/yr above the reference layer. Due to the coarse 4-cm sampling resolution, the ranges of carbon accumulation rates for each core were large, and the overall range was ~20 to ~125 g C m^{-2} yr^{-1}. There were no significant differences between the 2 treatments for peat growth and carbon accumulation rate as ranges overlapped.

DISCUSSION

We made an assessment of spatial variation of the ^{14}C content in the uppermost layers of peat profiles taken from an ombrotrophic blanket bog located in the north of England. The ^{14}C variation between cores can be explained, in part, by differences in peat growth rates over the period of the bomb-^{14}C spike. At the same time, rapid changes in atmospheric ^{14}C content over the 50-yr period of the bomb spike would have contributed to variation in the ^{14}C content between depth increments. For example, the least variation in ^{14}C content between cores was observed in the surface (0–4 cm)

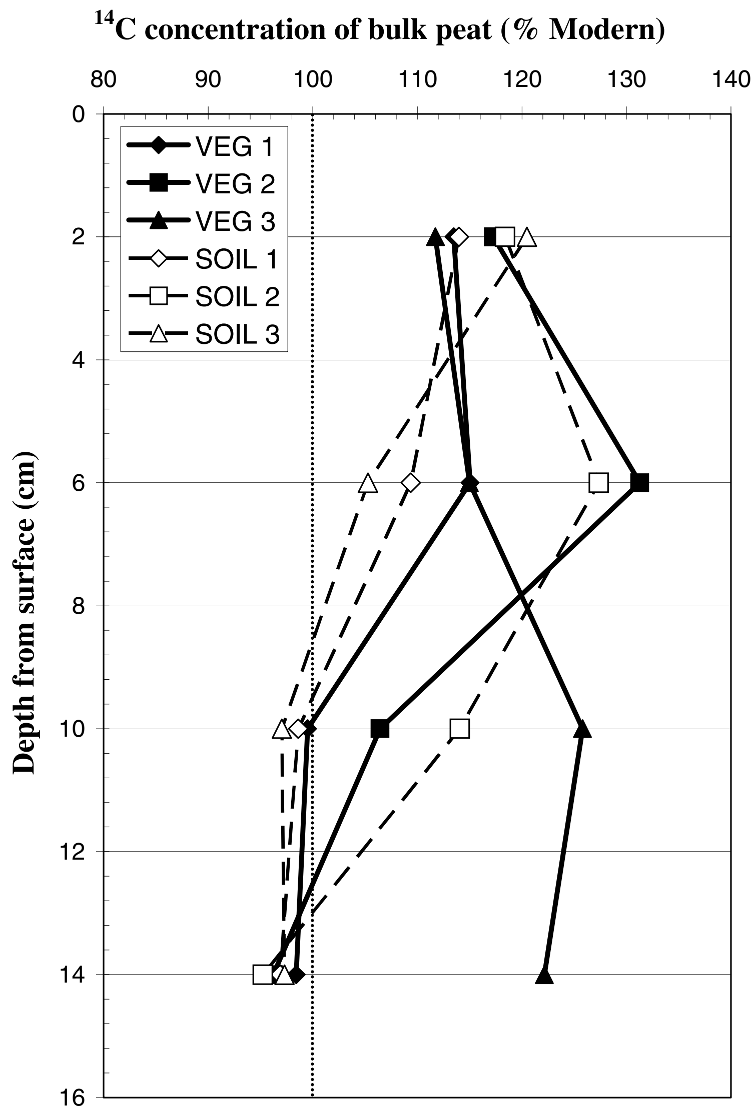

Figure 1 Profiles of ^{14}C concentration in the surface peat at the Hard Hill study site. VEG = plots with intact vegetation; SOIL = plots cleared of vegetation.

layer of peat. This peat represents the most recent carbon accumulation, with vegetation assimilating carbon when atmospheric ^{14}C levels were decreasing relatively slowly, i.e. over the last ~10–20 yr (Levin and Kromer 2004).

Pre-bomb ^{14}C concentrations were evident in the 12–16 cm layer of most of the cores despite the fact that these 4-cm slices of peat could have been accumulating over a considerable time (i.e. several decades). The small variation in ^{14}C content of the 12–16 cm layers is probably attributable to limited variations in the ^{14}C content of the atmosphere during the pre-bomb period. However, samples from the 4–8 and 8–12 cm layers, mainly cover the period when atmospheric bomb-^{14}C levels were highest and undergoing the most rapid changes. Thus, the variation in the 4–8 and 8–12 cm

Table 2 Calculated ranges of peat growth and carbon accumulation rate above the 100% Modern layer (i.e. for the last ~50 yr). VEG = plots with intact vegetation; SOIL = plots cleared of vegetation.

Core identifier	Depth containing the 100% Modern reference layer (cm)	Peat growth rate (cm/yr)	Carbon accumulation rate (g C m^{-2} yr^{-1})
VEG 1	4–8	0.08–0.16	19.6–60.0
VEG 2	8–12	0.16–0.24	82.6–123.0
VEG 3	>16	>0.32	>72.6
SOIL 1	4–8	0.08–0.16	33.2–88.0
SOIL 2	8–12	0.16–0.24	44.6–79.8
SOIL 3	4–8	0.08–0.16	30.4–71.0

layers between cores is likely to be partly due to the layers being comprised of slightly differing contributions of pre-bomb and bomb-peak carbon, as a result of different peat growth rates.

Peat growth rates are clearly an important factor contributing to the differences in the ^{14}C profiles. In particular, core VEG 3 was distinct from the other profiles in that bomb ^{14}C was evident even in the deepest (12–16 cm) layer. We can suggest several explanations for this observation, such as a higher rate of peat growth (i.e. height increase) at this location. Alternatively, if plot VEG 3 had undergone less compaction compared to the other coring locations, then we would expect a deeper penetration of bomb carbon with depth. As this site had been subject to light grazing, the possibility arises that varying degrees of compaction may have occurred and could explain the different pattern in ^{14}C content found in core VEG 3.

Peat bulk density values for VEG 3 were consistently lower at most depths than the other sampling locations (Table 1), suggesting that variation in density may be part of the explanation. This is illustrated in Figure 2, where the ^{14}C content of each profile is plotted against cumulative carbon (from the surface); this plot removes variations caused by differences in bulk density and shows that, in terms of carbon accumulation, the ^{14}C profile of VEG 3 is similar to the other profiles.

The presence of bomb ^{14}C in each of the 6 profiles is evidence that peat accumulation has at least been occurring in the surface layer of this blanket bog over the last 50 yr (although due to decomposition of peat below these layers, it is not possible to state whether the ecosystem still represents a net carbon sink). By using the layer containing the depth where ^{14}C concentrations first exceed 100% Modern as a chronological reference point common to all plots, we estimated recent carbon accumulation at each of the sampling locations. The use of this reference layer has limitations; for example, our samples were not subjected to chemical pretreatment because, from a carbon cycling point of view, we were interested in all carbon fractions that contribute to respiration. However, certain components in peat are known to be mobile, e.g. fulvic acids (Shore et al. 1995), and evidence for transport of modern carbon to depth by *Eriophorum vaginatum* (Kilian et al. 2000) and root channels (Barber et al. 2000) has been demonstrated. Therefore, our assertion that the 100% Modern layer represents ~AD 1955 should be treated with some caution. Despite this, our main aim was to use the 100% Modern reference layer to compare across all our coring points, and therefore, since vegetation cover was relatively homogeneous, it could be assumed that all cores would have been similarly affected by any migration of peat components or introduction of modern carbon to depth.

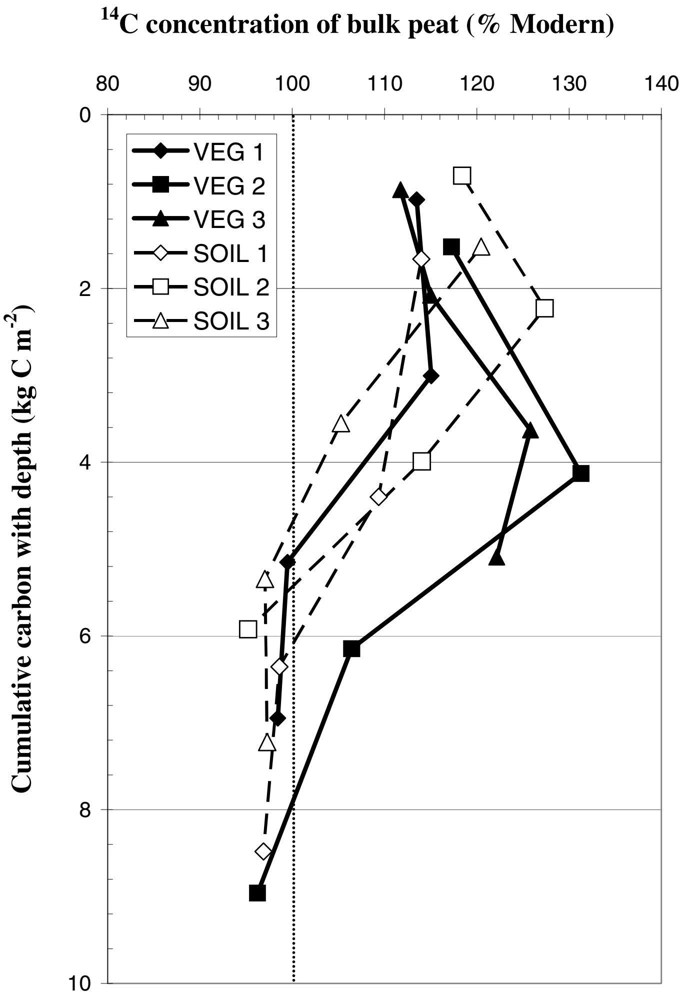

Figure 2 Profiles of cumulative carbon against depth at the Hard Hill study site. VEG = plots with intact vegetation; SOIL = plots cleared of vegetation.

We found no clear differences in the profiles of ^{14}C content or carbon accumulation under the 2 treatments (VEG and SOIL). However, it is notable that the 2 highest carbon accumulation rates were found in the VEG treatment. Since the fastest decay occurs in the first few years following senescence (Clymo et al. 1998), it is possible that the higher carbon accumulation rates in the VEG plots reflects the continued input of new organic matter from plants over the last 2 yr. Due to vegetation removal, no new plant inputs entered the SOIL plots over this period.

Our assessment of the rates of peat growth and carbon accumulation was hindered by the very coarse resolution of our sampling intervals (i.e. 4-cm depth increments). Thus, we only report maximum and minimum estimates for these rates, which in some cases cover a large range (Table 2). However, the approach adopted offered a useful means for the broad assessment of variations in peat growth and carbon accumulation across this small area of blanket bog. It should also be noted that our estimates for peat growth and carbon accumulation rate only cover peat formed over the last ~50 yr, and therefore, since much of the peat is still within the acrotelm and decaying relatively rapidly under aerobic conditions, our values are on average higher than estimates for long-term deep peat accumulation reported elsewhere (Turunen et al. 2002; Borren et al. 2004). Despite these limitations, our results show that there was greater variation in peat growth rates (depth increase) across the site than in rates of carbon accumulation over the last ~50 yr (see Figures 1 and 2).

CONCLUSIONS

The results of this study show that there is considerable variation in ^{14}C content of the 0–16 cm profile of this upland blanket bog (95–130% Modern) with the largest range in variation occurring in the 4–12 cm part of the peat profile. This was attributed to both rapid changes in atmospheric ^{14}C content and differences in peat growth and C accumulation rates. It is therefore important that natural variability, both horizontal and vertical, in bomb-^{14}C concentrations is considered in any assessment of peatland carbon dynamics that uses bomb-^{14}C values as a tracer.

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