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THE INFLUENCE OF AFFORESTATION ON UPLAND SOILS: THE USE OF 'BOMB ^{14}C' ENRICHMENT AS A QUANTITATIVE TRACER FOR CHANGES IN ORGANIC STATUS

D D HARKNESS
NERC Radiocarbon Laboratory, East Kilbride, Scotland
and
A F HARRISON
Institute of Terrestrial Ecology, Grange-over-Sands, Cumbria, England

ABSTRACT. A series of soil samples were collected in November 1984 from five stands of Sitka spruce planted at recorded times between 1951 and 1968. Within a comprehensive program of ecologic and biogeochemical analyses, natural ^{14}C measurements on selected organic components of the 0 to 5cm soil horizons serve to quantify progressive changes induced in the organic carbon inventory and relative to that of the original grassland. Points of particular interest are: 1) an enhanced input of fresh organic matter in the years immediately following planting; this, in parallel with a net decrease in the total carbon content of the topsoil; 2) this freshly introduced carbon predominates in the soil profile even after 30 years of afforestation; 3) during the 15- to 30-year growth period, the soil carbon content remains constant but progressive changes occur in its biogeochemical composition and rate of turnover.

INTRODUCTION

There are over 2,000,000ha of forest woodland in the UK, ca 75% of which is used commercially. A government statement (House of Lords Select Committee, 1981) projected an annual planting rate of ca 20,000ha, which would result in afforestation of 12% of the total UK land area by the end of the century. As a consequence of commercial forestry, this expansion is likely to involve the planting of exotic conifers grown mainly in monoculture and on upland tracts previously used as rough pasture. Such soils are commonly characterized by poor internal drainage; significant types are peaty iron pan soils, surface water, and peaty gleys and peats (Pyatt, 1970). The introduction of trees on these soil types usually involves site preparation by plowing and fertilizer application. However, once established, the nutrient requirement of upland forest must be increasingly met by recycling through litterfall and its decomposition (Jorgensen, 1980; Waring & Franklin, 1979). Consequently, the rate of turnover of soil organic matter becomes an important factor in the determination of fertility status where the availability of nitrogen and phosphorous supply controls growth.

The data presented and discussed here were determined as part of a comprehensive study of the effects of various tree species on typical upland soil (Ogden, 1986). They highlight the potential for exploitation of the 'bomb ^{14}C' transient in quantifying the progressive changes induced in soil organic matter status during the initial 30 years of afforestation by Sitka spruce (*Picea sitchensis*).

STUDY SITES

The study is based on a series of Sitka spruce stands within the Gisburn Forest, North Lancashire, England (53°56′N, 2°16′W, Natl Grid Ref SD 750 585). Tree stands had been planted at known dates between 1953 and 1968 on former hill grazing land at ca 280m alt. When sampled, in November 1984, the tree stands provided a frame of soil characteristics representative of the changes induced over a period of up to 31 years' growth.

The parent grassland soil is typified by control plots maintained within the adjacent Gisburn experimental layout (Ogden, 1986). Thompson (1972) described their character as intermediate surface-water gleys and peaty gleys of the Wildox series. Geologically, the region comprises carboniferous grits, sandstones and shales overlain by locally derived clayey drift. Due to these clayey deposits and a relatively high rainfall (ca 1350mm/yr) the natural grassland soils are poorly drained and have a tendency to peat formation. The pH of the 0 – 5cm mineral horizon is close to 4.5; the value which approximately delimits mor and mull formation in northern Europe (Swift, Heal & Anderson, 1979). The predominant vegetation consists of a form of *Festuca/Agrostis* grassland typical of many areas of rough grazing in the UK.

Ground preparation for forestry was by plowing at 1.5m spacing for turf on which the young trees were set out at ca 1.5m^2 spacing. The new stands had been dressed with a single application of phosphate fertilizer and some deeper drainage cut between plots.

PREVIOUS ANALYSES

Ladyman (1982) measured the ^{14}C enrichment in soil samples collected from the Gisburn grassland plots at various times between 1955 and 1981 (Table 1). While the moribund/detrital organic material on the soil surface had ^{14}C values representative of photosynthetic fixation over the previous two years, the carbon in the top 5cm of the soil profile was much older. No significant input from 'bomb ^{14}C' could be detected below 5cm depth even in 1981. However, for the 0 – 5cm soil, the increase in ^{14}C enrichment until 1983 could not be reconciled with the apparent 'pre-bomb' age of ca 1500 years. This evidence suggested a two-component carbon system as proposed by Jenkinson (1977, 1981) and indicated for a deciduous woodland by Harkness, Harrison and Bacon (1986), *ie*, the need to recognize organic components with 'fast' and 'slow' mineralization rates in the total carbon pool. A similar conclusion was reached from ^{14}C measurements of soil under different tree species, planted in 1955, within the Gisburn experimental layout

TABLE 1

Temporal changes in ^{14}C enrichment of grassland control plot; Modern ± 1σ

Colln date	Plant debris on soil surface	Total carbon in 4mm screened soil		
		0–5cm depth	5–10cm depth	10–15cm depth
1955	–	82.6±0.4	81.8±0.4	–
1959	–	84.5±0.6	80.1±0.4	–
1974	–	87.4±0.4	79.3±0.5	–
1977	138.3±0.5	92.0±0.5	80.8±0.6	78.6±0.5
1981	127.1±0.9	98.5±0.8	81.7±0.7	79.3±1.2
1983	127.9±0.5	103.2±1.0	–	–

(Table 2). Clearly, some form of component separation was necessary to resolve the imprint of 'bomb ^{14}C' over the residue of much older carbon even in the surface soil horizons.

TABLE 2

Gisburn experimental plot sampled October 1981

Plot	Plant debris on Soil surface	Total carbon in 4mm screened soil					
		0–5cm depth		5–10cm depth		10–15cm depth	
	^{14}C%Mod±1σ	Wt%C	^{14}C%Mod±1σ	Wt%C	^{14}C%Mod±1σ	Wt%C	^{14}C%Mod±1σ
Grassland control	127.1±0.9	20.1	98.5±0.6	14.4	81.7±0.5	13.9	79.3±0.7
Norway spruce	152.9±0.7	8.9	96.6±0.5	6.3	82.6±0.5	4.7	81.0±0.6
Scots pine	153.3±0.7	9.6	96.7±0.5	6.5	82.4±0.5	5.1	81.2±0.7
Alder	147.2±0.7	8.3	96.4±0.5	5.4	81.3±0.5	6.0	80.0±0.8

TABLE 3

Carbon content and ^{14}C enrichment of defined components in 0–5cm mineral soil of grassland control plot, collected November 1983

Plant debris on (> 1mm)		Amorphous soil (<1mm)				Total carbon (< 4mm)	
		Borax-soluble		Borax-insoluble			
Wt%C	^{14}C%Mod±1σ	Wt%C	^{14}C%Mod±1σ	Wt%C	^{14}C%Mod±1σ	Wt%C	^{14}C%Mod±1σ
2.9	109.3±0.6	3.7	107.6±0.6	12.8	100.6±0.5	19.4	103.2±1.0

Subsequent subdivision of grassland soil (Table 3) indicated that the ca 66% organic carbon impervious to extraction with sodium tetraborate was significantly older than the remaining plant debris and borax-soluble components.

SAMPLING AND ANALYTICAL PROCEDURES

Bulk Sampling. Field collection was by replicate coring (ca 10cm diam) at each site. Two grassland control plots were each cored in duplicate but at the Sitka spruce stands at least six replicates were taken in a random pattern from the relatively flat areas between the relict ridges and troughs (Fig 1). Cores were sectioned in the lab to separate the surface litter and recover the mineral soil in contiguous 5cm depth increments. The soil samples were bulked, air dried at 35°C and screened through a 4mm mesh.

Separation of Organic Components. Carbon fractions in the 4mm screened soils are defined by the procedure described in Figure 2. The use of sodium tetraborate for chemical differentiation is based on the procedure described by Tate (1979), who used borate extraction primarily to recover the smaller molecular-weight organic phosphorous components from soil. We also recognize that alkali solution is more commonly employed for the extraction/

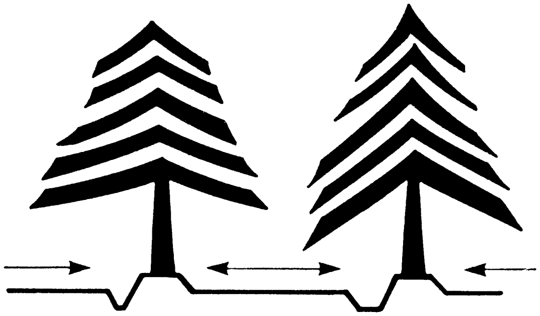

Fig 1. Schematic of the relict microtopography within tree stands as a result of initial plowing. ←→ denotes location of sampling areas.

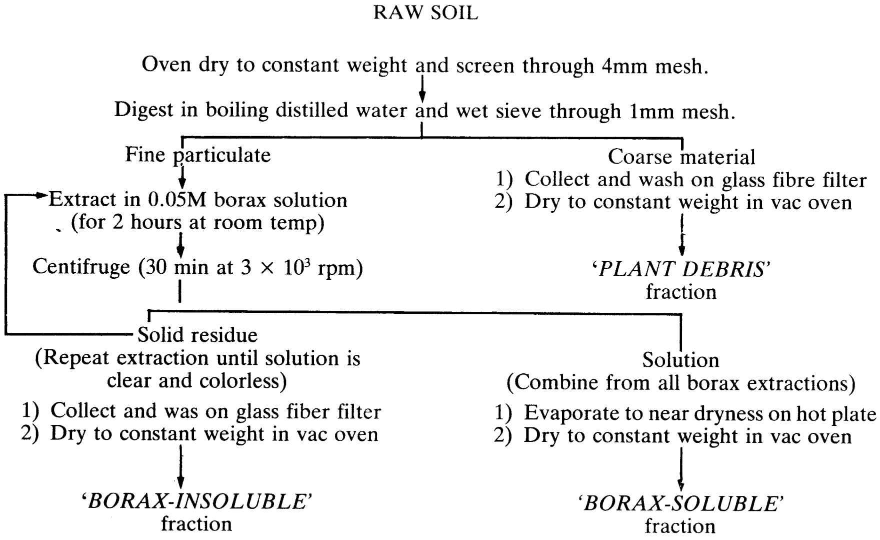

Fig 2. Soil separation procedure. Carried through quantitatively to allow determination of Wt% carbon content of defined fractions and total soil.

differentiation of bulk soil organic matter. We preferred, in this instance, to provide compatibility with extracts prepared for parallel gel filtration and NMR measurements (Ogden, 1986).

Determination of Carbon Content. The relative contribution (Wt%) of each defined component to the total carbon pool was determined via volumetric measurement of the CO_2 produced from quantitative oxidation (high-pressure combustion) of samples being prepared for ^{14}C analysis.

^{14}C Measurement. Natural ^{14}C enrichments were determined by the LS counting procedure routinely employed at the NERC Radiocarbon Laboratory (Harkness & Wilson, 1972). Results are expressed as % Modern (Stuiver & Polach, 1977) and at the ± 1σ level for overall analytical confidence.

Where appropriate, the ^{14}C enrichment value for total carbon was calculated as:

$$\% \, Mod_{(d)} \cdot f_{(d)} + \% \, Mod_{(s)} \cdot f_{(s)} + \% \, Mod_{(i)} \cdot f_{(i)}.$$

where d, s and i denote, respectively, the debris (> 1mm), borax-soluble and borax-insoluble fractions, and f is the corresponding fractional contribution to the total carbon pool.

RESULTS AND DISCUSSION

Data monitored to determine the carbon isotope distribution with time under Sitka spruce plantation are in Table 4.

TABLE 4

Carbon content and ^{14}C enrichment of defined components of Sitka spruce age series stands (0–5cm mineral soil horizon collected November 1984)*

	Plant debris		Amorphous soil (<1mm)				Total carbon	
Year	(> 1mm)		Borax-soluble		Borax-insoluble		(< 4mm)	
planted	Wt%C	$^{14}C\%Mod\pm1\sigma$	Wt%C	$^{14}C\%Mod\pm1\sigma$	Wt%C	$^{14}C\%Mod\pm1\sigma$	Wt%C	$^{14}C\%Mod\pm1\sigma$
1953	1.9	106.5±0.6	4.2	105.5±0.8	5.7	97.3±0.6	11.8	101.7±1.0
1956	0.6	104.9±0.8	3.8	99.5±0.6	7.2	89.9±0.5	11.6	93.7±1.0
1965	1.2	117.1±1.0	2.2	112.3±0.9	8.1	101.0±0.6	11.5	104.8±1.2
1967	2.0	122.8±0.7	2.0	109.8±0.6	7.9	101.1±0.6	11.9	106.3±1.0
1968	1.1	120.7±1.0	2.8	115.2±1.0	8.5	100.6±0.6	12.4	105.7±1.3

*Decomposing plant debris on the soil surface of individual stands at November 1984 recorded ^{14}C enrichment values in the range 131 to 135% Modern, *ie*, indicative of material photosynthesized during the period 1977 – 1980 (a mean age of 5 ± 2 yr).

The ^{14}C enrichment pattern has several informative features, *viz,*

1) As for the contemporaneous grassland (Table 3), the defined organic fractions in the 0 – 5cm soil horizons show a similar trend in ^{14}C concentration, *ie*, organic debris $\geqslant$ borax–soluble carbon > borax-insoluble carbon. This reinforces the concept of discrete "fast" and "slow" components in the organic pool. It is evident, however, from direct comparison of 'pre-' and 'post-bomb' enrichment values, that borax extraction is not wholly effective in isolating the older refractory carbon.

2) Despite an overburden of organic litter with a mean age of only 5 ± 2 yr (based on the prevailing trend in atmospheric ^{14}C concentration), the total carbon of the upper 5cm of these soils remains relatively depleted in 'bomb ^{14}C'. Indeed, differences from the parent grassland and as a function of tree age are marginal. There can be very little input to the soils from litter deposited on their surfaces.

3) As would be expected, the most evident temporal variations are reflected in those components with the faster turnover rate, *ie,* the >1mm

plant debris and borax-soluble carbon. However, it is again noticeable that there is no pronounced input to these components from organic material photosynthesized during the period of 'bomb ^{14}C'-enhanced atmospheric concentrations.

4) The ^{14}C concentrations of the 'faster' components seem more indicative of the atmospheric/vegetational values prevalent at the time of planting, eg, the longest established (pre-bomb) stand records the lowest ^{14}C enrichment. This pattern can result only from a predominant and persistent influence of atmospheric CO_2 transferred to the soil organic pool within a few years of planting. Incorporation of the vegetation growing on the parent grassland seems the obvious source.

5) The stand planted in 1956 records a suite of anomalously low soil-enrichment values. This probably reflects the preparation of an older topsoil by deeper plowing.

The progressive effects of tree growth on the total organic pool are summarized in Figure 3. Salient features here are:

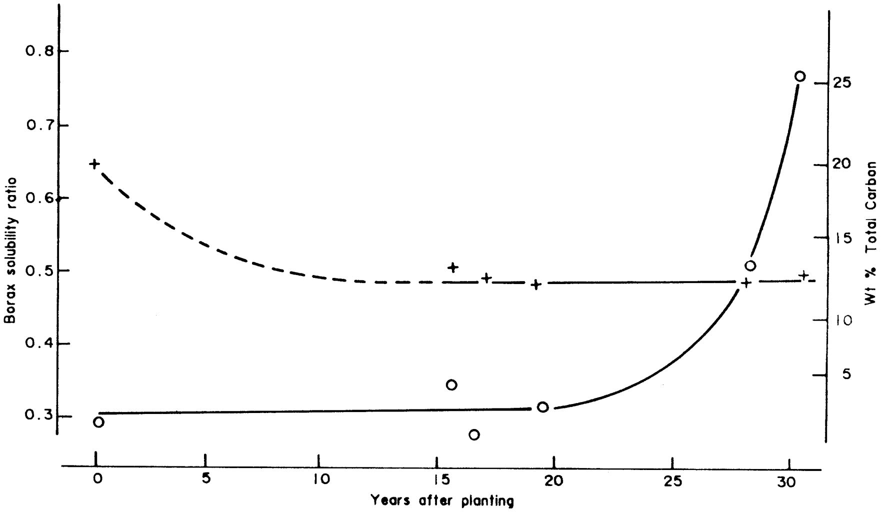

Fig 3. Changes in 0–5cm soil carbon with time under Sitka spruce plantation. + = Wt% of total carbon in 4mm screened soil. o = ratio of borax-soluble to borax-insoluble carbon in amorphous (<1mm screened) soil.

6) The total carbon inventory (as defined by 4mm screening) shows a significant loss during the first 10 – 15 years of tree growth but thereafter appears to attain a state of mass balance. The initial loss may well be a consequence of site preparation rather than a direct effect from the trees. Plowing and site drainage would serve to aerate the topsoil giving an opportunity for enhanced microbial degradation and a consequent net loss of organic matter relative to the original peaty gley.

7) After ca 20 years of tree growth, although the total carbon content and concentration of finely divided plant debris remain effectively constant, there is a marked and ongoing shift in the ratio of borax-soluble to borax-insoluble carbon. This feature can only result from the influence of the trees, and represents a progressive increase in the mean turnover rate of the soil organic matter.

CONCLUSIONS

Afforestation by Sitka spruce produces gradual but significant changes in the physical and chemical character of peaty upland soils. In particular is an apparent breakdown of the legacy of refractory organic matter with turnover rates in excess of 1500 years. The consequent increase in carbon turnover within the mineral soil must realize a significant improvement towards sustaining nutrient potential.

Natural and/or 'post-bomb ^{14}C' concentrations provide a unique opportunity for quantitative assessment of the changes in soil organic-matter status induced by afforestation. However, an adequate resolution of ^{14}C enrichment variations requires recognition of the fact that a given soil horizon is likely to contain organic components with markedly different rates of mineralization.

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