POTENTIAL FOR ESTIMATING CARBON FLUXES IN FOREST SOILS USING ^{14}C TECHNIQUES

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ABSTRACT

Three studies explored the potential of the conventional radiocarbon dating procedure combined with the analysis of the degree of incorporation of ^{14}C derived from nuclear weapons testing (^{14}C-bomb) during the early 1960s, for determining carbon turnover in forest soils.

The first study examined the gross annual turnover rate of soil carbon within the tree rooting zone of a mixed deciduous oak/ash/birch woodland (Meathop Wood) situated on an acid brown earth soil overlying carboniferous limestone. The turnover was estimated by dividing the soil carbon content of several soil layers (O + O_f, 0–5, 5–10, 10–15, 15–25, 25–35, and 35–50 cm depths) by their respective mean carbon age (carbon mean residence time) derived from the ^{14}C analyses. The total turnover of carbon, estimated as 3860 kg C/ha/yr, very closely agreed with the estimated total carbon inputs to soil as litter components (leaf litter, twigs, flowers and fruits, herb layer throughfall, and stem flow plus root decay) of 3895 kg C/ha/yr. The latter data were derived from intensive site studies carried out during the International Biological Programme. Close agreement between the estimate for carbon turnover derived from the ^{14}C data and the estimate for the annual total litter input is considered to validate the use of the isotope approach. It is also clear that different components within the litter layer and roots within the mineral soil layers, have different ^{14}C-bomb signatures, thus indicating the potential to determine mean residence times of different forest litter materials within the O-horizon or roots within the mineral soil.

The second case study investigated the effects of birch on carbon dynamics in acidic heather moorland soils. Birch has gained the reputation of being a soil improver and has been shown to increase earthworm numbers, pH and extractable calcium, and mineralisable nitrogen, and significantly decrease the C:N, C:P, and C:K ratios in surface soils. Though these changes may be induced by a number of differing and interacting processes, an increase in the rate of soil organic matter decomposition, through enhanced biological activity, was thought to be a dominant factor. Using a chronosequence of sites from heather moor to 90-year-old birch stands at a single site in Scotland showing characteristic changes in soil properties, ^{14}C measurements were made in 1976 on different soil horizons down to 40 cm depth. These showed a clear pattern of increasing ^{14}C enrichment and the isotope penetration deeper into the soil profile with increasing stand age. These results accord with the hypothesis that there is an increasingly rapid turnover of the moorland soil humus and its partial replacement with younger birch-derived organic matter, with increasing birch stand age up to approximately 40 years.

The potential use of these ^{14}C techniques in research on the dynamics of carbon in upland and high latitude soils containing high amounts of organic matter, in respect to the possible effects of global warming, has been suggested by studies of brown earth soils at four sites in an altitudinal gradient on the Pennines in northern England. Results showed that the soil carbon at the coolest site at 747 m had lower ^{14}C enrichment values than that at the warmest site at 425 m. The sites differed in mean annual temperature by approx. 2°C. Furthermore ^{14}C-bomb, indicating younger contemporary carbon, had penetrated only to c.3 cm at the highest site but had been incorporated to >5 cm at the lowest site. The combined results indicated that soil carbon turnover is much slower at the highest than at the lowest altitude site.

These ^{14}C techniques might be used to partially validate computer models of carbon dynamics in forest ecosystems and at different scales of resolution (process, ecosystem, and landscape) in environmental studies.

Keywords: radiocarbon; ^{14}C-bomb; carbon dynamics; soil improvement; upland grassland; moor; global warming; modelling; *Calluna vulgaris*; *Betula pendula*; *Betula pubescens*.

INTRODUCTION

The fate of inputs of organic matter to soils controls many aspects of forest and other natural ecosystems. These include governing the function and productivity through sustained nutrient cycling, effects on soil properties and retention of elements within the profile, and the amounts of carbon stored within the ecosystem. Recently, two additional and important roles of soil organic matter have been highlighted which are relevant to the current debate on global carbon budgets and to global warming. Firstly, soils may provide an answer to the phenomenon of the "missing sink" for 50 GT of carbon not accounted for in the atmospheric carbon budget. Secondly, global warming "kick started" by industrial activity may lead to increasing carbon release to the atmosphere from organic-rich soils of vast areas of the northern latitudes, e.g., Canada and Siberia.

Inputs to soils of organic matter in litter, dead root systems, and other detritus generally decomposes at a rate dependent on factors such as site temperature and moisture conditions, soil microbial and faunal activity, and the nature of the organic matter itself (Swift *et al.* 1979). Decomposition of these litters generally follows a negative exponential pattern, at least during the early stages of the decomposition processes (Olsen 1963; Berg 1986). A varying proportion of the decomposing litter material enters the mineral layers of the soil profile and is often stabilised by one of a number of processes (Sollins 1992).

Whether research is involved in detailed studies of ecosystem function or changes in carbon fluxes and balances in relation to global warming, knowledge of the residence times and relative proportions of older stable and younger, perhaps more labile, soil organic matter is of key importance. The early rates of decomposition or turnover of leaf litter or even branch material on the soil surface can be directly determined. However, determination of the turnover or flux rate of total O-horizon organic matter or that sequestered within the mineral horizons is technically difficult.

Conventional radiocarbon dating (Libby 1955) can be used to determine the age or mean residence time (MRT) of the older organic matter >150 years, whether this is the total carbon content or a component fraction of the organic matter within the soil. This procedure relies on the assumption of a quasi-constant input of ^{14}C to the atmosphere generated by cosmic radiation and its general incorporation into plant materials via photosynthesis. The rate of decay of the ^{14}C isotope (based on its half-life of 5570 years) and its low concentration (13.5 dpm/g C in living tissues) limits age resolution to >150 years. There are numerous reports containing information on ages of fossil soils and of older organic matter components of contempory soil horizons (Paul *et al.* 1964; Campbell *et al.* 1967a, b; Tamm & Holmen 1967; Scharpenseel 1972; Scharpenseel & Schiffmann 1977; Guillet 1975, 1982).

Much of the organic matter in soils is, however, considerably younger than 150 years. This younger organic matter, as a result of its role in nutrient cycling and its effects on biological, chemical, and physical soil properties, has a major influence on the functioning of forest ecosystems. It is therefore important to be able to determine the MRT of this younger soil organic matter. As was first recognised by Jenkinson (1963), the pulse of ^{14}C introduced into the atmosphere by nuclear weapons testing in the late 1950s and early 1960s offers potential for studying the turnover of younger soil organic matter. This pulse of "^{14}C-bomb" in the atmosphere, resulting from the interaction of neutrons on the atmospheric nitrogen, is of a transient nature as the isotope gradually becomes absorbed into oceans (Broecker & Olsen 1960) and incorporated into the terrestrial organic cycle. Unlike the naturally generated ^{14}C utilised in radiocarbon dating, the nuclear weapons-derived ^{14}C incorporation into the terrestrial organic matter cycle via photosynthesis is not constant but is declining with time. This offers a unique opportunity for determining MRT of the soil organic matter less than 150 years old. Studies involving the use of "^{14}C-bomb" as a tracer for the input and turnover of organic carbon have been reported for various plant-soil systems (Rafter & Stout 1970; Martel & Paul 1974; Jenkinson & Rayner 1977; O'Brien & Stout 1978; Ladyman & Harkness 1980; Stout & Goh 1980; O'Brien 1984). Much more progress is now possible, however, using sophisticated isotopic techniques, particularly since the advent of analysis by accelerator mass spectrometry which can be performed on comparatively small samples (Trumbore *et al.* 1989).

We have been investigating since 1971 the potential application of both conventional radiocarbon dating and ^{14}C-bomb carbon incorporation for estimating MRT of soil organic matter and producing a carbon turnover budget for a mixed deciduous woodland in northern Britain. These studies (Harkness *et al.* 1986, 1991; Harrison *et al.* 1990) will briefly be described here, together with an outline of other ecological applications which the Institute of Terrestrial Ecology and the Natural Environment Research Council Radiocarbon Laboratory have currently under way. Finally, the potential of these techniques in studies of forest carbon dynamics and carbon sequestration in soils will be addressed.

CARBON DYNAMICS IN A DECIDUOUS WOODLAND—MEATHOP WOOD

Early studies were concentrated on a mixed-deciduous oak/ash/birch woodland, Meathop Wood, Cumbria, which was the UK woodland studied under the International Biological Programme (IBP) and for which there is available a large amount of supporting tree production and soil data. The soil is an acid brown earth derived mainly from Silurian slates and shales, overlying carboniferous limestone. Details of the woodland have been given elsewhere (Harrison *et al.* 1990). The woodland has been coppiced at approximately 15-year intervals for at least 300 years (Satchell 1984). The surface O-horizon and mineral soil, mainly down to 15 cm depth (the maximum likely depth of ^{14}C-bomb penetration), have been sampled at intervals since 1973, but some soil samples for years 1961, 1969, and 1970 were available from earlier IBP studies. Replicate random samplings taken in this woodland and in another in the southern Lake District showed that spatial variability in isotopic enrichment is low. Soil sampling, preparation, and analytical procedures have been detailed elsewhere (Harkness *et al.* 1986; Harrison *et al.* 1990).

The results of isotopic analysis have shown that surface organic and the 0–5 cm mineral soil layers, in particular, have become significantly "labelled" by the ^{14}C-bomb carbon. The enrichment of the O and O_f layers has been declining since 1973, whilst that of the 0–5 cm mineral layer has been increasing until approx. 1980 but now is in decline. The enrichment of the 5–10 and 10–15 cm layers is showing a slow increase (Fig. 1). Soils below 15 cm contained little ^{14}C derived from the nuclear weapons. The penetration of the soil organic matter by the ^{14}C-bomb is slow but gradual, progressing from the litter input at the soil surface down the profile.

Using a simple theoretical model, based on the concept of proportional replacement of soil carbon (i.e., an MRT of 10 years implies that 10% of the soil carbon is replaced each year), and an assumption that the woodland ecosystem is in quasi-equilibrium, the changes in ^{14}C-bomb with time have been converted into approximate MRT for the various soil depths. Modelled changes in ^{14}C-bomb for constant MRT of 2, 10, 50, and 100 years have been superimposed on the enrichment data for Meathop Wood (Fig. 1). The declining ^{14}C-bomb enrichment values for the O or litter layer "fit" almost precisely the 2-year modelled curve, implying this layer has an MRT of 2 years. Those for the O_f layer, also declining with time, approximate the 10-year MRT curve, and so on (Harkness *et al.* 1986; Harrison *et al.* 1990). Together with data on the amounts of carbon present in each soil layer, it is possible to develop a carbon flux budget for the woodland (Table 1). The total annual turnover of carbon in the soil is approximately 3860 kg/ha/yr. This amount closely approximates the estimated inputs of 3895 kg/ha/yr for organic carbon measured for this woodland during the IBP studies (Table 2). Similarly close agreements have been found for the estimated annual rates of nitrogen and phosphorus mineralisation from the pools of organically bound nitrogen and phosphorus within the soil profile and the estimated annual uptake of nitrogen and phosphorus by the trees and herb layer vegetation of the woodland (Harrison *et al.* 1990).

Thus we were able to "translate" ^{14}C-bomb enrichment data into MRT for organic carbon in different soil layers to provide an estimate of the total carbon, nitrogen, and phosphorus released annually within the soil profile for the woodland and actually "calibrate" the estimates by a suite of entirely different measurements. We consider that this validates the overall approach of the research.

In addition to examining the turnover of the total organic matter in the soil system, it is possible to differentiate between different organic matter components. Different components within the litter layer have different "mean ages" as indicated by their ^{14}C-bomb signatures (Table 3). Though only a few components have been analysed, it is clear that there is the

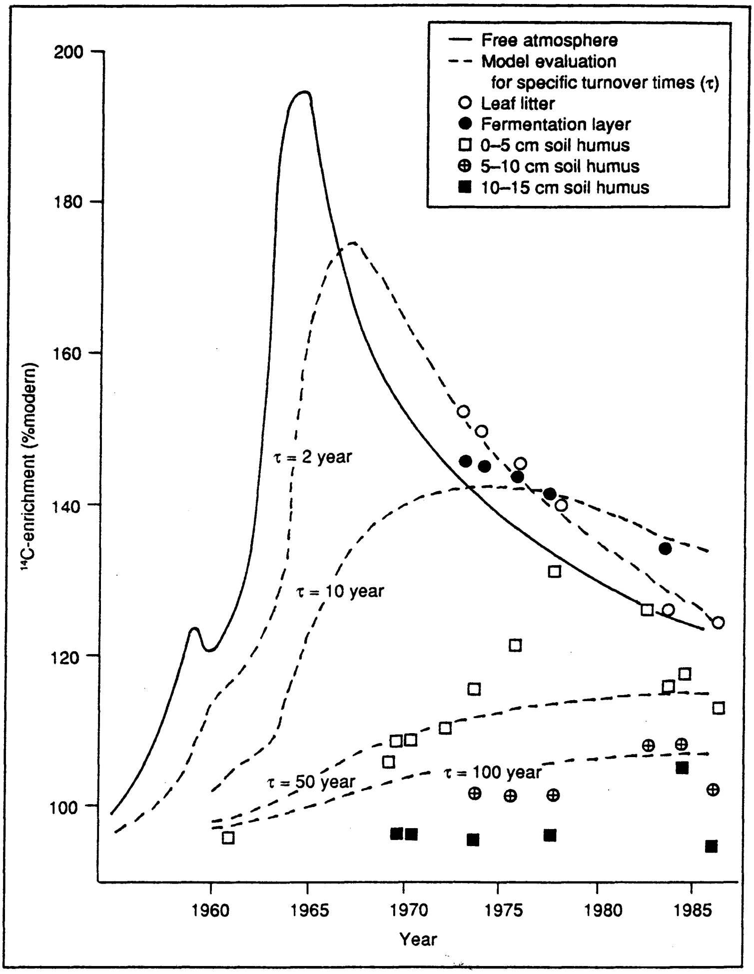

FIG. 1–Comparison of measured and modelled ^{14}C enrichment values
The fermentation or F-layer is defined as "the partly decomposed or comminuted litter, remaining from earlier years, in which some of the original plant structures are visible to the naked eye" (Avery 1980).

TABLE 1–Carbon content, estimated carbon mean residence times (MRT), and annual carbon flux from the rooting zone of the Meathop Wood soil profile.

Depth (cm)	Carbon content (kg/ha)	MRT (yr)	Carbon flux (kg/ha/yr)
O + O_f	4 650	2	2325
0–5	18 030	18	1001
5–10	14 200	40	355
10–15	11 990	100	120
15–25	15 270	500	30
25–35	10 100	600	17
35–50	7 280	600	12
Total			3860

TABLE 2–Estimated carbon inputs to soil as litter components for Meathop Wood.

Litter component	Carbon input (kg/ha)
Tree and shrub leaf*	1620
Branches and twigs*	640
Flowers and fruits*	80
Herb layer (above and below ground)†	330
Throughfall and stemflow‡	230
Root decay§	995
Total	3895

* from Sykes & Bunce (1970)
† Meathop database, and Taylor (1980)
‡ Meathop database
§ Using the estimates for the mean dead root biomass and the average monthly decay rate, derived from direct field measurements (J.M.Sykes pers.comm.). Root exudates probably account for <10 kg/ha/yr (Smith 1976)

TABLE 3–Measured ^{14}C concentrations in leaf litter, twig, branch, and fine undecomposed fragments sampled from Meathop Wood, spring 1984

Sample description		^{14}C enrichment (% modern ±1.0)	
Leaf litter (O_l)		126.0	
Twig material	(2–5 mm diam.)	126.2	
Twig material	(5–10 mm diam.)	131.7	
Branch material	(10–20 mm diam.)	152.2	
Branch material	(20–50 mm diam.)	117.9	
Soil fragments*	(0–5 cm depth)	126.5	(117.0)†
Soil fragments	(5–10 cm depth)	113.5	(109.0)
Soil fragments	(10–15 cm depth)	110.0	(105.0)

* Organic fragments including fine rootlet material separated by flotation prior to analysis of soil "humus".
† Value for the amorphous "humus" of the same soil sample

potential using ^{14}C to determine the mean residence times of different forest litter materials within the O horizon.

EFFECTS OF BIRCH GROWTH ON CARBON DYNAMICS IN HEATHER MOORLAND

Birch has gained the reputation of being a soil-improving species (Dimbleby 1952; Gardiner 1968). In a series of field studies in northern Britain, Miles & Young (1980) have shown that birch (*Betula pendula* Roth. and *B. pubescens* Ehrh.) is able to induce significant changes in acidic heather moorland soils. Over a period of 90 years prior to its own scenescence, the birch induces vegetation changes including the gradual death of the heather (*Calluna vulgaris* (L.) Hull) and its replacement by *Deschampsia flexuosa* (L.) Trin., *Vaccinium myrtillus* (L.), and grasses characteristic of woodlands and grasslands. These vegetation changes are symptomatic of soil changes taking place. Main soil changes in the top 15 cm of the soil profile are:

(i) Increases in earthworm numbers from 1 up to 127 per square metre
(ii) The conversion of old *Calluna* mor humus to mull-like humus
(iii) Increases in pH from 3.8 to 4.9 and a three-fold rise in extractable calcium in surface layers
(iv) Increases in the potential rates of cellulose decomposition both in the surface soil and down the profile to 20 cm depth
(v) Increases in the mineralisable nitrogen from c.0 to 45 mg/dm^3/week, and
(vi) Significant decreases in the C:N, C:P, and C:K ratios.

Though these changes are probably induced by a number of differing and interacting processes, an increase in the rate of soil organic matter decomposition through enhanced biological activity may be a dominant factor. Changes in the nature of the surface soil organic matter, increases in the potential to decompose vertically buried cotton strips (Latter & Howson 1977), and increases in soil faunal activity point to this.

Using a chronosequence of sites from heather moor to 90-year-old birch stands at a single site at Tulchan, Scotland, showing the characteristic changes in vegetation and soil properties, ^{14}C enrichment measurements were made in 1976 on different horizons of the soil profiles down to 40 cm depth (Ladyman & Harkness 1980; Ladyman 1982). There was a pattern of increasing ^{14}C enrichment, with the isotope penetrating deeper into the soil profile with increasing birch stand age to approximately 40 years and older (Fig. 2). These results accord with the hypothesis that there is an increasingly rapid turnover of the moorland soil humus and a partial replacement with younger birch-derived organic matter with the age of the birch stand.

Conversion of the ^{14}C enrichment data into MRT and mean annual carbon flux rates in this earlier heather moor study is not yet possible without more complex modelling than that used for the Meathop Wood study. There are several reasons for this situation. Firstly, there are ^{14}C data only for 1976, but there need to be data over a wider span of time. Secondly, the ecosystems being studied are in a state of slow change rather than being stable and at equilibrium with the environment. Nevertheless, two points can be made. The increasing amounts of ^{14}C within the uppermost 20–30 cm of the soil profiles with increasing age of the birch stands indicate increasing rates of organic matter turnover. The results support the concept that birch colonisation of upland moorland improves the soil properties through enhancing organic matter turnover. Also, the greatest change in ^{14}C enrichment occurs in the period 28–40 years at the time when there is the main change from mor-like to mull-like conditions in the profile. For further isotopic details and interpretation, *see* Ladyman & Harkness (1980).

After 20–30 years' afforestation of upland areas of the UK, trees of different species (i.e., Norway spruce (*Picea abies* (L.) Karst), Sitka spruce (*P. sitchensis* (Bong.) Carr.), alder (*Alnus* spp.), and pine (*Pinus sylvestris* L.)) may also be influencing the nature and turnover of organic matter, as indicated by ^{14}C enrichment data (Ogden 1986; Harkness & Harrison 1989; Brown 1992). However, the effects may be less pronounced than with birch and may be elucidated only by examination of soil carbon fractions. Though the changes induced by other tree species appear, at this preliminary stage in the studies, to be relatively minor, the conclusions could be changed after acquisition of additional ^{14}C enrichment data and the application of more suitable fractionation techniques, such as those reliant on physical (e.g.,

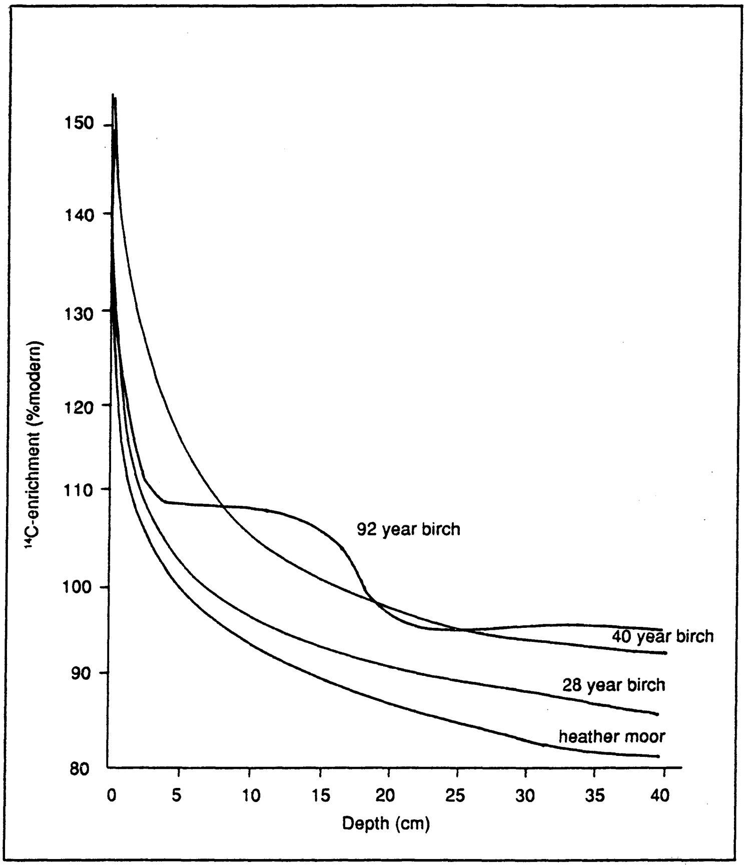

FIG. 2– Changes in radiocarbon enrichment induced by birch colonisation on heather moor soil at Tulchan—measurements 1976 (source: Ladyman 1982)

Oades *et al.* 1987) rather than chemical methods. Small changes in the long-term carbon balance in soils under forestry may nonetheless be significant in terms of the global carbon budget, because of the large geographical areas committed to forestry.

USE IN DETERMINING EFFECTS OF FORESTRY AND CLIMATE ON CARBON DYNAMICS IN UPLAND ENVIRONMENTS

The role of forestry, particularly in respect to the potential of trees for carbon sequestration in timber and soil, has become a major component in the debate on the global carbon budget. Though forests may be important, the global warming effect itself will also have a major impact on the potential transfers of carbon as carbon dioxide from soil to the atmosphere. As indicated earlier in this paper, large areas of more northern latitudes have sequestered large amounts of carbon in their organic soils (Weetman 1992). If the release of carbon dioxide from these sources is enhanced by rising temperatures associated with global warming, this could have a "knock-on" effect on the global warming process. The main question to address is whether or not increasing the area planted in forestry in order to increase sequestered carbon can, in signifcant amounts, offset carbon released to the atmosphere from these soils through global warming. It has been suggested that the amounts of carbon sequestered by afforestation may be quite insignificant compared to the impacts of global warming (Weetman 1992).

In Britain, many upland soils (particularly peats, peaty gleys, and peaty podsols) have stored large amounts of carbon. Such soil types are commonly afforested with Sitka spruce and/or lodgepole pine (*Pinus contorta* Loudon). The processes of site preparation and planting of these exotic forests undoubtedly have an impact on the "native" organic matter and the dynamics of its carbon. How much change in carbon content and its rate of turnover is brought about in upland soils by afforestation is still a matter for research.

We have however begun to apply the ^{14}C-bomb carbon techniques to the study of the effects of climate on the turnover of organic matter in these upland soils. This is being done by exploiting the different climatic conditions on an altitudinal gradient on the northern Pennines. A series of four grassland sites on brown earth soils, ranging from 425 to 747 m a.s.l. and differing by about 2°C in mean annual air and soil temperature (K.Taylor, pers. comm.) have been investigated. These soils, though having relatively low organic carbon contents, were selected initially as (i) this soil type is similar to that of Meathop Wood on which the ^{14}C techniques have been successfully demonstrated, and (ii) the sward productivity and nutrient cycling of these sites have already been studied for some years (Harrison *et al.* 1991). Early results (Fig. 3) show that differential incorporation of ^{14}C-bomb into the surface mineral soil organic matter has occurred, with lowest ^{14}C enrichment values at the highest site which is coolest and wettest. At this highest site, the ^{14}C-bomb has become incorporated to a depth of only 3 cm, with a rapid decrease in ^{14}C with each successive 1-cm layer, whilst at the lowest altitude site ^{14}C incorporation has occurred to >5 cm, with relatively little decline with each 1-cm layer down to 5 cm depth. The results indicate that the organic carbon is older and less rapidly turning over at the highest altitude site than at the lowest. The mean annual turnover rates of the total soil carbon pool for each of the four altitudinal sites using the same protocol as used for the Meathop Wood study descibed above, have yet to be computed, but these results show the techniques are clearly able to detect effects of climatic changes of the magnitude predicted for global warming on carbon dynamics.

It may therefore be possible to use the ^{14}C techniques to examine the impacts of both forestry and global warming on the dynamics of carbon sequestered in soils.

USE OF ^{14}C DATA IN THE VALIDATION OF COMPUTER MODELS

In attempts to predict long-term trends in carbon budgets, many computer models have been developed to cover a varied range of geographical and time scales. These models are developed theoretically utilising a mixture of well-defined and generalised relationships between parameters combined with the "best available knowledge". Many models are developed until the outputs accord with what seems reasonable, but with no means of real validation possible. For models which integrate soil input-output processes and soil carbon stores with vegetation productivity, particularly over a long timespan, partial validation of the model output might be possible using ^{14}C and radiocarbon dating methods.

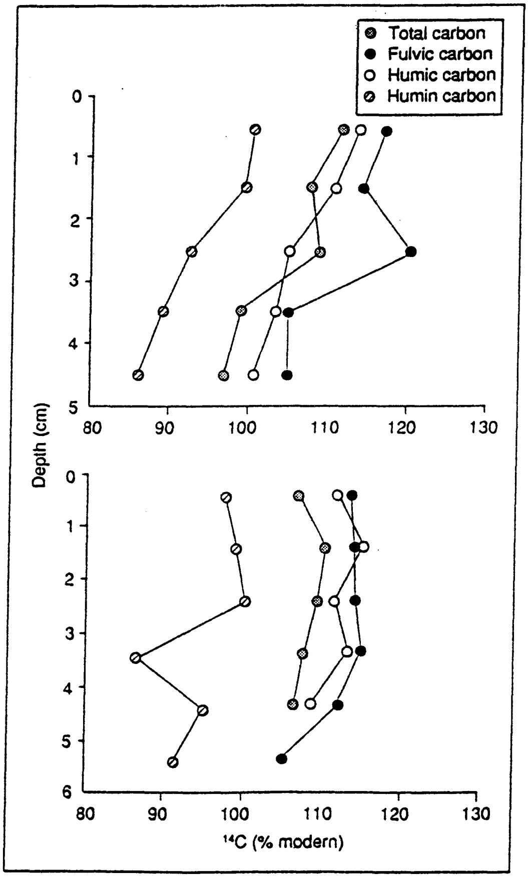

FIG. 3–^{14}C enrichment of total carbon and humus fractions in the 0–5 cm soil layer of grassland sites at two altitudes on the Pennines.
Top: Knock Fell, 747 m
Bottom: Low Cairn, 425 m

Jenkinson (1990) has developed a computer model to predict changes in soil organic matter contents over 140–160 years for a range of organic matter inputs in several of the Rothamsted long-term experiments. The inputs that generated the best fit to soil organic carbon contents measured since the inception of the experiments, also generated accurate estimates of the ^{14}C-bomb carbon incorporation (Jenkinson *et al.* 1992). These ^{14}C measurements, therefore, can be regarded as providing a partial validation of the model and its construction. It has been proposed (Jenkinson *et al.* 1992) that the model could be used "in reverse" to predict the net primary production and organic matter input to the soil under steady-state conditions, given knowledge of crop removal from site, how much organic matter is in a soil, its ^{14}C-bomb/radiocarbon signature, the history of the soil, its texture, and the prevailing climate.

Other modellers could emulate this example and make use of the latent potential of the isotopic technique. It must, however, be emphasised that ^{14}C enrichment values need to be measured for a site over a span of several years, as with the Meathop Wood study.

BROADER ASPECTS OF THE POTENTIAL OF THE ^{14}C-BOMB TECHNIQUE IN FORESTRY AND GLOBAL CARBON BUDGET STUDIES

There has been considerable discussion, during the debate on global climate change, about the role of forests in sequestering carbon. As soils in many areas of the globe, particularly in the northern latitudes, may contain far more carbon than in the total above-ground biomass of mature forests, it is just as essential to understand the role of soils in the transfers of carbon to and from the atmosphere, as it is to understand the role of the tree component of the forest. In understanding the role of soils in this context, it is necessary to examine soils at three different interconnected scales, from the detailed process level, through the ecosystem level, to the landscape level.

The ^{14}C-bomb/radiocarbon technique can be used at each of these levels. At the detailed process level it can be utilised to investigate the age and dynamics of soil fractions. This is the area which has received most attention and on which most of the ^{14}C research has been published so far. Two studies, the Meathop and Tulchan, have been presented earlier in this paper, giving details of how the technique can be used at the ecosystem level. Both indicate the potential of the technique to distinguish "young" from "old" organic matter and to detect differential effects of tree species on the transfer of O-horizon litter material into the mineral horizons. Lastly, our present studies on the potential effects of climate on soil organic matter illustrate an application at the landcape level.

Whatever level the application, however, it is essential to consider carefully the sampling strategy used, for this will constrain, in both a positive way and a negative way, the possible interpretations of the data obtained. It is important, for example, not to take too large or deep a series of samples, which results in a "dilution" of the ^{14}C-bomb incorporated into an upper narrow band within the total carbon of the whole sample, causing a loss in sensitivity. As in any other soil study, it is still necessary to investigate "within sample-between sample" or "within site-between site" variability patterns, which may tend to be easily dispensed with because of costs. Finally, as the pulse of ^{14}C-bomb is transient and the ^{14}C specific activity in the atmospheric carbon dioxide is changing with time, so the ^{14}C incorporated into soil via plant photosynthate will also vary with time. Hence, as shown by the Meathop study, ^{14}C enrichment of organic matter in a surface soil layer will change with time, even though the organic matter may be turning over at a constant rate. Applications for determining MRT will therefore require variations in ^{14}C enrichment with time to be taken into account.

Now that the AMS technology has been developed, smaller samples can be analysed more quickly and with less manpower input per sample, thus giving potentially an overall saving in cost per sample compared with radiometric measurements. There are, therefore, real opportunities to examine soil carbon dynamics in a wider range of experimental situations than was realistically possible before, particularly if combined with a modelling approach.

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