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SOME EFFECTS OF AFFORESTATION ON SOIL ORGANIC MATTER

A thesis submitted in May 1986 by

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for the degree of

DOCTOR OF PHILOSOPHY

UNIVERSITY OF STIRLING

5/87

ABSTRACT

Some of the effects of afforestation on poor soils, typical of those at present undergoing large-scale tree planting were examined. The majority of the research work was carried out in an experimental plantation in N.W. England, with supplementary work in the surrounding commercial plantations of Sitka spruce.

The quantitative, qualitative and dynamic nature of the soil organic matter was assessed. Quantitative studies revealed that there was no evidence for a build up of organic material in the soil, and an equilibrium was established in the forest floor after 10 years. Marked fluctuations in total carbon content were observed in both the forest floor and soil during a seasonal sampling programme.

The qualitative and dynamic nature of the soil organic matter was studied using techniques which identified long term changes, ie ^{14}C enrichment studies, gel filtration and NMR spectroscopy.

The radiocarbon studies revealed that these afforested soils were characterised with carbon incorporated into the soil at the time of planting. The resistance of some components of the litter to decomposition seemed to be the rate determining factor in the slow incorporation of 'recent' material. Readily decomposable material, such as fine roots, appeared to be respired rather than added to the soil organic matter pool. Gel filtration showed that there were slight differences in the molecular weight distribution of soil extracts from under different tree stands, and that these could be related to the rate of soil organic matter turnover.

The use of NMR spectroscopy was not successful in this study. The reasons for this are not clear, but may be related to the use of sodium borate as the soil extractant.

There was strong evidence that changes in the qualitative nature of the

soil organic matter had occurred, which were related to the rate of soil organic matter turnover under different tree stands, and the length of time under afforestation.

CONTENTS

ACKNOWLEDGEMENTS

I would like to thank all the staff at Merlewood Research Station for their encouragement and help throughout the course of this research work. I am particularly grateful to Mrs. D. Howard and Dr. P. Bacon for their assistance in data interpretation and statistical matters and also to Mr. A.H.F. Brown for putting previous data obtained from the Gisburn Experiment at my disposal.

I also wish to thank everyone at the N.E.R.C. Radiocarbon Laboratory, for their friendliness and technical assistance during my visits to East Kilbride. My especial thanks go to Dr. D.D. Harkness for his advice, criticism and encouragement given throughout the whole of this research project.

Finally I would like to thank my supervisors, Dr. I.C. Grieve and Dr. A.F. Harrison for their support throughout this study, and without whose help this thesis would not have been possible.

The work was supported throughout by a Natural Environment Research Council Studentship.

CHAPTER 1: INTRODUCTION

1.1 General introduction

There are over 2 million hectares of forest and woodland in the U.K. with about 75 per cent of this being managed for commercial production. A recent Government statement (House of Lords Select Committee, 1981) suggests that new planting should be at a rate of approximately 20000 ha annually, which would result in a total of about 12 per cent of the land area of the U.K. being afforested by the year 2000. The majority of the stands have been established on land which was previously used for rough pasture, with soils characterized by poor internal drainage; the important soil types being peaty iron pan soils, surface water and peaty gleys and peats (Pyatt, 1970). In order to grow trees on these poor soils, site preparation in the form of ploughing (Thompson, 1984) and fertilizer application (Malcolm, 1979) is usually necessary. Once established, much of the nutrient requirement of upland forest is met by re-cycling through litterfall and its decomposition. With nitrogen and phosphorus, however, appreciable proportions are immobilised in humified soil organic matter. Consequently the rate of turnover of the soil organic matter is the major factor in the fertility status of such sites, in which nitrogen and phosphorus supply limits growth.

In 1955, experimental plantations of different tree species were made on former hill grazing land in the newly acquired Forestry Commission area near Gisburn, N. Lancashire. The site was chosen because the soils were regarded

by W.H. Pearsall as 'poised' (Brown, pers. comm.), being transitional between surface-water gleys and peaty gleys and would be susceptible to being altered through land-use changes. The initial pH of the 0 - 5 cm mineral soil horizon was close to pH 4.5, which is the value which approximately delimits mor and mull formation in the U.K. and northern Europe (Swift et al. 1979). The experimental layout consisted of plots of four single species with all possible combinations of two species admixtures, replicated three times.

The Gisburn experiment provides a unique opportunity to study the general effects of afforestation and these attributable to specific tree species and their mixtures on soil organic matter. Thus an assessment can be made as to what the possible consequences of long term forestry will be on soil organic matter, and therefore on the ability of the soil to provide nutrients for future tree rotations. Although the majority of this research programme was carried out within the experimental layout, some study was undertaken in an age series of Sitka spruce stands located in the surrounding forest. These stands provided an important link for relating changes induced in soil organic matter in experimental plots to those produced as a result of commercial forestry practices.

Chapter 2 : THE GISBURN EXPERIMENT

2.1 Introduction

The Gisburn experiment was established in N. Lancashire (G.R. SD750585) in 1955, the general location of the site is shown below :

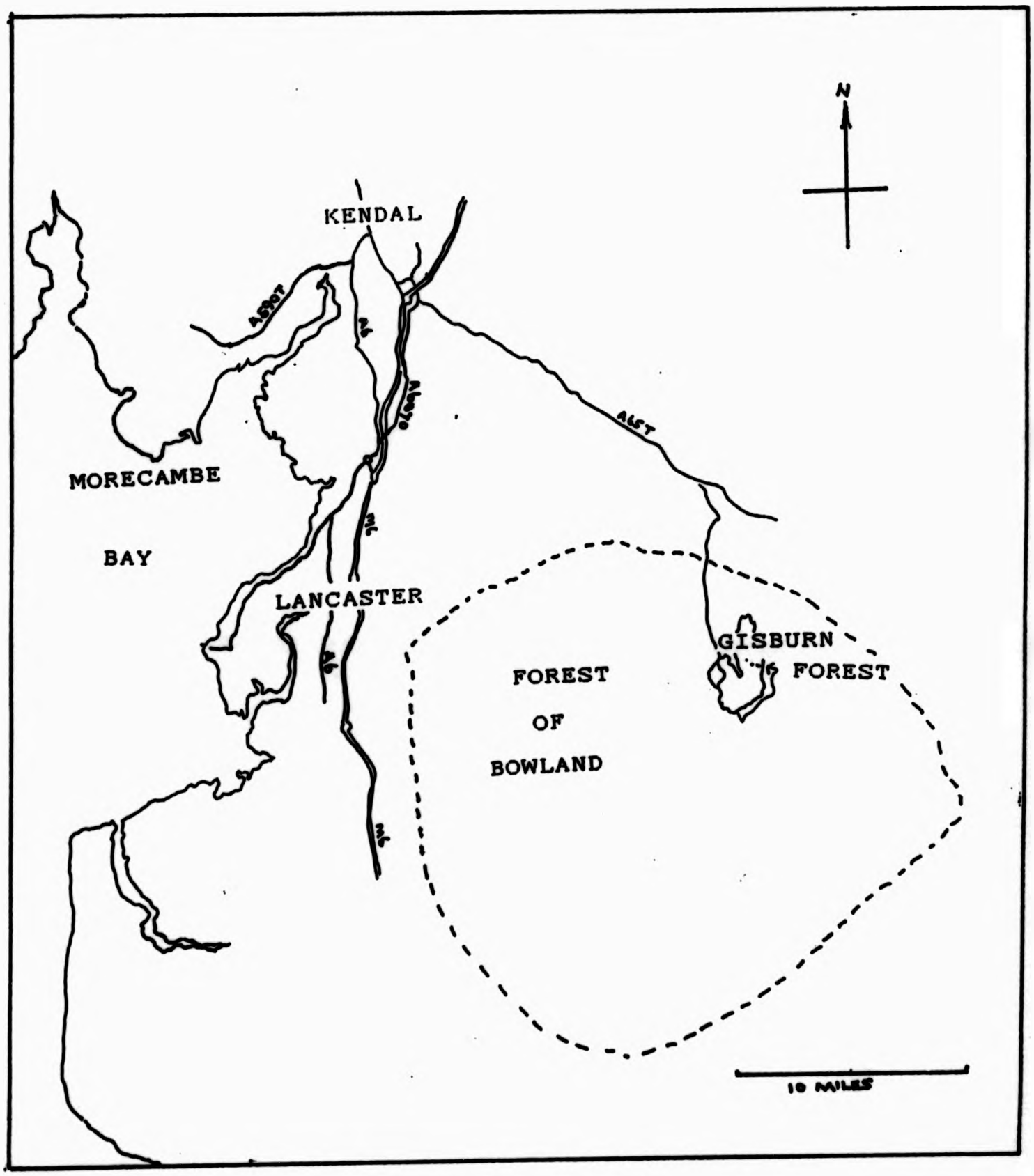


Fig 2.1 General location of the Gisburn forest.

The original objectives of the study were :

"To raise mixed and pure crops under comparable conditions in order to compare their growth (above and below ground), outturn, disease and pest resistance, effect on ground vegetation and resulting changes in the soil. Control plots grazed by sheep and ungrazed are included ".

These were subsequently modified to emphasize effects on vegetation and soil; growth was restricted to normal Forestry Commission mensuration The tree species planted were Norway spruce (Picea abies), Scots pine (Pinus svlvestris), alder (Alnus glutinosa) and oak (Quercus petraea). Although a great deal of work has been carried within the Experimental layout, much of it is an unpublished form. The results of these studies, which are outline in this chapter, have kindly been made available to me by Mr. A.H.F. Brown.

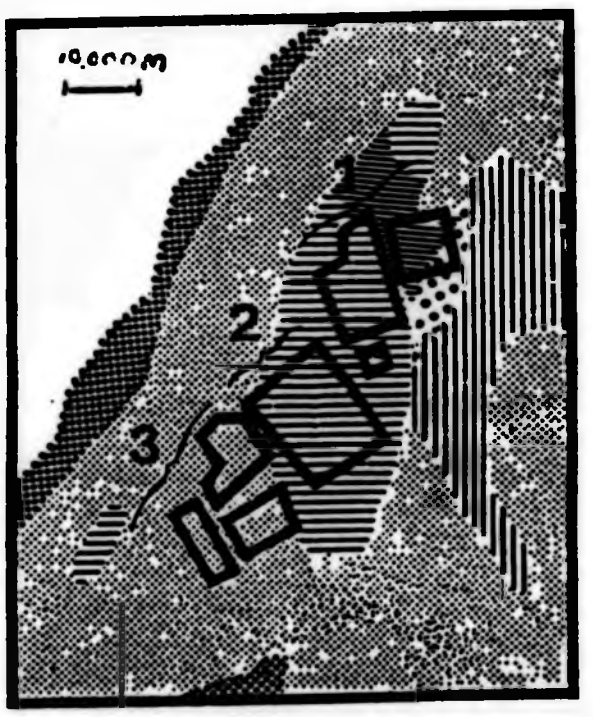
2.2 Site description

2.2.1 Climate

The experimental plots are at an altitude of 280m and lie on a slope of W.S.W. aspect. They are subject to severe exposure to the south-west, but are moderately sheltered to the north and east. Within the forest as a whole, windthrow amongst stands more than 30 years old is a serious problem. The mean annual rainfall is 1350 mm(data provide by N.W.W.A), and the site is characterized by cool summers and cold winters.

2.2.2 Soils

The soils of the Gisburn forest as a whole have been surveyed by staff of the Soil Survey of England and Wales (Thompson, 1972) based on the soil series described by Hall and Folland (1970) for Lancashire. The majority of the Experimental layout was planted on soils that are intermediate between the surface water gleys of the Brickfield series and the peaty gleys of the Wilcocks series (Fig 2.2), but Block I also covers a small area of peat of the Winter Hill series. Geologically, the area consists of carboniferous grits, sandstones and shales (of the Millstone Grit series) usually overlain by locally derived clayey drift. Owing to these clayey deposits and the high rainfall, the majority of the soils are poorly drained with a tendency for peat formation. At the start of the Experiment, these soils were regarded by Pearsall as 'poised' between mull and mor humus types, and were liable to be changed depending on management or tree species.



Key

- Peaty gley (sandy clay loam)
- Peat
- Peaty gley (silty clay)
- Surface water soil (silty clay)
- Gleyed brown earth (sandy loam)
- Surface water soil
- ..... Forest boundary

Fig 2.2 Soils present in the Gisburn experiment (after Thompson, 1972).

Fig 2.2 indicates that there is a boundary between surface-water gleys in Block III and peaty gleys in Block II, but there is now no evidence of any clear distinction between the soils of these two blocks.

Dr D. F. Ball did a limited survey at Gisburn in 1966, and he judged the soils of experimental Blocks II and III to be similar, and transitional between peaty gleys and surface water gleys.

Block I coincides with a very heterogeneous area of the soil map, and soil chemical analyses of 1955 samples revealed that Block I was significantly different from the others, with respect to all the chemical elements analysed. In particular, parts of Block I had a 10-fold higher level of extractable calcium, which probably indicates that these sites had once been limed. Typical profile descriptions provided by Ball are shown in Table 2.1

The uppermost horizons (Table 2.1) have a good loam structure and historically, the soils supported reasonable quality grassland provided that manurial and drainage treatments were carried out.

At the start of the Experiment, the soils were regarded as 'poised', both because of the inherent characteristics of the soils and also because the high mean annual rainfall indicates a potential for peat formation (Pyatt, 1970). Less intensive management of land within the area generally, has meant that many areas have reverted to wet moorland

Table 2.1 Summary Profile Descriptions at Gisburn

1) Block II Oak

0-6" Black (10 YR 2/1) Peaty stoneless loam, moderate cloddy structure abundant roots, merging boundary to

6-12" Very dark brown (10 YR 2/2) with rusty mottle loam, weak cloddy structure, frequent roots, fairly sharp boundary to

12-18"+ Mottled grey (10 YR 5/1) and Yellowish-brown (10 YR 5/4) clay loam with patches of rotted sandstone, massive structure, (possibly prismatic on drying) frequent roots.

2) Block II Ungrazed grassland

0-2" Black (10 YR 2/1) Peaty loam, weak cloddy structure, abundant roots, merging boundary to

2-10" Very dark brown (10 YR 2/2) with rusty mottle, loam, strong cloddy structure, abundant roots, fairly sharp boundary to

10-18"+ Mottled, dominantly 10 YR 4/1, Dark grey with 2.5 Y 5/0 grey and flecked with 5 YR 5/8 Yellowish-red, clay loam to sandy clay loam with sandy patches, massive structure (possibly prismatic if dry) frequent roots.

3) Block III Spruce/Alder mixture

0-4" Black (10 YR 2/1) Peaty loam, strong small cloddy structure, abundant roots, merging boundary to

4-12" Very dark brown (10 YR 2/2) loam, strong, cloddy structure, abundant roots, sharp boundary to

12-18" Mottled grey (10 YR 5/1) with yellowish-red (5 YR 5/8) clay loam with sand patches, compact massive structure,

4) Block I Spruce/oak

0-4" Black (5 YR 2/1) Peaty sandy loam, weak crumb structure, abundant roots, merging boundary to

4-8" Black (5 YR 2/1) Peaty sandy loam as above, sharp boundary to

8-14" Dark grey (10 YR 4/1) mottled with 10 YR 6/2. Light brownish grey, and speckles of 5 YR 5/6. Yellowish-red sandy clay loam shale stones dominant, large cloddy structure, frequent roots

heath (Hall and Folland, 1970). Any further increase in wetness could lead to an extension of the small areas of existing peat; and conversely, drying out of the site could tip the balance away from peaty gleys to surface-water gleys. Thompson (1972) has suggested that this may in fact have happened through afforestation, because of the artificial drainage carried out, or through the presence of trees through transpiration or both. The peaty gleys of the Wilcocks series are more extensive outside the forest than within it; and the land in the general area of the forest around the experiment mapped in 1971 as surface water gleys, had been regarded prior to afforestation as a peaty gley.

The soil sequence is distinguished according to the degree of wetness and the depth of the associated organic or peaty horizon. Thus, surface water gleys merge into wetter peaty gleys which in turn are arbitrarily separated from the organic soils at a peat depth of 15". Both surface water and peaty gleys are further subdivided into two types dependent on variation in the parent material as shown in Table 2.2.

Table 2.2 Soil series present at Gisburn in relation to parent material and degree of wetness.

		← Increasing wetness →		
		Less wet; thin organic layer. Gentle slopes, usually upto c. 600'. Rainfall 40-45"	Wetter, thicker organic layer. Gentle slopes backed by steeper slopes. Above 600'. Rainfall 40-60"	Organic layer >45cm Above c.900' Rainfall 50-70"
Parent Material	**Texture of surface horizons**	**Surface water gleys**	**Peaty gleys**	**Peats**
Till: clay with many weathered and unweathered sandstone and gritstone fragments	Variable, but mostly sandy clay loam	Brickfield	Wilcocks	Winter Hill
(These types are the predominant ones) →				
Till:clay with weathered shale; virtual absence of coarser sand - and gritstones	Fine - medium texture texture; more plastic and stickier than above	(Hallsworth) not mapped in the experimental area	Roddlesworth	

2.2.3 Original vegetation

The original vegetation consisted of a form of Festuca-Agrostis grassland which is characteristic of many areas of acidic rough grazing in Britain. A summary of the main species and their frequencies is given in Table 2.3.

Table 2.3 A summary of the most frequent species of higher plants in the original vegetation at Gisburn. (based on 1 m^2 quadrat).

Frequency > 60%		Frequency 20% - 60%	
Species	% frequency	Species	% frequency
Agrostis tenuis	62	Carex nigra	43
Anthoxanthum odoratum	68	Carex sp. (glaucous)	51
Deschampsia cespitosa	62	Holcus lanatus	31
Festuca ovina	85	Juncus conglomeratus	38
Nardus stricta	72	J. effusus	49
Galium saxatile	83	Luzula multiflora	25
Potentilla erecta	70	Luzula spp.	22
		Rumex acetosa	28

The relatively high values of Juncus effusus and J. conglomeratus indicate poor soil drainage conditions. The vegetation of Block I reflected the soil chemical differences already referred to, and contained more Holcus lanatus, Rumex acetosa and Ranunculus acris but less Nardus stricta and Potentilla erecta than the other blocks.

2.2.4 Experimental design

The experiment was set up using a replicated randomized block design, the layout of which is shown in Fig 2.3. The four tree species were planted in pure stands, and in all the possible combinations of two species admixtures. The mixtures were formed by alternating groups of eighteen trees of each species (3 rows x 6 lines) arranged in a chequerboard fashion. The plots cover 0.2 ha; with the original tree spacing at 5' x 5', except for oak which was at half this spacing. Ground preparation was ploughing at 5' spacing for turves, together with some deeper draining between plots. There were no fertilizer applications.

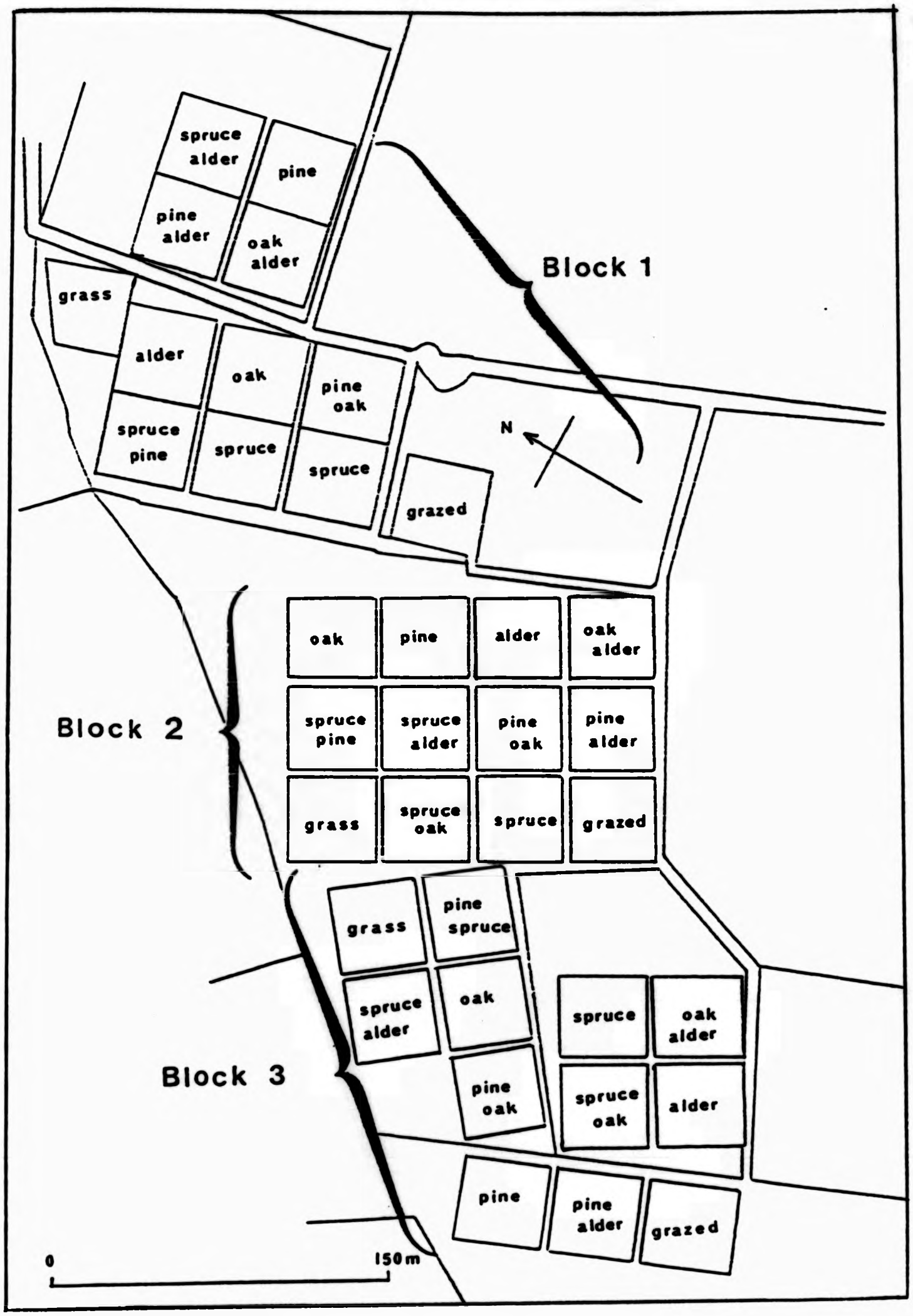


Fig 2.3 Experimental layout of the Gisburn experiment.

2.3 Previous Experimental results

2.3.1 Tree growth

Top height measurements have shown that Norway spruce and oak grow taller when admixed with Scots pine and alder. Alder showed improved growth when mixed with Scots pine, whereas the height of Scots pine was unaffected regardless of whether it is grown in mixture or pure stands. Care must be taken when interpreting these results, as top height measurements were only taken from the six 'best' trees per plot (in accordance with standard Forestry Commission practice) , consequently they do not reflect the growth of the stand as a whole.

2.3.2 Vegetation changes

The general changes in ground flora since afforestation are summarized in Table 2.4. Regardless of tree species, the majority of forbs and some grasses, sedges and rushes have either disappeared or markedly declined, and the grass Deschampsia flexuosa has increased in frequency. Only a relatively limited range of species are classed as variable, and these reflect differences found beneath the various canopy types. These general changes in ground vegetation occur not only under the tree canopies but also in the unplanted plots, indicating that the cessation of grazing has played a major role in altering the vegetation of this site.

Table 2.4 General changes in vegetation since afforestation at Gisburn.

Species (virtually) disappeared	Species much reduced	Variable species
Achillea ptarmica	Potentilla erecta	Galium saxatile
Cerastium spp.	Anthoxanthum odoratum	Rumex acetosa
Cirsium spp.	Festuca spp.	Agrostis tenuis
Conopodium majus	Luzula spp.	A. stolonifera/canina
Lotus uliginosus	Nardus stricta	Carex nigra
Polygala serphyllifolia		Deschampsia cespitosa
Ranunculus acris		Juncus effusus
R. flammula		
R. repens		
Succisa pratensis		
Trifolium repens		Species increased
Viola palustria		
V. riviniana		
Carex panicea		Vaccinium myrtillus
Juncus conglomeratus		Deschampsia flexuosa
Poa pratensis		Dryopteris dilatata
Sesleria caerulea		
Sieglingia decumbens		

2.3.3 Soil biology and chemical changes.

In 1974, the soil was resampled and analysed chemically and the results compared with those obtained at the start of the Experiment in 1955. The results showed that there had been marked changes in most elements with time. Over the plots as a whole, increases had occurred in the concentrations of total nitrogen, potassium, whereas extractable phosphorus and calcium had decreased, with magnesium and sodium giving variable results. There was no statistically significant increase in soil organic matter as measured by loss-on-ignition. Differences between plots in 1974 were neither statistically significant nor consistent between blocks, except for calcium. This element was highest in the unplanted sites and alder plots for Blocks II and III, but in Block I the unplanted site had the lowest calcium level, although originally it had one of the highest.

Differencs in microbial activity were more readily detectable (Brown, 1977). Using the rate of cotton strip decomposition as an indicator, it was found that microbial activity was greatest in soils planted with alder and least under Norway spruce, with oak and Scots pine being intermediate. In 1978, a seasonal survey of microbial activity and soil chemistry was instigated, and marked seasonal changes in both these parameters were observed. Interestingly the two conifers (although synchronous between each other) did not show the same seasonal patterns as the two hardwoods (equally synchronous with each other). Christensen (1982) conducted a pilot study to examine the effect of afforestation on the total carbon and nitrogen content of the soil, he found that both of these elements were lower in the tree-covered plots compared with the grassland.

Recently work has been concentrated in the mixed plots. Brown and Harrison (1982) examined the effects of tree mixtures on earthworm populations, nitrogen mineralization rates and phosphorus status. These three parameters all increased under Norway spruce canopies in the stands where Norway spruce was mixed with Scots pine and alder, when compared with the pure Norway spruce stand.

2.3.4 Results from previous Radiocarbon studies

Ladyman (1982) investigated the radiocarbon enrichment of soil samples collected from the ungrazed plot in 1955, 1959, 1974 and 1977 (Table 2.5). Since 1955, there has been no significant change in the "bomb" carbon enrichment below 5 cm, indicating that below this depth, the soil was unaffected by the change in site management (cessation of grazing) and by post 1950 fluctuations in atmospheric enrichment. Conventional ages for these samples (Table 2.5) show that the grassland soil is extremely stable. The 0-5cm soil sampled in the 1970's was apparently much younger, which Ladyman attributed to either an increase in the rate of turnover or organic matter accumulation.

Table 2.5 Conventional ages and radiocarbon enrichment for Gisburn grassland

Year Sampled	Plot (depth cm)	% Modern	Conventional Age
1955	Block 3 (0-5)	82.2 ± 0.5	1570 ± 50
1955	Block 3 (5-10)	82.6 ± 0.5	1540 ± 50
1955	Block 2 (0-5)	82.9 ± 0.4	1510 ± 50
1955	Block 2 (5-10)	80.9 ± 0.5	1700 ± 50
1959	Block 3 (0-5)	No measurement	
1959	Block 3 (5-10)	80.6 ± 0.4	1730 ± 50
1959	Block 2 (0-5)	84.5 ± 0.6	1350 ± 60
1959	Block 2 (5-10)	79.5 ± 0.4	1840 ± 50
1974	Block 3 (0-5)	87.2 ± 0.4	1100 ± 50
1974	Block 3 (5-10)	85.5 ± 0.4	1260 ± 50
1974	Block 2 (0-5)	87.6 ± 0.4	1060 ± 50
1974	Block 2 (5-10)	79.0 ± 0.5	1890 ± 50
1977	Block 2 (Litter)	126.8 ± 0.5	
1977	Block 2 (0-5)	92.0 ± 0.5	670 ± 50
1977	Block 2 (5-10)	80.8 ± 0.5	1710 ± 50
1977	Block 2 (10-17)	78.6 ± 0.5	1930 ± 50
1977	Block 2 (17-27)	59.1 ± 0.4	4220 ± 50

2.4 Summary of previous work

a) Vegetation changes - The results indicate that the cessation of grazing has had a much greater impact on the ground vegetation than has the introduction of trees. In all the plots, whether afforested or not, there has been an increase in the grass D. flexuosa with an associated decrease in forbs, sedges and rushes.

b) Tree growth - Marked improvement in top height has been observed in some of the mixed stands, especially for N. spruce and oak when grown with alder or S. pine.

c) Chemical changes - There have been marked changes in the concentration of most elements with time. In particular, concentrations of total nitrogen and potassium have increased, whilst extractable phosphorus and calcium have decreased. Consistent differences between blocks were difficult to detect, but marked seasonal fluctuations were observed.

A pilot study indicated that total nitrogen and carbon were lower in the tree covered plots relative to the grassland.

Work in the mixed plots showed that nitrogen mineralization rates and phosphorus status had increased in the soil under N. spruce canopies when grown with alder and S. pine relative to the pure N. spruce.

d) Biological changes - Cotton strip decomposition has been used as the main index of biological activity in the plots. Microbial activity was greatest in the alder plot, least under N. spruce, with oak and S. pine being intermediate. Seasonal changes in microbial activity were observed, with different patterns under the coniferous and deciduous trees.

e) Radiocarbon studies - Conventional ages for the soil sampled in the 1950's show that the original grassland organic matter was extremely stable. More recent samples indicate that a change has occurred either due to an alteration in the organic matter cycle, or as a result of the incorporation of "bomb" carbon.

Chapter 3: LITERATURE REVIEW

3.1 Effect of afforestation on soil organic matter

Afforestation is generally associated with organic matter accumulations particularly on the soil surface (Forest and Ovington, 1970; Turner, 1981), since the annual production of litter often exceeds the rate of decomposition of the forest floor. One well documented example is the classic Rothamsted "wilderness", where two small areas of old arable land at Broadbalk and Geescroft were allowed to revert to deciduous brush and trees in the 1880's; over a 90 year period 20900-45500 kg ha^{-1} of organic carbon had been gained (Jenkinson, 1970).

A consequence of commercial forestry in Britain has been the introduction of large plantations of exotic conifers grown mainly in monoculture. Early work by Ovington (1950 and 1951) examined the effects of afforestation with Scots pine and Corsican pine on sandy soil at Culbin and Tentsmuir in Scotland. The initial soil conditions were quite different; at Tentsmuir there was a raw humus formed under heather, whereas at Culbin the vegetation was sparse with no formation of surface organic layer until the plantations were established. In both areas, afforestation caused a loss of nutrients from the soil, but the organic matter content of the soils increased. In addition, the physical nature of the initial raw heather humus at Tentsmuir was changed to a softer, less acid form. The preferred species for commercial planting is Sitka spruce and little is known of the potential effects of this species on the soil, although work in Ireland on Sitka spruce grown on peaty gley soils has produced conflicting results. Carey and Farrell (1978) found that litter accumulations increased with increasing stand age, whereas Adams

(1974) found a levelling off of forest floor weight. Further work by Carey (1982) showed that the rate of litter build-up was linked with the vigour of the stand, better tree growth is associated with less accumulation, he proposed two opposing pathways to explain this:

i) fast growth is a consequence of accelerated turnover of organic matter or nutrients or both in the forest floor.

ii) tree growth and litter decomposition are affected by the same factors but to a different degree.

The rate of organic matter turnover within the forest floor becomes more important as trees mature, since the forest floor supplies an increasing amount of their nutrients (Jorgensen et al. 1980; Waring and Franklin, 1979). The former authors reported that the forest floor in a 16 year old Loblolly pine plantation supplied 34% of the trees nitrogen requirements, whereas in a 30-40 year old plantation this had increased to 85%. Contrasting results were reported by Miller et al. (1979), who studied nutrient cycles in Corsican pine at Culbin Sands. They found that despite tight cycling of nutrients such as nitrogen, phosphorus and calcium, the trees continued to make significant demands on the soil throughout their lives, due to the high rates of immobilization within the humus and low atmospheric input.

A popular misconception exists that planting pure conifers produces adverse soil conditions with the development of mor humus, whilst deciduous trees promote better soil conditions, with the formation of mull humus. It is often difficult to substantiate these claims, since the initial soil conditions are usually unknown. In order to try and verify that birch can act as a soil improver, G.W. Dimbleby set up a long term experiment on a heather moor in 1948, in which the site conditions were recorded at the outset. Birch litter was applied at controlled rates and frequency with supplementary planting of birch seedlings. After 30 years, Satchell (1980) examined the potential of

the experimental plots as a habitat for earthworms, in particular Lumbricus terrestris, as these are regarded as essential for the promotion of a crumb-mull structure in temperate forest soils. He concluded that there was no evidence that the birch could ameliorate the soil to a condition tolerable to Lumbricus terrestris, consequently it was unlikely that a brown earth would develop.

However, Miles (1978) reported an increase in pH at 0-3cm soil depth from 3.8 to 4.9 in 90 years, after birch colonized moorland dominated by heather. He also found (Miles,1985a) that substantial changes occurred in the colour, organic content, porosity, structure and cementation of surface horizons under birch during the life of the stand.

In a recent review paper, Miles(1985b) reported that broadleaved trees in Europe have been associated with a wider range of pedogenic trends than conifers, varying from podzolisation to depodzolisation. In general however, they seem to maintain higher topsoil pH values and to retard podzolisation compared with most conifers.

Many of the problems associated with pure conifers such as poor growth, lack of windfirmness, difficulty in establishing second rotations have been attributed to the initial site conditions at planting (Jones, 1965). Indeed, several continental studies (Van Goor, 1954; Van Goor, 1967; Holmsgaard et al. 1961) have shown no decline in yield over subsequent generations of pure conifers. One noticeable effect of conifer afforestation, has been the irreversible drying of organic horizons (Malcolm, 1979), e.g. Abies grandis, which is generally found on flushed peat, is capable of inducing a type of peat 'mull', which is readily dispersed by drip from the canopy.

In some circumstances, improved tree growth and nutrient turnover can be achieved by planting mixed stands. Nitrogen fixing species such as alder (Dawson et al. 1983; Tarrant et al. 1983) and legumes (O'Carroll, 1982) have been shown to improve tree growth, although in some cases problems due to competition can arise (Harrington and Deal, 1982). Other tree species such as larch (O'Carroll, 1978) and birch (Kovalev, 1969; Meilikainen, 1980) can also improve the growth of trees such as spruce and pine by improving the nutrient supply due to enhanced litter breakdown. Kovalev (1969) found that admixtures of 15-20% birch and 20-50% caragana in pine plantations accelerated the process of litter decomposition by 1.2-1.6 fold compared with pure pine plantations.

Many problems arise when attempts are made to link soil change to individual species (Stone, 1975), in particular there is often an inadequate perception of inherent soil heterogeneity. In order to evaluate precisely any soil change which is attributable to tree growth, studies must be carried out in experimental plots designed specifically for the purpose. Unfortunately there have been few research programmes carried out under these conditions. Those that have (Challinor, 1968; Gilmore 1977 and 1980) found that differences in soil properties were concentrated in the top soil (0-10 cm) and were related to differences in the rate of litter breakdown; even these results must be treated with caution, as Gilmore based his results on one bulk soil sample per species. Another factor which must be taken into account when assessing soil changes is seasonal variability in soil properties.

Balzar (1979) showed marked statistically significant seasonal fluctuations in soil chemical properties over an 18 month period in the Vienna woods soils. Earlier work by Frankland et al. (1963) in Lake District woodlands, found that despite an intensive sampling programme, large spatial variability obscured possible monthly differences. Similar problems were encountered by Lousier and Parkinson (1979), who found peaks in the organic matter content of a forest floor in spring, summer and autumn, but had insufficient samples to establish a statistically significant seasonal pattern.

3.2 Use of soil extracts in studying soil organic matter.

In order to study the chemical and colloidal properties of soil organic matter, it is first necessary to separate it from inorganic soil constituents by extraction. There are two major types of compounds which can be distinguished:

i) non-humic substances, consisting of compounds belonging to the well-known classes of organic chemistry e.g. carbohydrates, proteins.

ii) humic substances, a series of high molecular-weight brown to black substances formed by secondary synthesis reactions. These humic substances have characteristics which are dissimilar to polymers from other natural sources.

The two groups are not easily separated, because some non-humic substances, such as carbohydrates, may be bound covalently to the humic matter (Stevenson, 1982).

The ideal soil extraction method is one which meets the following objectives (Dubach and Mehta, 1963):

i) The method leads to the isolation of unaltered material.

ii) The extracted humic substances are free of inorganic contaminants, such as clay and polyvalent cations.

iii) Extraction is complete, thereby ensuring representation of fractions from the entire molecular-weight range.

iv) The method is universally applicable to all soils.

It is safe to say that the objectives listed above have yet to be realized. The traditional approach dating from 1786 (Stevenson, 1982) is to extract soil organic matter with alkali (usually NaOH) and then adjust the pH of the solution by adding acid. The alkali soluble, acid insoluble fraction being called "humic acids", the acid soluble, alkali soluble fraction called "fulvic acid" and the remaining insoluble fraction being called "humin". The validity

of this method of classifying components of soil organic matter has been questioned in the past (Page, 1930), and Waksman (1936) recommended the abandonment of such terms since:

"The labels designate, not definite chemical compounds but merely certain preparations which have been obtained by specific procedures".

It has also been recognized that the use of strong alkali extractants can alter the chemical nature of the soil organic matter under examination (Tinsley and Salam, 1961). Changes due to autoxidation can be limited by extracting under an inert gas (Swift and Posner, 1971). These problems have lead to the increased use of milder extractants, but this is associated with a decrease in extraction efficiency (Stevenson, 1982). Many different soil extractants have been tested eg sodium pyrophosphate (Gascho and Stevenson, 1968), anhydrous formic acid (Tinsley and Walker, 1964), sodium tetraborate (Tate, 1979). Sodium tetraborate was chosen as the most suitable extractant for this study, for the following reasons:

i) It is a mild extractant.

ii) It has been used successfully in gel filtration experiments (Swift and Posner, 1971; Tate, 1979).

iii) It is suitable for use in carbon dating techniques, as it does not contain carbon.

The main disadvantage of borate buffers as soil extractants, is that they form complexes with coloured substances (Christman and Minear, 1971), thereby altering the chemical nature of the material under investigation.

3.3 Radiocarbon

3.3.1 Introduction

Carbon has three naturally occurring isotopes, one of which, ^{14}C, is radioactive. The average isotope abundance in environmental carbon are:

a) 98.89% for ^{12}C

b) 1.11% for ^{13}C

c) 10^{-10}% for ^{14}C

Radiocarbon (^{14}C) is a beta emitter with a radioactive half-life of 5730 ± 30 years. It is continually produced in the upper atmosphere by the interaction of cosmic-ray induced neutrons with nitrogen atoms

$$^{14}N + n \longrightarrow {}^{14}C + p$$

Conventional radiocarbon dating (Libby 1946) is based on an assumed balance in nature between the rates of cosmogenic production (ca 2 ^{14}C atoms cm^{-2} sec^{-1}) and the cumulative radioactive decay of ^{14}C within the geochemical carbon cycle. This equilibrium distribution giving rise to a constant ^{14}C specific activity of 13 dpm g^{-1} carbon in the atmosphere and living biosphere. Living plants and animals accurately reflect the atmospheric ratio of $^{14}C/^{12}C$ due to the direct uptake of carbon dioxide by photosynthesis and feeding. However, when an organism dies the isotopic balance is no longer maintained and the ^{14}C concentration of the detrital carbon decreases due to radioactive decay and at a rate determined solely by the ^{14}C half-life value i.e.

$$A = A_o e^{-\lambda t}$$

where A = ^{14}C specific activity at time t

A_o = natural ^{14}C specific activity in the atmosphere and living plants

λ = the decay constant for ^{14}C

Therefore, comparison of the residual ^{14}C specific activity in a sample with that characteristic of living material can provide a direct estimate of the time (t years) elapsed since death i.e., the conventional radiocarbon age of the sample.

Since the beginning of the present century, man has significantly altered the concentration of ^{14}C prevalent in the earth's atmosphere. With the onset of the industrial revolution increasing amounts of '^{14}C free'

carbon dioxide have been released to the environment by the utilization of fossil fuel reserves. This progressive dilution of the natural ^{14}C concentration (Suess 1955) had reached ca 3% by the early 1950's when it was immediately swamped by a relatively massive input to the atmosphere of ^{14}C produced during nuclear weapon's test programmes. A test moritorium in 1962 effectively halted this artificial production of ^{14}C.

The 'bomb' effect, which resulted from the neutron flux released in the detonation of fission and fusion devices, produced an almost immediate doubling of the natural atmospheric ^{14}C concentration by 1962/63. Since that time the concentration of ^{14}C in the atmospheric carbon dioxide available for uptake by plants has decreased steadily due to the net transfer of the 'bomb' produced excess to the world oceans.

It is the post-1962 transient conditions, as the 'bomb' ^{14}C tends towards an eventual uniform distribution throughout the natural carbon cycle, that offer a unique opportunity for tracing the dynamics of soil carbon. Conventional radiocarbon dating can of course be applied in the study of soil carbon, but this approach is constrained by the ultimate analytical precision that can be achieved in ^{14}C measurement. This is, at best, limited to $\pm 0.5\%$ which is equivalent, in terms of the ^{14}C decay rate, to a maximum age resolution of ± 40 years. However, the measurable rate of change in 'bomb' ^{14}C concentrations is not defined by radioactive decay and for post-nuclear plant growth the 'dating' possibilities (based on the well documented changes in atmospheric ^{14}C concentration) has a potential capability for precise year by year resolution. However, realisation of this ideal situation is virtually impossible in soil

study, the determinant factor here being the heterogeneous and often poorly defined chemical nature of soil organic matter. Physically and/or chemically defined components within the total organic pool invariably derive from carbon fixed into plant tissue over several years. Consequently, the measured ^{14}C enrichment must be regarded as providing a semi-quantitative time estimate rather than a 'mean age' in the conventional dating sense (Ladyman, 1982). For resilient organic fractions and deeper (older) soil horizons, particular attention must be given to the identification and possible resolution of carbon that is representative of pre and post-bomb growth (Harkness et al. 1985).

3.3.2 Studies using radiocarbon measurement

Soil turnover rates in a forest and pasture soil were compared by Stout and O'Brien (1972), they concluded that differences in the ^{14}C enrichment of the topsoil arose because of greater productivity in the pasture. Further work (O'Brien, 1984) emphasised the important role that earthworms play in soil organic matter dynamics. The presence of large numbers of earthworms in the pasture led to an increase in the downward diffusion rate of carbon compared with the beechwood, where the litter layer contained high levels of "bomb" ^{14}C, but with little incorporated into the topsoil. Tate (1972) studied the same site and used ^{14}C enrichment of humic acid and whole humus to postulate that the pasture subsoil had been largely derived from the original forest vegetation.

Carbon isotope measurement has been used as an index for soil development (Ladyman and Harkness, 1980), where changes in the isotopic nature of a soil were linked to the progressive transition of mor to mull humus under the influence of a birch plantation.

Radiocarbon measurement has been applied to soil extracts, in particular to the fulvic acid, humic acid and humin fractions to examine the traditional theory that humus formation followed the pathway:

fulvic acid → humic acid → humin.

Several authors have found evidence to support the traditional view (Paul et al. 1964), but Nakhla and Delibrias (1967) used the movement of 'bomb' ^{14}C through the humic components to argue that humin was formed before humic acid. Sharpenseel (1972) obtained conventional radiocarbon age patterns from chernozem and podzolised soils; data from the chernozem supported the traditional order of formation, whereas data from the podzol supported the conflicting theory. It is unlikely that the results indicated different pathways of formation for these two soil types, since in other studies on podzols, humic acid has been shown to be older than humin (Goh and Pullar, 1977; Goh and Molloy, 1978), whereas Gerasimov and Chichagova, (1971) found humin to be the oldest component of the organic matter. These problems have mainly arisen because the products of the classical alkali/acid extraction technique have been regarded as definite compounds or steps in organic matter formation, while in fact, as mentioned previously, these organic matter components are only produced as a result of specific chemical procedures.

Recent work (Harkness et al. 1985 in press) investigating the temporal distribution of 'bomb' ^{14}C in a forest soil has shown that there was a delay in the incorporation of 'bomb' ^{14}C into the soil relative to the

atmospheric peak (see Fig 5.15) and that this delay increased with increasing depth down the profile. The authors suggested that this time lag was due to selective microbial humification of leaf litter, branch and root debris. The results also indicated that there was a two component system of 'fast' (< 20 year) and 'slow' (about 350 year) cycling carbon in the top soil.

Radiocarbon measurement was used in this study, as it provided an opportunity to investigate whether the observed differences in microbial activity of cotton strip breakdown under the various treatments (Chapter 2.3.3), actually reflected differences in the soil organic matter turnover rate. In addition, this method was also employed, to examine whether there was any change in the radiocarbon enrichment of the soil, after 30 years of afforestation with Sitka spruce.

3.4 Gel filtration

3.4.1 Introduction

Gel filtration provides a method for molecular size differentiation based on elution through a bed of porous beads. There are several different types of gel available commercially, the one chosen for use in this study was Sephadex, which is described as: "a modified dextran obtained by crosslinking the linear macromolecule (polysaccharide) to form a three-dimensional network, whose pores are determined by the degree of crosslinking of the polymer".

Separation by gel filtration is accomplished by a type of molecular sieving, as illustrated diagrammatically in Fig 3.1.

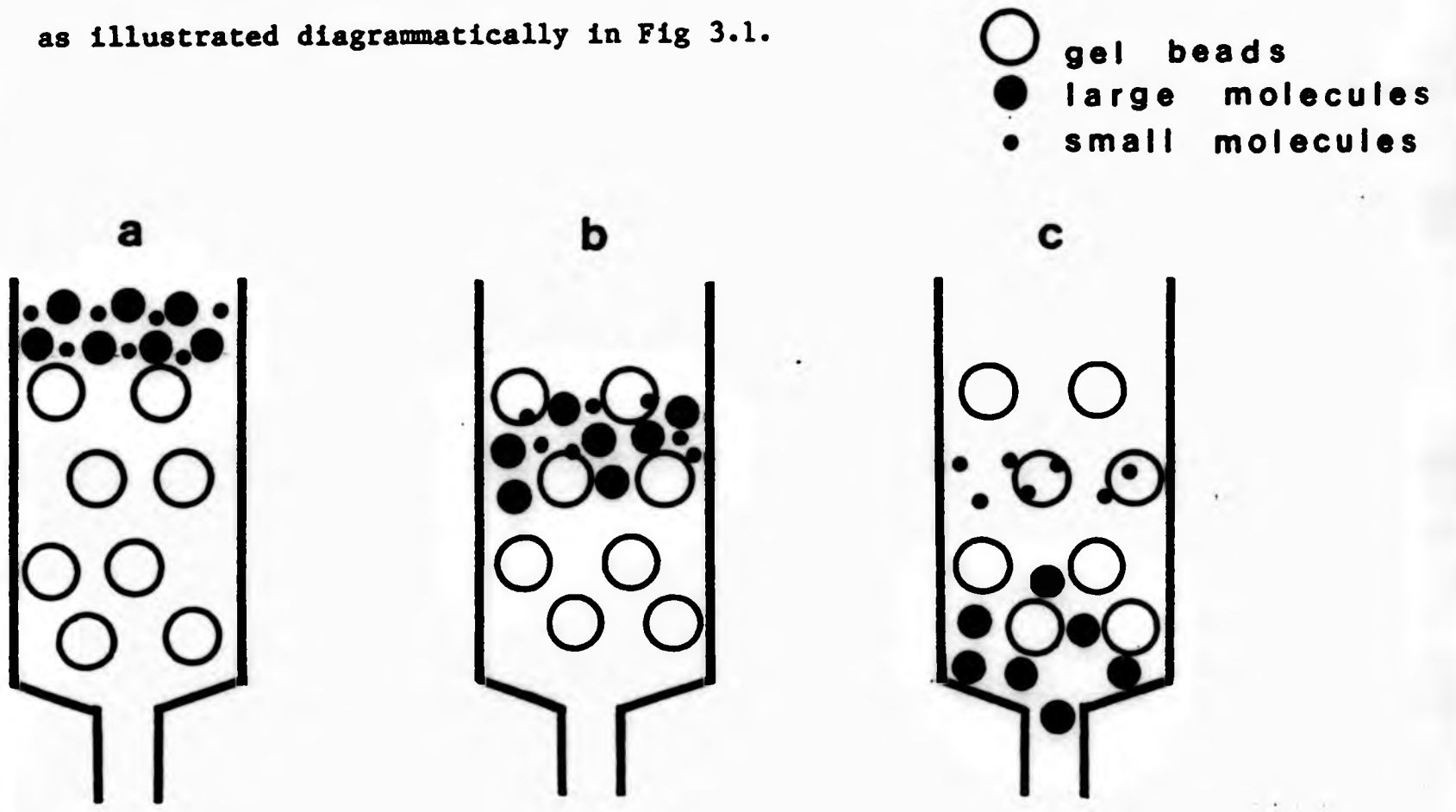


Fig. 3.1 Separation of particles of different sizes by gel filtration (after Determann, 1968).

The material to be examined is applied to the surface of the gel bed (a) and then eluted with an aqueous solvent. Small particles move with the elutant both within and outside the gel particles, while large particles move only outside the gel particles (b). Thus the large particles are eluted first, followed in order by the progressively smaller particles (c).

Seven grades of Sephadex are available each with a different pore size (Table 3.1).

Table 3.1 Sephadex Types and Fractionation Range

Type	Approximate limit for complete exclusion (MW)	Fractionation Range (MW)
G - 10	700	0 - 700
G - 15	1,500	0 - 1,500
G - 25	5,000	100 - 5,000
G - 50	10,000	500 - 10,000
G - 75	50,000	1,000 - 50,000
G - 100	100,000	5,000 - 100,000
G - 150	150,000	5,000 - 150,000
G - 200	200,000	5,000 - 200,000

The estimates of molecular weight exclusion values as quoted by the manufacturers cannot be applied directly to fractionated soil extracts, since these have markedly different properties from the calibrating species (Cameron et al. 1972). This is because separations achieved by gel filtration are related to the hydrodynamic sizes of particles, not just to the molecular weight and will depend therefore on properties such as charge, shape and the degree of hydration.

Adsorption onto gel surfaces can sometimes be a problem when fractionating soil humic substances, but this can usually be avoided by appropriate choice of gel and buffer type (Posner, 1963; Swift and Posner, 1971).

3.4.2 Use of gel filtration in soil organic matter studies

Gel filtration has been used to subdivide both humic and fulvic acids into less heterogeneous molecular weight fractions which in turn allows more meaningful investigations of their chemical and spectral characteristics (Schnitzer and Skinner, 1968; Swift et al. 1970). Goh and Reid (1975) found that elution patterns of humic and fulvic acids were similar, leading to the conclusion that the two have similar nominal molecular weight distributions.

Long term changes in soil organic matter have been investigated via gel filtration experiments. Goh and Williams (1982) examined extracts from soil chronosequences using Sephadex G - 75, which

nominally separates at a molecular weight of 50,000. They proposed a three-phase theory of organic matter development, consisting of a two-phase system represented by the extractable active (<50,000) and passive (>50,000) fractions and a third relatively inert and extremely stable non-extractable component. Tate (1979) used gel filtration chromatography to show differences in the molecular weight distribution of extracts from two soils representing different stages of soil development in a climosequence of tussock grasslands in New Zealand.

The potential effects of different tree species on soil organic matter composition have also been examined (Candler and Van Cleve, 1982). Aqueous extracts obtained from B horizons of birch and aspen forest showed spectral differences in the fractions, suggesting that there are different materials present under the two forest types.

Gel filtration techniques were used in the present study for two main reasons; first of all to examine whether there were any differences in the molecular size distribution of soil extracts from under the various treatments, and secondly, to try and relate any changes to soil organic matter turnover and pedogenesis.

3.5 Nuclear magnetic resonance spectroscopy

The application of carbon-13 nuclear magnetic resonance (NMR) spectroscopy to structural investigations of humic substances is a relatively new technique (Hatcher et al. 1980); Schnitzer

and Preston, 1983), which makes possible direct observations of the macromolecular carbon skeletons and examinations of the gross structures of the heterogeneous polymers. The basic principles and application of NMR spectroscopy to soil organic matter research has recently been reviewed (Wilson, 1981), so only a few important points will be mentioned here. In theory, with the rapid advances in NMR techniques (Pines et al. 1973; Barron, 1980) and equipment, it should be possible to obtain good NMR patterns from soils without the need for extraction. Few research laboratories possess the sophisticated equipment for solid state NMR research, so most of the work on soil organic matter has been carried out using humic materials obtained by the classical extraction techniques, which may of course alter the nature of the material being examined (Swift and Posner, 1971; Ceccanti et al. 1978). Worobey and Webster (1981) used milder techniques and concluded that the method of extraction is very important in determining aromaticity, and that it was possible that the classical acid-base extraction scheme may artificially cause aromatic structures to form from indigenous carbohydrates.

N.M.R. techniques were applied to soil extracts, to try and assess whether changes occurred in the chemical nature of the functional groups contained in the soil organic matter, which could be related to afforestation with individual tree species, or to the length of time under afforestation.

3.6 Objectives of study

Four main objectives for study were undertaken, in order to assess some of the effects of afforestation on soil organic matter. These are outlined below :

1) To define the change in soil organic carbon content due to afforestation with different tree species. This area of study investigated whether the distribution of total carbon above and within the soil varied according to tree species. Particular attention was paid to the relative effect of conifers and deciduous trees as soil improvers or degraders. Work was also carried out to see whether the previously observed improvement in growth of N. spruce, earthworm populations, N mineral rate and P status (Brown and Harrison 1982) was reflected in difference in the carbon content.

2) To examine the dynamic nature of the organic matter pool through analysis of seasonal change and modelling.

This objective looked at the dynamic nature of soil organic matter on two different time scales. Short term changes were those related to seasonal changes throughout the year. Different seasonal patterns of microbial activity had been observed in the coniferous relative to the deciduous plots in 1978 (Brown,unpub.). In this study, carbon contents of the soil and litter layer were measured at six weekly intervals over

an 18 month period, to see whether observed changes could be related to several easily measured parameters eg % moisture, litterfall, bulk density.

Long term changes were assessed using a simple model analysis, based on the assumption that the individual tree stands had reached a steady state. The model looked at the distribution and cycling of total carbon between the above ground tree biomass, the forest floor and soil organic matter pools.

3) To assess the change in total organic carbon content in the soil and litter layer produced by one tree rotation

This objective investigated whether a trend could be observed over time due to afforestation with Sitka spruce. Sikta spruce is an important commercial tree species, but it has been associated with soil acidification and podzolisation (Hornung,1985).

Soil acidification under conifers is usually accompanied by a repositioning of organic matter within the profile, with mor humus accumulating at the surface but with decreasing amounts in the A horizon. The surface organic matter accumulations often show cyclic trends following the life cycles of the stands (Mihai,1969;Page,1968). Surface organic matter content tends to increase with stand age until the trees begin to senesce, after which conditions become more

favourable to decomposition. As the Sitka spruce stands in the present study were comparatively young (15-30 yrs old), an accumulation of surface organic matter was expected.

4) To examine qualitative changes in soil organic matter and to relate these to species and temporal effects.

Qualitative studies were undertaken using methods which can identify long term changes in the nature of the soil organic matter. Two the techniques chosen ie radiocarbon enrichment studies and gel filtration have been used successfully to investigate soil organic changes due to species (Tate, 1979, Chandler and Van Cleve,1982), and as indices for soil development (Ladyman and Harkness,1980;Goh and Williams,1982). Nuclear magnetic resonance spectroscopy has been applied successfully to relatively crude alkaline soil extracts (Newman and Tate, 1984), and was used in this study to try and assess whether differences could be detected in the chemical nature of functional groups, in soils taken from under the different treatments.

CHAPTER 4: METHODS

4.1 Sampling strategy

4.1.1 Introduction

For meaningful results to be obtained for comparison of soil properties, an effective sampling strategy must be adopted, as otherwise spatial and temporal variation make data interpretation difficult. Previous work at Gisburn (Howson, pers. comm.) indicated that at least 10 replicate samples were necessary to allow for random variation. Due to the large numbers of soil samples required for inter-species comparisons, sampling was carried out in a stratified random manner. Samples were collected from the relatively undisturbed flat areas (Fig 4.1) between the ridges and the troughs, as these areas should be the least variable and changes due to species effects should be easier to detect.

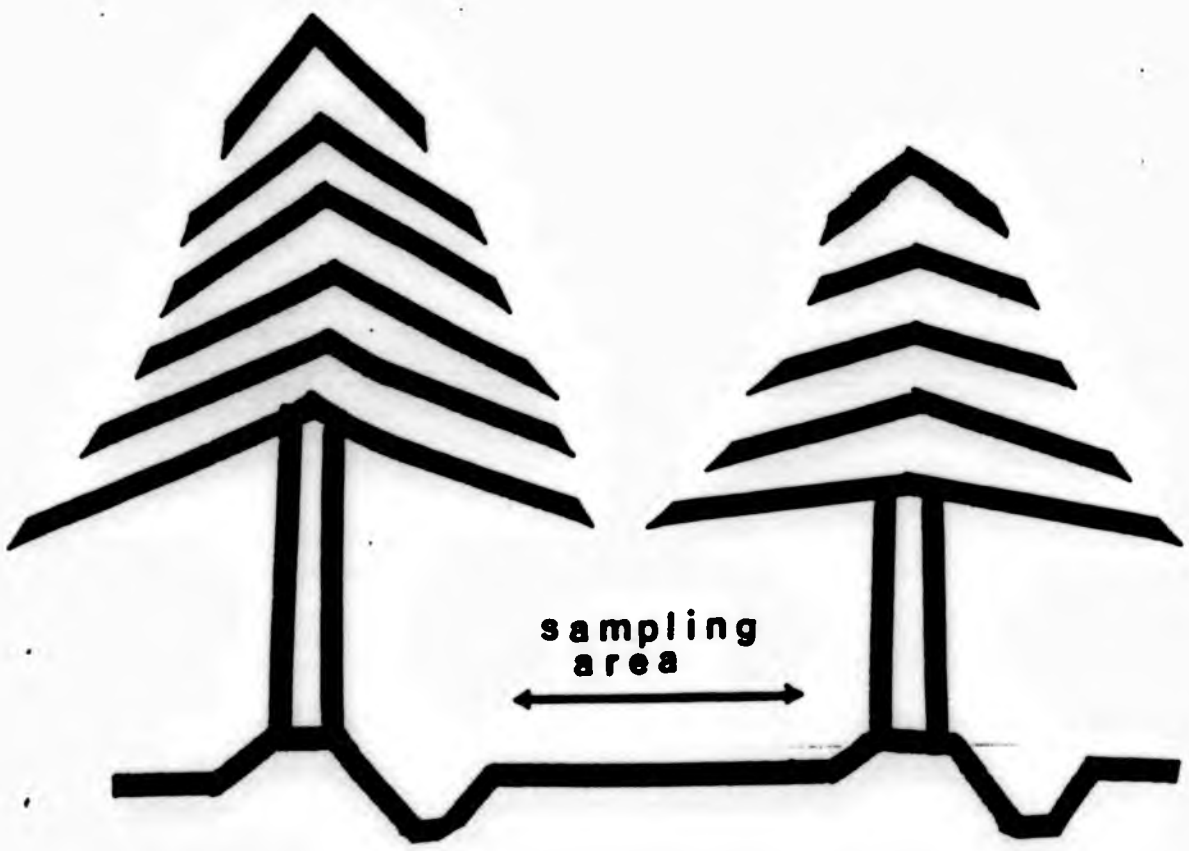


Fig 4.1 Diagram of the microtopography within a tree stand as a result of ploughing, and the location of sampling sites.

In order to avoid bias when taking the samples, the sampling positions were determined in the laboratory prior to sampling. Each tree stand at Gisburn had been mapped, and the rows of trees numbered along the x and y axis of each plot. Thus the positions of sampling sites could be located by obtaining the coordinates by the use of random numbers.

Five major sampling schemes were adopted during the course of this work, which are described below. In addition large bulked samples were collected for radiocarbon measurement and qualitative work. Bulking was carried out to overcome spatial variation, since these techniques were too time-consuming to allow for adequate replication.

4.1.2 Sampling procedures

1) Preliminary sampling in Block II

In October, 1982, ten replicate cores (to a depth of 20 cm) were taken randomly in each of the pure tree stands and grassland site. This study was undertaken to assess whether differences in total soil carbon content could be detected, and if so, to what depth in the soil profile.

2) Investigation of organic carbon content in the surface soils of all three blocks.

On the basis of the results obtained from the initial sampling, a second sampling programme was undertaken in February 1983, primarily to establish whether the results obtained from the pure stands in Block II were representative of the experiment as a whole. In addition, soil was collected from under the Norway spruce canopies in the mixed plots, to see if soil carbon content had altered as a result of mixing. The sampling procedure was carried out in the same manner as that described above, except that only the 0 - 5 cm soil and the litter layer were taken.

3) Seasonal sampling

Seasonal sampling was carried out at six weekly intervals from April, 1983 to November, 1984 in Block II. Ten random samples (litter layer + 0 - 5 cm soil) were taken from the pure Norway spruce, Scots pine and alder stands and from beneath the canopies of Norway spruce and Scots pine and also from the interface between these canopies in the mixed plot.

4) Sitka spruce age series

In June, 1983, samples were taken from Sitka spruce stands planted in 1970, 1968, 1967, 1965, 1956 and 1953. Samples were taken from two stands of each age. The five oldest stands were managed by the Forestry Commission and were situated in the Gisburn forest. The youngest stands were planted on similar soil at Old Park Wood (SD 6008) and were owned by Tilhill Forestry. All the stands had been fertilized at planting with a single application of phosphate.

Thirty random soil cores (litter + 0 - 5 cm) were taken from each stand, as the sites were thought to be more heterogeneous than those within the Gisburn Experiment.

A further sampling of the 0 - 5 cm soil was carried out in November, 1984, where a larger range of stand ages was examined (with the number of replicates per stand being reduced to six). The sites were planted in 1967, 1961, 1960, 1958, 1953, 1952 and 1951.

5) Soils for qualitative and radiocarbon analysis

Large bulked samples (0 - 5 cm) were collected in November 1983, from the grassland, Norway spruce, Scots pine, oak, alder and Norway spruce/Scots pine interface, and from an unfertilized Sitka spruce plot planted at the same time and within the boundary wall of the Gisburn Experiment.

Samples were also taken from the Sitka spruce age series in November, 1984.

4.1.3 Preliminary sample treatment

Soil cores taken in the field were placed in self-seal polythene bags, transported to the laboratory and stored overnight at 5°C.

The litter layer (L + F) was separated from the soil, which was then cut up into the appropriate depths. The soil and litter samples were dried in aluminium foil trays in an air-circulating oven (35°C).

Soils collected during seasonal sampling were weighed before and after air drying to determine the moisture content.

The air-dried soil samples were sieved through a 2 mm mesh; most samples were sieved by hand, but a roller mill was used for the large bulked samples.

Litter samples were ground in a Glen Creston mill (mesh diameter 0.5 mm). Samples were stored in sealed plastic bags at room temperature.

4.2 Above ground tree biomass determination

4.2.1 Introduction

In order to make a comparison of the stands, it is necessary to have an estimate of their biomass, since the pattern of tree growth varies according to species. The most direct method of obtaining the biomass of a tree stand is to fell and weigh all the trees, usually this is not possible and only a sample of trees are felled. A regression equation is then developed linking some easily measured component such as girth to tree weight, and the formula applied to each tree within the stand. Unfortunately this technique could not be used, since several other studies within the Experiment are ongoing, so a third, less destructive and less satisfactory method of biomass estimation had to used. This method is based on the assumption that a tree bole approaches a paraboloid of rotation (Newbould, 1967), the estimated volume can then be converted to dry weight knowing the specific density of wood.

4.2.2 Procedure

The diameter and height of at least twenty trees per species were measured using a girth tape, a telescopic pole and hypsometer (the latter instrument was used on trees over 10 m tall). Additional measurements for Scots pine were taken from windthrown trees.

A regression relationship linking diameter at breast height to total tree height was obtained, and the equation used to estimate individual tree heights from diameter, since the diameter of all trees in each plot had been measured by the Forestry Commission in November 1982.

Heights for the unfertilized Sitka spruce plot were obtained in a similar manner. The D.B.H/height relationship for Stika spruce was obtained from Forestry Commission records of heights and D.B.H. from individual trees previously measured in the Gisburn Forest. The diameters of all trees in the unfertilized Sitka spruce stand were assessed in November 1983 by the Forestry Commission.

Parabolic volume (Vp) was calculated using the formula:

$$Vp = \frac{\pi r^2 h}{2}$$

r = radius

h = height

Using the specific density of wood (D) (Table 4.1), individual tree biomass was established according to the equation: Vp x D. Stand biomass was then calculated by summation of the individual components.

Table 4.1 Specific density of wood (kg m^{-3}) at 15% moisture content. (Data supplied by the Timber Research and Development Association).

Tree species	Density (kg m^{-3})
Norway spruce	482
Oak	700
Alder	530
Scots pine	510
Sitka spruce	450

4.3 Analysis of soil carbon content

4.3.1 Introduction

The most accurate measure of soil carbon content is obtained from the quantitative conversion of soil organic carbon to carbon dioxide via combustion. Although this is the optimum method, it is extremely time consuming, and so was used only to check the other methods employed ie wet-oxidation techniques and loss-on-ignition. There was no evidence of inorganic carbon in the Gisburn soil, so analyses for total carbon gave the total organic carbon content.

4.3.2 Absolute carbon determination by combustion.

Measurements for absolute carbon determination were carried out at the N.E.R.C. Radiocarbon Laboratory, East Kilbride, using a microrig (Fig 4.2). Basically this rig can be considered as comprising of three interconnected sections, each of which may be isolated and with independent access to both high and low vacuum manifolds ie the combustion section, the gas scrubbing/collection train and the standard volume. Use of the microrig is described fully in Harkness and Miller (1980), and therefore only a brief description is given here. The sample (10 - 20 mg) was weighed into a quartz boat, which was inserted into the combustion tube. The combustion tube was closed and evacuated, before flushing with oxygen. The sample was then oxidised completely by heating to 650°C, which produces gaseous carbon dioxide and water, with non combusted oxygen remaining. The carbon dioxide was dried by passing it through a series of cryogenic traps and then purified by double distillation. The volume of carbon dioxide recovered was monitored in a calibrated manometer, allowing quantification of the sample carbon content.

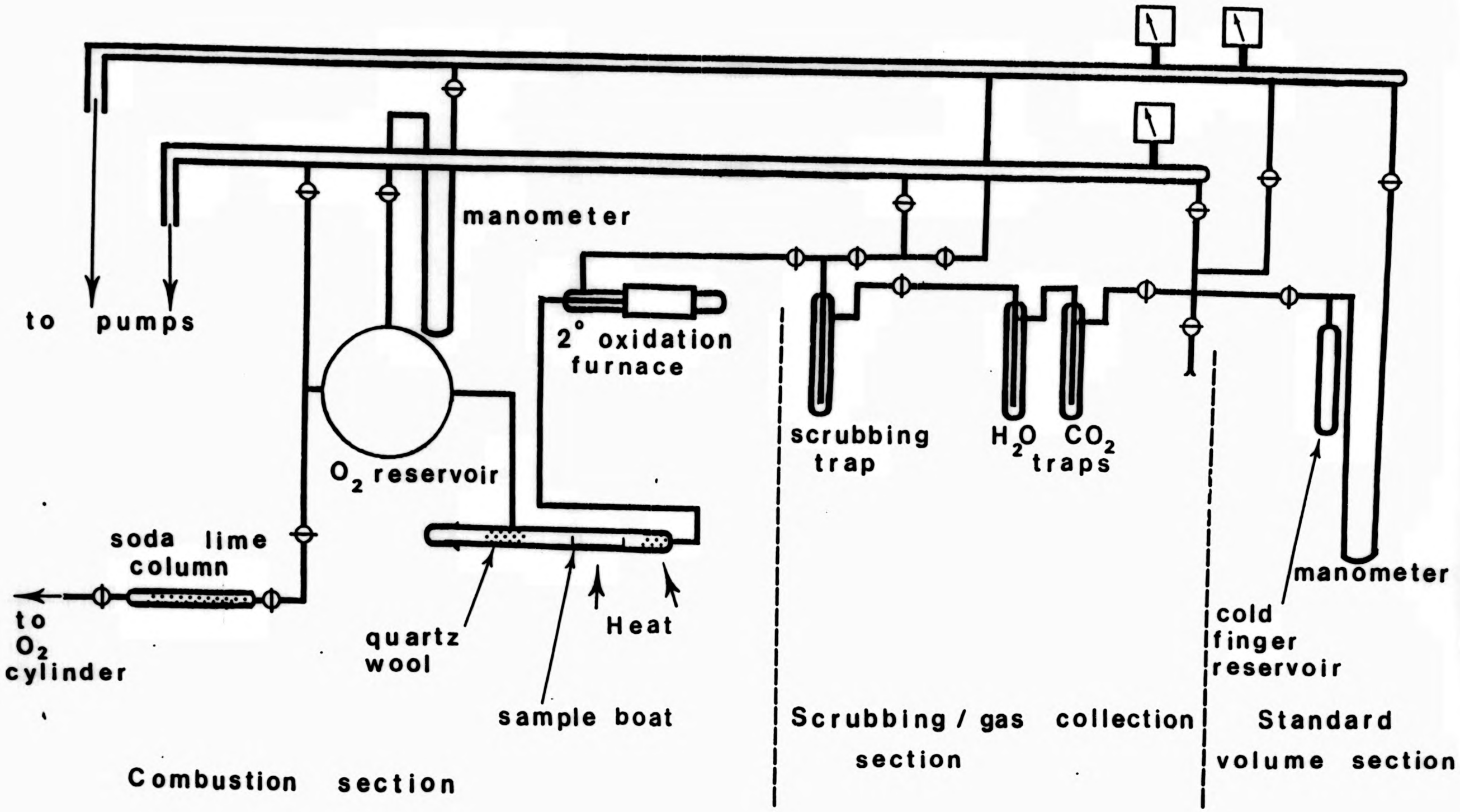


Fig 4.2 : Diagram of the micro-rig

A sample of the gas was also analysed on the mass spectrophotometer to estimate the $^{13}C/^{12}C$ ratio, to see if there was any evidence of isotopic fractionation.

4.3.3 Wet oxidation techniques

4.3.3.1 Introduction

Two slightly different oxidation techniques were adopted, but both were based on the oxidation of organic matter by chromic acid. The first was the Tinsley procedure as outlined by Kalembasa and Jenkinson (1973) which was used routinely by the Chemical Services Section, I.T.E. for soil and vegetation samples. In the second method (Sims and Haby, 1971), the titration stage was replaced by colorimetry to allow for rapid processing of samples, and this method could easily be adapted (Maciolek, 1962) to estimate the low carbon levels found in soil extracts, particularly after fractionation by gel filtration.

4.3.3.2 The Tinsley method

Reagents

1. 0.5 N potassium dichromate
2. Sulphuric - phosphoric acid mixture (5:1 v/v)
3. Indicator : 0.2 g N-phenylanthanilic acid in 100 ml 0.2% Na_2CO_3 solution.
4. 0.5 M ferrous ammonium sulphate.

Procedure

The air-dry sample (containing 5 - 15 mg organic carbon) was weighed into a 250 ml flat bottomed flask, and 20 ml dichromate added followed by 30 ml acid mixture. The flask was fitted with a vertical condenser placed on a heating mantle and refluxed for 20 minutes. After cooling the condenser was rinsed with water and indicator was then added to the contents of the flask before titrating against ferrous ammonium sulphate. A blank was treated in exactly the same way.

Calculations

Let weight of sample = Wg

If (blank - sample) ml ferrous ammonium sulphate ≡ ml 0.5 N dichromate used and 1 ml 0.5 N dichromate ≡ 1.5 mg organic carbon

Then amount C oxidised in 100 g air dry sample is

$$= (\text{blank sample}) \times \frac{1.5}{10^3} \times \frac{100}{W} \text{ g organic C}$$

To convert to a dry weight basis multiply by $\frac{100}{\%\text{ dry matter}}$

Validation

The validity of the Tinsley method was assessed against the combustion technique, by comparison of results obtained from analysis of 42 finely ground soil and litter samples (subsamples were taken using the cone quartering technique, Mullins and Hutchinson, 1982), taken from under various stands and at different soil depths within the Gisburn Experiment. A highly significant linear regression relationship was obtained:

$y = 0.852x + 1.18$ $\quad r^2 = 0.96,\ p < 0.001$

x = % C (combustion)

y = % C (Tinsley)

Increased scatter was noticed at the higher carbon values (30 - 40%C), which either reflects increased heterogeneity within the litter subsamples or incomplete oxidation. The regression line does not pass through the origin possibly because of inaccuracies introduced by the use of a conversion factor in the calculation.

4.3.3.3 Colorimetric carbon determination

Reagents

1. 1.0 N potassium dichromate
2. Sulphuric acid
3. Glucose

Procedure

The air-dry sample (0.5 - 0.1 g depending on C content) was weighed into a 250 ml conical flask and 10 ml 1.0 N potassium dichromate added followed by 20 ml concentrated sulphuric acid. The contents of the flask were mixed by swirling and left to stand for 30 minutes. The contents were transferred into a 250 ml volumetric flask and made up to 250 ml with distilled water. The solution was filtered through Whatman GF/C filter paper and the absorbance measured at 600 nm using a 1 cm cell in a Perkin-Elmer spectrophotometer. The carbon content of the samples were determined by calibrating the spectrophotometer using glucose standards

(0, 5, 10, 20 mg C) which had been digested in the same way as the samples. Soil extracts were treated in a similar manner, except that a known volume of of soil solution was added to the reaction vessel, and this was dried prior to digestion. Samples with low carbon contents (0 - 0.5 mg C) could be analysed by adjusting the reagent concentrations according to the micromethod of carbon determination (Maciolek, 1962).

Validation

The validity of this technique was assessed in the same way as the Tinsley method; the highly significant linear relationship obtained after analysis of 48 sample was:

$y = 0.899x + 0.946 \quad r^2 = 0.97, \; p < 0.001$

x = % C (combustion)

y = % C (colorimetric)

Increased scatter was again observed at high carbon concentrations and the regression line did not pass through the origin, the latter observation may be partially explained by the lack of sensitivity of spectrophotometers at low absorbance values (Reilley and Sawyer, 1961).

4.3.4 Loss-on-ignition and % carbon regression relationships

4.3.4.1 Introduction

Loss-on-ignition (L.O.I.) and its conversion to carbon content are perhaps the commonest ways of estimating organic matter contents of soils. The methods are based on the assumption (Christensen and Malmos, 1982) that:

a) L.O.I. is due only to organic matter

b) The carbon content of organic matter is constant

Although neither of these assumptions are strictly justified, L.O.I. is often used as a routine assay because it is quick and easy to perform. Errors arise due to loss of inorganic materials, especially when high temperatures (400 - 300°C) and long ignition times (16 - 24 hours) are used. These losses are reduced by using lower temperatures (375°C) but longer ignition periods (16 hours) are then required (Ball, 1964).

In order to take into account the problems mentioned above, two L.O.I. temperatures were compared and regression relationships established between L.O.I. and % C measured by the combustion and Tinsley methods.

4.3.4.2 Procedure

Two subsamples were taken from soil and litter samples, whose carbon content had already been determined. The subsamples were oven-dried (105° for 24 hours), and the loss-on-ignition determined in a Gallenkamp muffle furnace under the following conditions;

a) 375° C for 24 hours

b) 550° C for 1 hour

Validation

The results (Table 4.2) showed that there were good correlations between the two different L.O.I. temperatures and the two methods of carbon analysis. The relationships were all linear but did not pass through the origin, indicating that bound water and other volatiles were being lost (Howard, 1966). Increased scatter occurred at higher carbon levels.

Table 4.2 Relationships obtained between % carbon content and LOI.

Variables	Linear regression	r^2	
x = LOI (375° C)	y = 0.435x + 0.944	0.96	$p < 0.001$
y = % C (Tinsley)			
x = LOI (550° C)	y = 0.493x - 0.599	0.98	$p < 0.001$
y = % C (Tinsley)			
x = LOI (550°C)	y = 0.559x - 1.474	0.96	$p < 0.001$
y = % C (combustion)			
x = LOI (375° C)	y = 0.506x - 0.116	0.98	$p < 0.001$
y = % C (combustion)			

Since both L.O.I. regimes gave equally good estimates of the sample carbon contents, it was decided to adopt the more rapid procedure. In order to cover a greater range of soil conditions, the carbon content (Tinsley method) and L.O.I. (550° C for 1 hour) of another 44 samples were measured. The results are shown in Fig 4.3. The regression equation used for the routine assaying of soil samples was:

$y = 0.496x - 0.975 \quad r^2 = 0.97, \; p < 0.001$

y = % C (Tinsley)

x = L.O.I. (550° C for 1 hour)

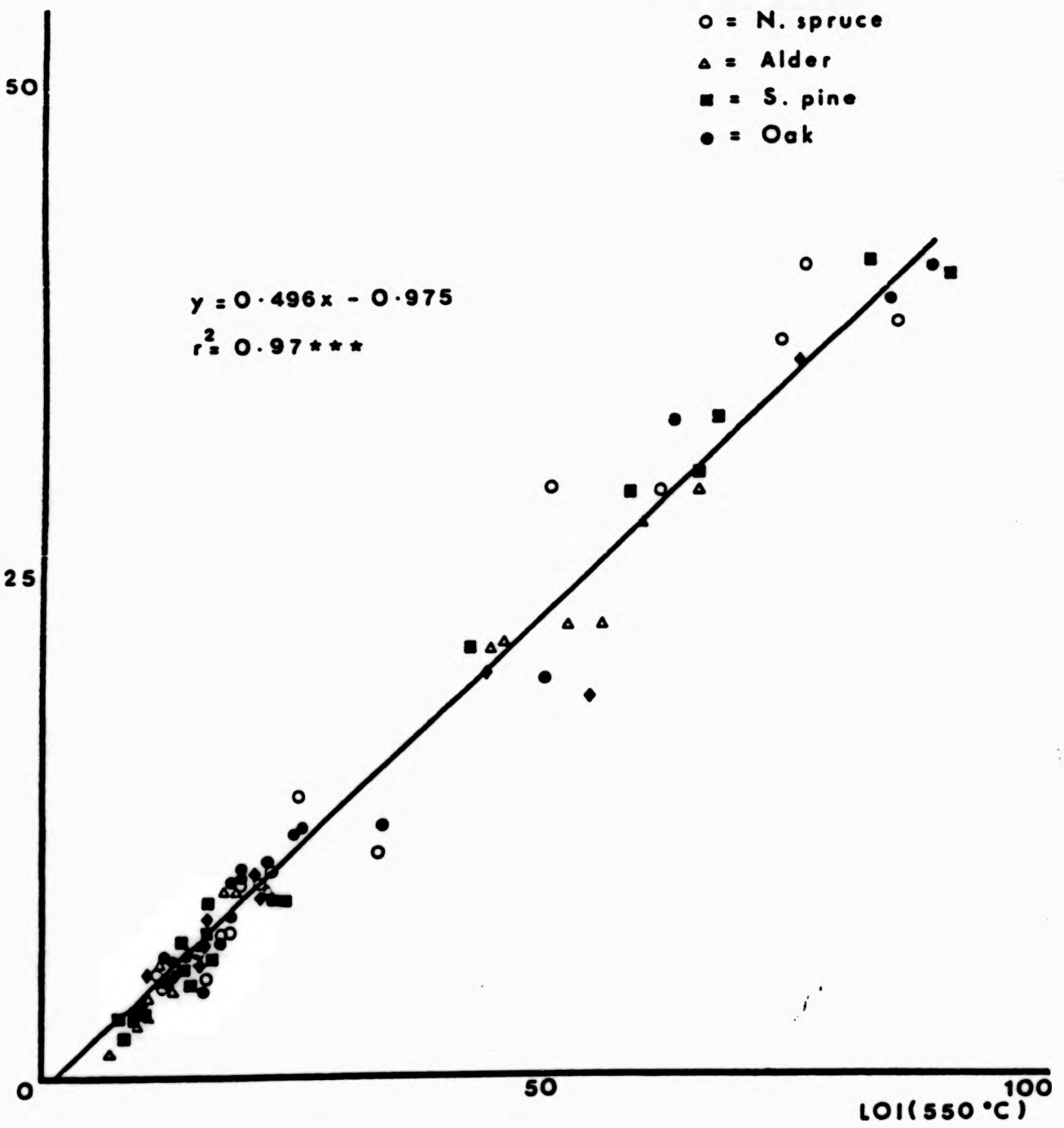


Fig 4.3 Relationship between LOI and %C of soil and litter from different treatments in block II.

4.4 Determination of ^{14}C and ^{13}C enrichment values in soil carbon.

4.4.1 Introduction

Previous work at Gisburn (Chap. 3.3.4) has indicated that there was little difference in ^{14}C enrichment values in the soil under the tree stands, therefore, it was decided to investigate the enrichment values of soil extracts as well as the whole soil (0 - 5 cm), since the presence of a large background of 'old' grassland organic matter could be masking differential ^{14}C enrichment of the total carbon content of the various tree plots. In addition, samples were also taken from the Sitka spruce age series to see whether the pattern of ^{14}C enrichment in the soil had been altered by the length of time that the soil had been under afforestation.

4.4.2 Procedure for soil extraction

25 g sieved ($\leq$2 mm) air dry soil were weighed into each of four 250 ml plastic centrifuge bottles. The bottles were filled with 0.05 M sodium borate and then shaken for 1 hour before centrifugation at 3 x 10^3 rpm for 30 minutes. The supernatant was decanted off and filtered through Whatman GF/C to remove and recover rootlets and plant fragments. The solid residue was then resuspended in fresh borate solution and extracted in the same way, until the supernatant was clear and virtually colourless (about 10 extraction cycles). The insoluble residues were washed from the centrifuge bottles using distilled water and the washings filtered through glass fibre paper. The washings were combined with the borax soluble extract. The insoluble residue was dried to a constant weight in an air cabinet.

The combined extract was adjusted to pH 3 by the addition of 2 M sulphuric acid and simmered on a hot plate. The acidified filtrate was left to stand overnight to allow the precipitate to coagulate and settle in a beaker. The bulk of the solution was decanted off, and the remaining precipitate centrifuged and the final solution recovered. The acid insoluble precipitate was washed with cold water and dried to constant weight in an air cabinet. The acid soluble filtrate was evaporated to near dryness on a hot plate, with final drying to constant weight in a vacuum oven.

The rootlets/plant fragments were digested in hot water (80°C for 24 hours), recovered by filtration and dried to a constant weight.

The weight of each fraction recovered was recorded, and its weight contribution as a percentage of the initial soil sample calculated. 0.5 g subsamples were retained for independent semi-micro analysis. The remainder of each fraction was then passed for ^{14}C age measurement.

Once the results from the above fractionation procedure were known (see Chapter 5.7), it was apparent that the initial sieving was inadequate in separating rootlets and undecomposed vegetation material from the amorphorus soil. Consequently a more stringent initial selection was adopted, of boiling 100 g of soil in water to break down the granules, the plant debris was then isolated by wet sieving through a 1 mm mesh. The amorphous soil was then extracted with 0.05 M sodium borate as described previously, but with no recovery of an acid soluble fraction.

4.4.3 Sample preparation and determination of ^{14}C enrichment.

The technique used to determine the relative abundance of $^{14}C/^{12}C$ was in routine use at the NERC Radiocarbon Laboratory, East Kilbride. As the method is already fully documented (Harkness and Wilson, 1972), only a brief description will be given here. Basically the method involves the conversion of carbon in the soil via carbon dioxide and acetylene to benzene, which is a suitable medium for assessing the abundance of ^{14}C using liquid scintillation counting techniques. The apparatus is shown in Fig 4.4 The sample was placed in the combustion vessel and burnt in oxygen (100 - 200 psi) to produce carbon dioxide. The carbon dioxide produced was cleaned and the volume measured. The carbon dioxide was reacted with molten lithium to form lithium carbide, addition of distilled water to the cold carbide produced acetylene. The acetylene was purified by passing through dry-ice traps and phosphoric acid columns before being passed over a heated catalyst to produce benzene. A scintillant was added to an accurately weighed aliquot of this benzene and the specific radiocarbon activity was determined in a liquid scintillation counter.

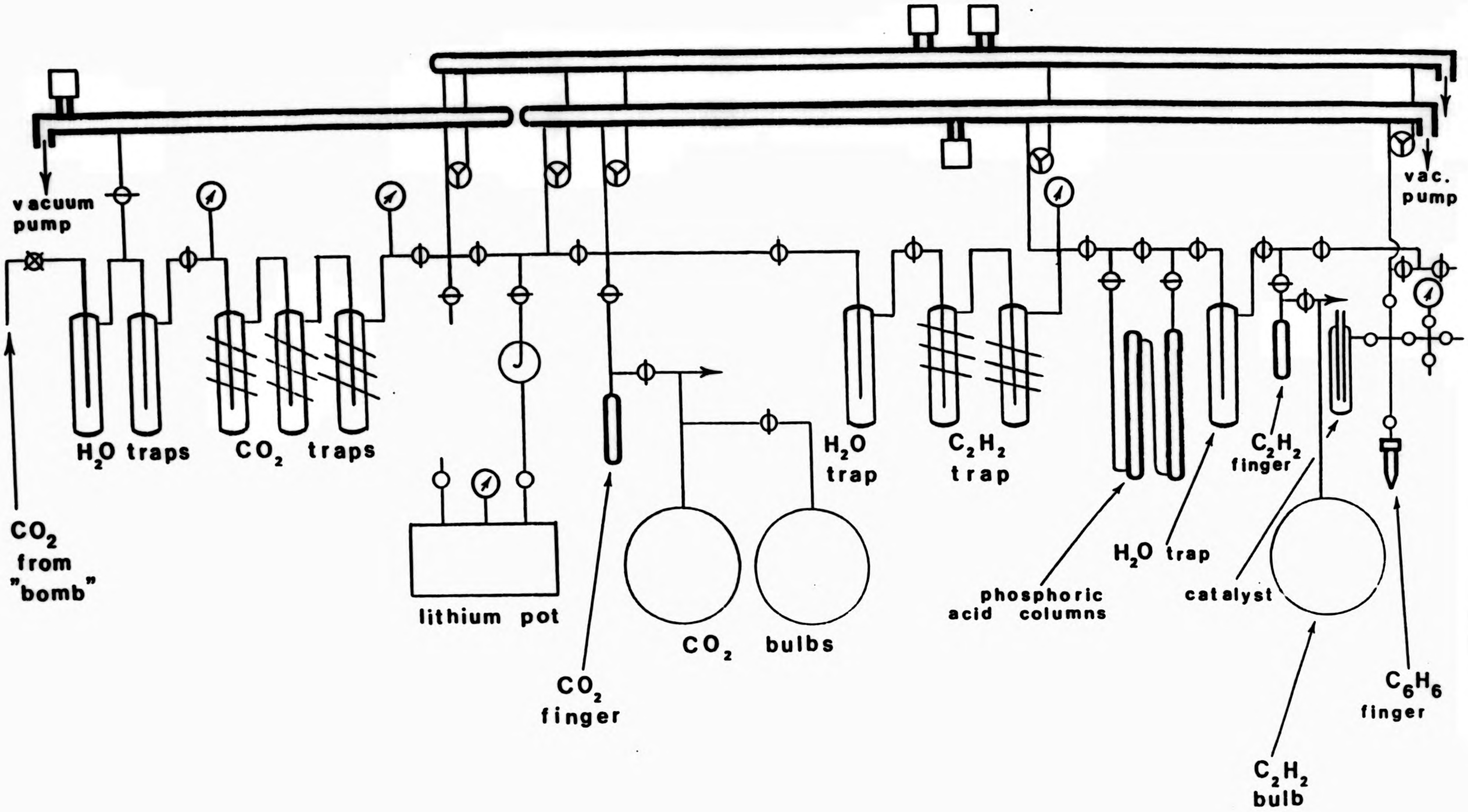


Fig 4.4 : "Bomb" benzene synthesis rig

4.4.4 Determination of ^{13}C enrichment using mass spectrometry.

A VG 602 B mass spectrometer was used to determine the ^{13}C enrichment of carbon dioxide gas samples obtained from the benzene synthesis rig and the microrig. This mass spectrometer has a double collector and double inlet system. Ladyman (1982) gave a detailed description of the principles and operating procedures for the VG 602 B, so only a brief summary will be given here.

Basically, a mass spectrometer is an instrument which produces, accelerates, deflects and detects ions from a given sample so as to measure its isotopic composition. The ions are produced from the sample gas by bombarding it with electrons. The ions are accelerated by passing through a potential difference and the ion beam collimated by slits and plates, which can be set at various different potentials in the source. The ion beam is then deflected by a magnetic field and split into beams of similar masses, two of which are selected and enter the detectors, one into each detector. The double collector arrangement is necessary to register the two ion beams, the simultaneous recording of both isotopes means that any fluctuations in the ion beam intensity does not affect the ratios being measured. The use of the double inlet system is essential, since it allows the comparison of a sample of unknown

isotopic composition with that of a reference gas of known composition. Thus the results can be quoted as enrichment (δ), rather than an absolute ratio:

$$= \left[\frac{Rx}{R_r} - 1 \right] 10^3 \quad 0/00$$

where R_x = unknown ratio

R_r = reference ratio

The most popular $\delta^{13}C$ enrichment scale is based on carbon dioxide gas prepared from Belemmite (Belemmitella americana) from the Cretaceous Peedee formation of South Carolina, normally abbreviated to PDB. Although the original supply of PDB limestone standard has long been exhausted, the use of this reference scale is maintained via 'secondary' standards. The ones used for this study were Solenhofen limestone ($\delta^{13}C_{pdb}$ = -1.06 0/00) and graphite ($\delta^{13}C_{pdb}$ = -27.79 0/00) and are supplied by the American National Bureau of Standards.

4.4.5 Definition of ^{14}C enrichment values.

i) Radiometric enrichment

$$d\ ^{14}C\ 0/00 = \left[\frac{(^{14}C/^{12}C)\ \text{sample}}{0.95\ (^{14}C/^{12}C)\ \text{standard}} - 1 \right] 10^3$$

The international reference standard is oxalic acid issued by the U.S. National Bureau of Standards.

ii) Normalised radiometric enrichment

$$D\ ^{14}C\ 0/00 = d\ ^{14}C - \left[(2\ \delta\ ^{13}C \text{ sample} + 50)\ (1 + \frac{d\ ^{14}C}{10^3}) \right]$$

D ^{14}C is used to denote instances where the measured radiometric enrichment (d ^{14}C) has been normalised, to compensate for natural and laboratory induced fractionation.

iii) Percent modern notation

$$\% \text{ modern} = \left[1 + \frac{D\ ^{14}C}{10^3} \right] 10^2$$

This is used as an alternative to d ^{14}C or D ^{14}C, and in particular where the measured enrichment relates to organic material of post nuclear origin.

4.5 Gel filtration

4.5.1 Introduction

Initially it was intended to use exactly the same extraction procedure for gel filtration, N.M.R. and radiocarbon measurements to allow direct comparison of results. However, problems developed during sample concentration, which meant that slightly different methods were used. During preparation of samples for radiocarbon dating, concentration of extracts was achieved by acidification and heating. Although this treatment is unlikely to affect the distribution of the radiocarbon, it will lead to chemical changes, and is therefore inappropriate when studying the chemical nature of the extract. Consequently, less drastic methods of concentration were needed for the qualitative studies ie freeze-concentration and rotary film evaporation. Problems arose during the initial concentration using the freeze concentrator, as the high levels of sodium tetraborate (even after dialysis) interfered with ice-crystal formation (Baker, 1970) rendering the technique unsatisfactory.

Eventually 0.025 M sodium borate was adopted as a suitable extractant, since dialysis could reduce the salt content sufficiently to allow the freeze-concentrator to work effectively, but this was associated with a decrease in extraction efficiency from 30% (0.05 M sodium tetraborate organic carbon to less than 20% (0.025 M sodium tetraborate).

4.5.2 Preparation of soil extracts

50 g of sieved ($\leqslant$ 2 mm) air-dried soils were extracted by shaking with 0.025 M sodium borate for 30 minutes. The suspension was centrifuged (3,000 rpm for 30 minutes); the supernatant was poured off and retained, and the residue extracted with fresh sodium borate. The initial extraction was performed with 100 ml sodium borate, as a large amount of liquid was taken up by the highly organic soil during rewetting, subsequent extractions were performed using 50 ml extractant. The extraction procedure was repeated 20 times until the solutions were almost colourless.

The extracts were filtered through Whatman GF/C filter paper prior to dialysis through Visking tubing. The extracts were then initially concentrated in a freeze concentrator (Benham, 1985), as this technique minimizes thermal and biochemical decomposition. The apparatus illustrated (Fig 4.5) in an edge freeze concentrator, where the vessel containing the sample is cooled by heat exchange. The sample is stirred during cooling so that only pure ice forms on the walls of the vessel, whilst the nonaqueous matter remains unfrozen in a reduced quantity of water. The samples were then filtered through GF/F and 0.45μ membrane filters to lower the ash content, before concentration to a volume of 10 - 30 ml (15 - 40 mg C ml^{-1}) on a Buchl rotary film evaporator.

It was necessary to dilute the samples by a fifth and refilter (0.2μ), after preliminary runs on the gel filtration column showed poor separation which was probably due to high sample viscosity, and contamination of the gel surface by particulate material.

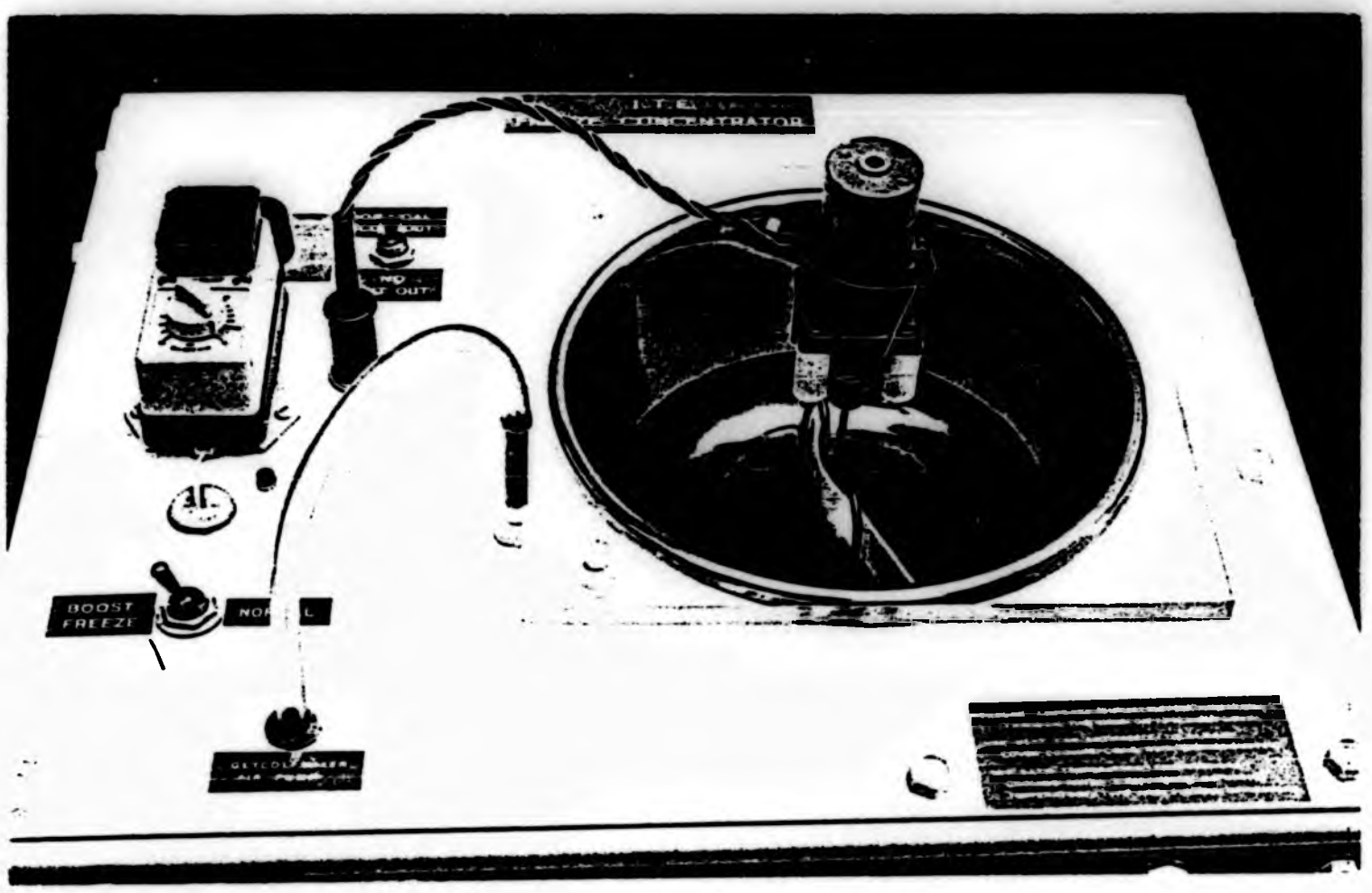


Fig. 4.5 Layout of the freeze concentrator.

4.5.3 Procedure for gel filtration experiments

Sephadex G - 75 gel was swollen in 0.025 M sodium tetraborate and packed in a 2.5 cm x 90 cm column according to the manufacturers instructions. The homogeneity of the bed was checked with Blue Dextran (Pharmacia, Uppsala), which was also used to estimate the void volume, (Vo) (Fig 4.6). The elution volume (Ve) was estimated with potassium dichromate. Once the column was set up, 2 ml of sample was applied to the drained bed surface using an applicator cup. When the sample had entered the gel, the column was filled with 0.025 M sodium borate and connected to a reservoir. The column flowed under gravity and 9 ml aliquots were

collected using a fraction collector. The absorbance of the fractions was measured at 400 nm, since elution patterns do not usually vary significantly when measured at different wavelengths (Roletto et al. 1982), even though humic substances wtth dissimilar nominal molecular weights may show different extinction coefficients (Ladd, 1969).

4.5.4 Validation

The results of a typical gel filtration experiment using a sodium tetraborate soil extract is shown in Fig 4.6. Fractionation of the sample was shown to be by molecular weight alone as:

1) Analysis of the fractions for carbon showed 100% recovery of applied sample

2) Potassium dichromate was eluted after the major sample separation. The tailing off beyond Ve, indicates that slight reversible adsorption had occurred.

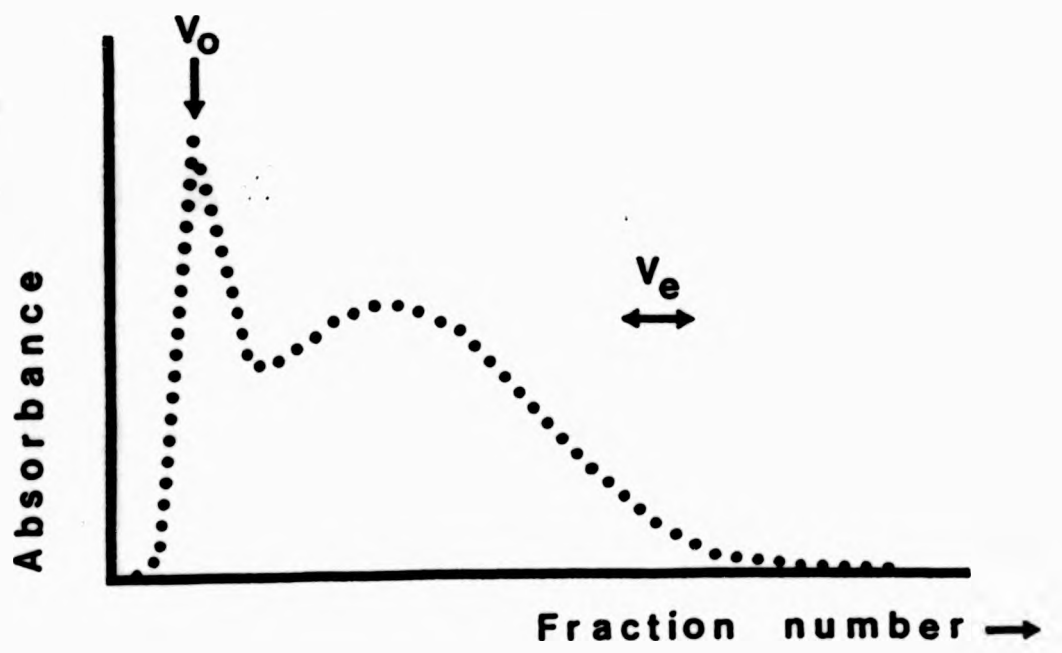


Fig. 4.6 Typical results obtained after fractionating a soil extract by gel filtration.

4.6 Analysis of seasonal changes

4.6.1 Carbon content

The carbon content of litter and soil samples was determined by loss-on-ignition, using the regression relation previously mentioned (Chapter 4.3.4).

The results were expressed on a volume basis (e.g. TC ha^{-1} per 0.5 cm soil).

4.6.2 Moisture content

The moisture content of air dry samples (35°C) prior to sieving was determined using the following equation:

$$\% \text{ moisture} = \frac{\text{loss in weight on drying}}{\text{initial sample weight}} \times 100$$

4.6.3 Bulk density

The bulk density of the whole soil was calculated using the equation:

$$\text{bulk density} = \frac{\text{oven dry weight soil}}{\text{volume of soil core}}$$

4.6.4 pH

The pH of air-dried samples were determined according to the method outlined in the Soil Survey Book of Laboratory Methods (Avery and Bascombe, 1974).

4.6.5 C/N ratios

In order to calculate C/N ratios, total N analyses were performed on a limited number of soil samples taken from pure stands of alder, Scots pine, Norway spruce and the Norway spruce half of the Norway spruce/Scots pine mixture. The analyses were carried out by the ITE Analytical Section (Merlewood) using the Kjeldhal method (Allen et al. 1974).

4.6.6 Litterfall

Aerial litterfall was collected over six weekly periods in each of the pure stands. There were five litter traps per plot.

The litter traps were made by suspending nylon bags inside the dustbins (surface area of traps = 0.72 m^2). Holes were drilled near the base of the dustbins to allow for drainage of rain water.

4.7 Nuclear magnetic resonance spectroscopy

The scanning of the soil extracts using NMR spectroscopy was carried out by the Department of Chemistry, University of Stirling.

The NMR spectrophotometer was set up according to the instructions outlined by Newman and Tate (1984), and the samples scanned over a 72 hour period.

4.8 Statistical Methods

4.8.1 Introduction

The sampling procedures (Chapter 4.1) for examining comparative differences between tree stands were chosen, so that they could be easily analysed using standard statistical methods. These methods are briefly outlined below, but can be found in detail in texts such as Steel and Torrie (1980); Sokal and Rohlf (1969).

4.8.2 Analysis of designed experiments

a) Randomized complete block

In an attempt to reduce the residual variance and hence increase efficiency, the plots were laid out in three blocks. Each block contains every treatment just once, so that every treatment within a block is affected similarly. In an analysis of variance of a randomized complete block design, part of the variation is attributed to block effects, leaving a smaller residual variance against which to test the treatment effects with greater sensitivity. However, the efficiency of this design in the Gisburn experiment was greatly reduced due to the heterogeneous nature of the soil within Block I, consequently comparison of means was performed on data from individual blocks using either one-way or two-way analysis of variance.

b) Completely randomized design

i) One-way analysis of variance

One-way analyses of variance were used on several occasions (e.g. Chapter 5.1.1 and 5.3), where there was only one assignable cause of variation in the analysis and a completely randomized design had been used.

ii) Two-way cross-classification analysis of variance

This analysis was used where there were two assignable causes of variation by which the data could be classified e.g. in the analysis of seasonal changes (Chapter 5.4), where differences between tree stands and over time were examined.

The cross-classification analysis allowed for the detection of any interaction factors.

c) Homogeneity of variances and transformations.

An important assumption when performing analysis of variance is that the plot variances are homogeneous. Homogeneity of variances was checked using Bartlett's test. When Bartlett's test suggested that there was heterogeneity of variance (e.g. Chapter 5.4.1), Taylor's power law was used to give the transformation which would stabilize the variances.

d) Multiple comparisons of means.

Significant differences between pairs of means were tested using Tukey's honestly significant difference test.

4.8.3 Regression analysis and correlation.

Regression analysis was used to examine relationships between variables (e.g. Chapter 5.4.4). In some cases linear relationships were found but tests were carried out to check for curvature of the relationships. Where there was more than one dependent variable, multiple regression analysis was used to derive a regression equation for predicting the independent variable in terms of the dependent variable.

r is a measure of linear association between 2 variables

r^2 is the proportion of variance of y that can be attributed to its regression on x

4.8.4 Test for randomness

Kendall's test for randomness was applied to the seasonal sampling data (Chapter 4.6), to examine whether or not observed fluctuations were random in nature.

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Preliminary sampling in Block II

5.1.1 Carbon content

The total C content of the soil was compared using ten replicate cores per plot, for the litter layer and each 5 cm layer down the profile, using one-way analysis of variance and Tukey's 'HSD'. Tukey's 'HSD' is a multiple comparison of means test which uses an experimentwise error rate (expected proportion of experiments with one or more erroneous statements when the overall null hypothesis is true). It is therefore more conservative than the multiple comparison of means test, which use a comparisonwise error rate (proportion of all comparisons which are expected to be erroneous when the null hypothesis is true). The results are shown diagrammatically in Fig 5.1. (Full results are shown in Appendix 1).

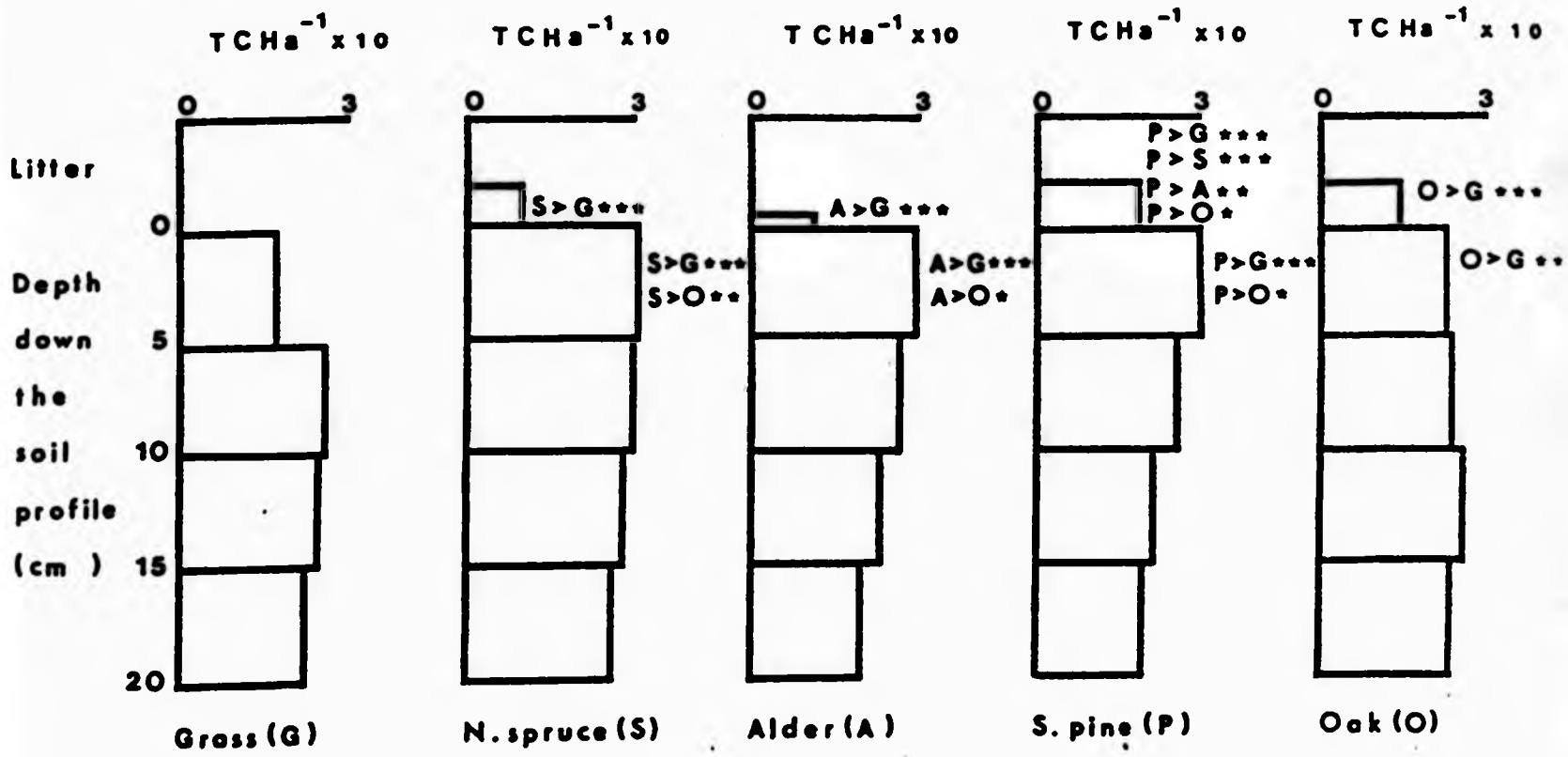


Fig.5.1 Distribution of carbon ($TCha^{-1}$ x 10) under different treatments in block II, sampled in September 1982 (***$p < 0.001$, **$p < 0.01$, *$p < 0.05$).

The most noticeable effect of afforestation relative to the grassland site was the development of the forest floor and the increased carbon content of the 0-5cm soil.No statistically significant changes in carbon content were found below this depth.

However, the grassland site can not be regarded as a true experimental control, since sheep were removed from this plot at the start of the experiment. Grazing plays an important role in the organic matter cycling on upland pastures (Floate, 1970). The removal of sheep is often associated with a slowing down of organic matter turnover, and consequently a build up of organic material on the soil surface.

Christensen(1982) reported that there had been a decrease in organic carbon under the trees relative to the grassland soil(Fig 5.2).The major discrepancy between the two data sets occurs in the grassland site, and a comparison of the percentage carbon contents of soil in this plot, shows that Christensen recorded much higher values(Table 5.1) than did this present study.

Table 5.1 Differences between %C down the profile in the grassland plot in 1981 and 1983.

Christensen(1981)		1983	
Depth(cm)	%C(mean+SD)	Depth(cm)	%C(mean+SD)
F(0-7)	52(2.6)	Litter(negligible)	
A (7-11)	30(6.3)	0-2.5	25(9.3)
A (11-28)	10(2.8)	2.5-5.0	9(1.3)
		5-10	6(0.2)
		10-15	6(0.5)
		15-20	4(1.0)

The grassland plot differs from the tree plots by having a thick living root mat on top of the mineral soil, but with negligible dead leaf and root material, so it would appear that Christensen included this root mat in his estimation of grassland carbon content.In addition the %C content of the A horizons was much higher than that found in the present study, which suggests that there was either incomplete separation of root material from the mineral soil, or it could be a result of inadequate sampling, as Christensen took samples from the sides of only one soil pit.

The results from this study show that differences among tree species are limited to the much greater development of the forest floor under S. pine, and the apparent loss of carbon in the 0-5cm soil under oak relative to the other tree species. These differences have probably arisen as a result of varying rates of decomposition of litter and root material and their incorporation into the soil. In the oak plot, the initial planting was at half the spacing of the other trees, resulting in a much greater disturbance of the soil, which may have caused enhanced decomposition of the organic matter.

There was no evidence that afforestation, particularly with conifers, had caused a redistribution of soil organic matter, as has been observed in Europe (Miles,1985). This may be partially due to poor tree growth, and also due to the comparatively short time that the stands have been planted.

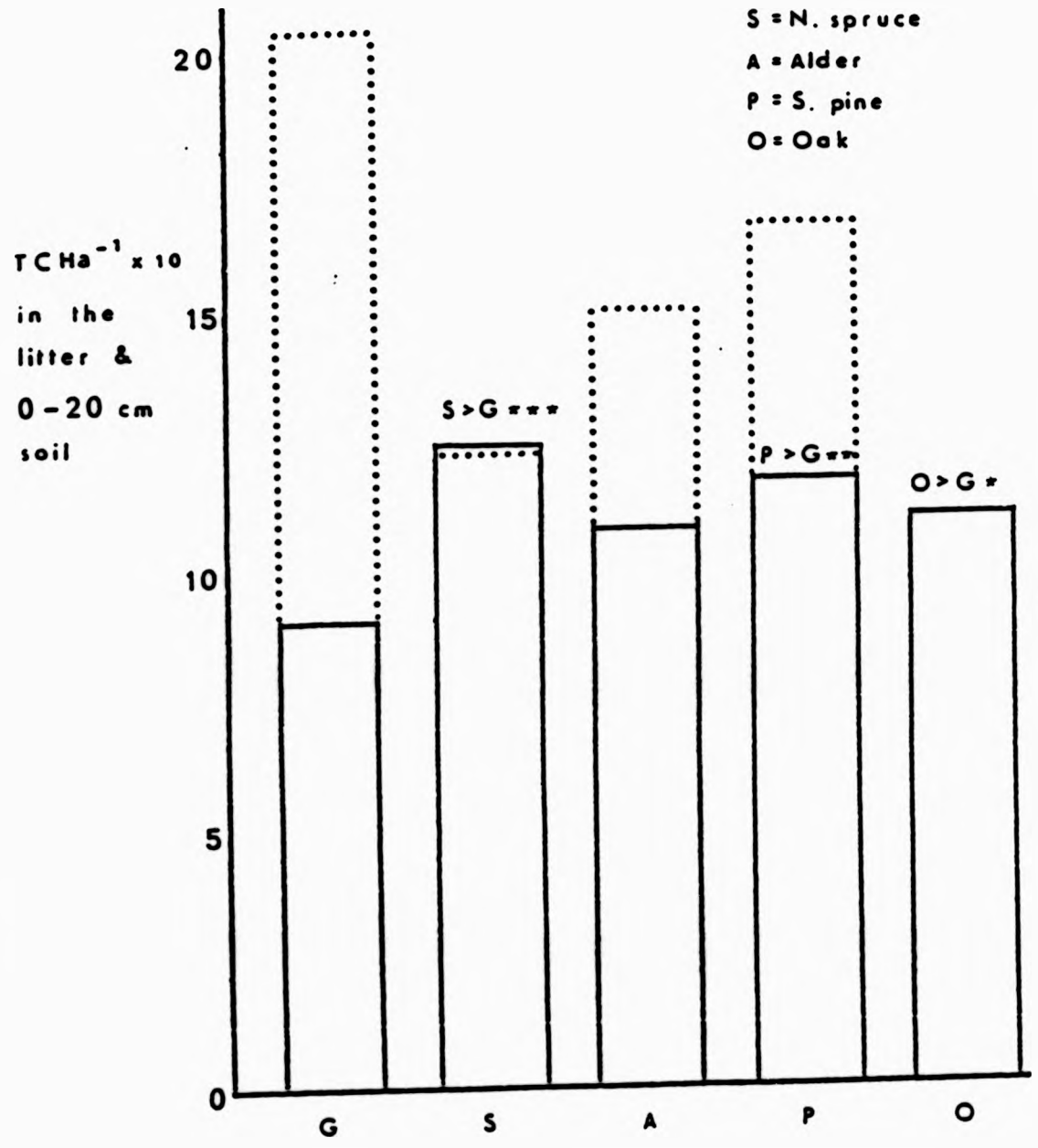


Fig 5.2 TC ha^{-1} x 10 in the litter and 0-20 cm soil under the different treatments. Dotted lines represents data from Christensen (1982).

5.1.2 Soil bulk density

Soil bulk densities were measured primarily so that the soil carbon content could be expressed in terms of volume rather than of mass, as this is more relevant to plant growth, since plant roots invade a given volume of soil rather than a given mass (Gosselink et al, 1984).The results were also used to examine whether the individual tree species had induced changes in the physical nature of the soil. The bulk densities were very variable particularly in the top soil, but in spite of this, the bulk densities under S. pine and alder were in general higher than those in the other plots(Table 5.2).Grieve(1978) found that bulk densities were higher under deciduous species compared with conifers, but in a later study found no differences between grassland and woodland sites(Grieve, 1980). A curvilinear relationship between percentage carbon and bulk density (Fig 5.3) was obtained. Samples from the grassland and oak plots with high percentage carbon contents had lower bulk densities, than samples from other plots with corresponding carbon values.

Table 5.2 Bulk density (gcm^{-3}) with % coefficients of variation, at different depths(cms) down the soil profile.(***p < 0.001, **p < 0.001 *p< 0.05).

Depth	Grass(G)	N.spruce(S)	Alder(A)	S.pine(P)	Oak(O)
0-2.5	0.07(1.4)	0.31(8.1)	0.28(3.2)	0.28(1.4)	0.35(14)
2.5-5	0.38(4.2)	0.59(2.7)	0.61(2.6)	0.58(2.8)	0.47(1.9)
		S>G**	A>G**	P>G**	
5-10	0.68(0.5)	0.74(3.4)	0.81(1.1)	0.77(3.2)	0.7(2.3)
10-15	0.73(2.2)	0.79(1.1)	1.01(0.9)	0.91(2.7)	0.85(1.9)
			A>G***	P>G**	
			A>S***		
			A>O**		
15-20	0.9(2.8)	0.9(1.0)	1.15(3.1)	1.21(1.3)	0.94(0.96)
			A>G**	P>G***	
			A>S**	P>S***	
			A>O*	P>O***	
			A>O**		

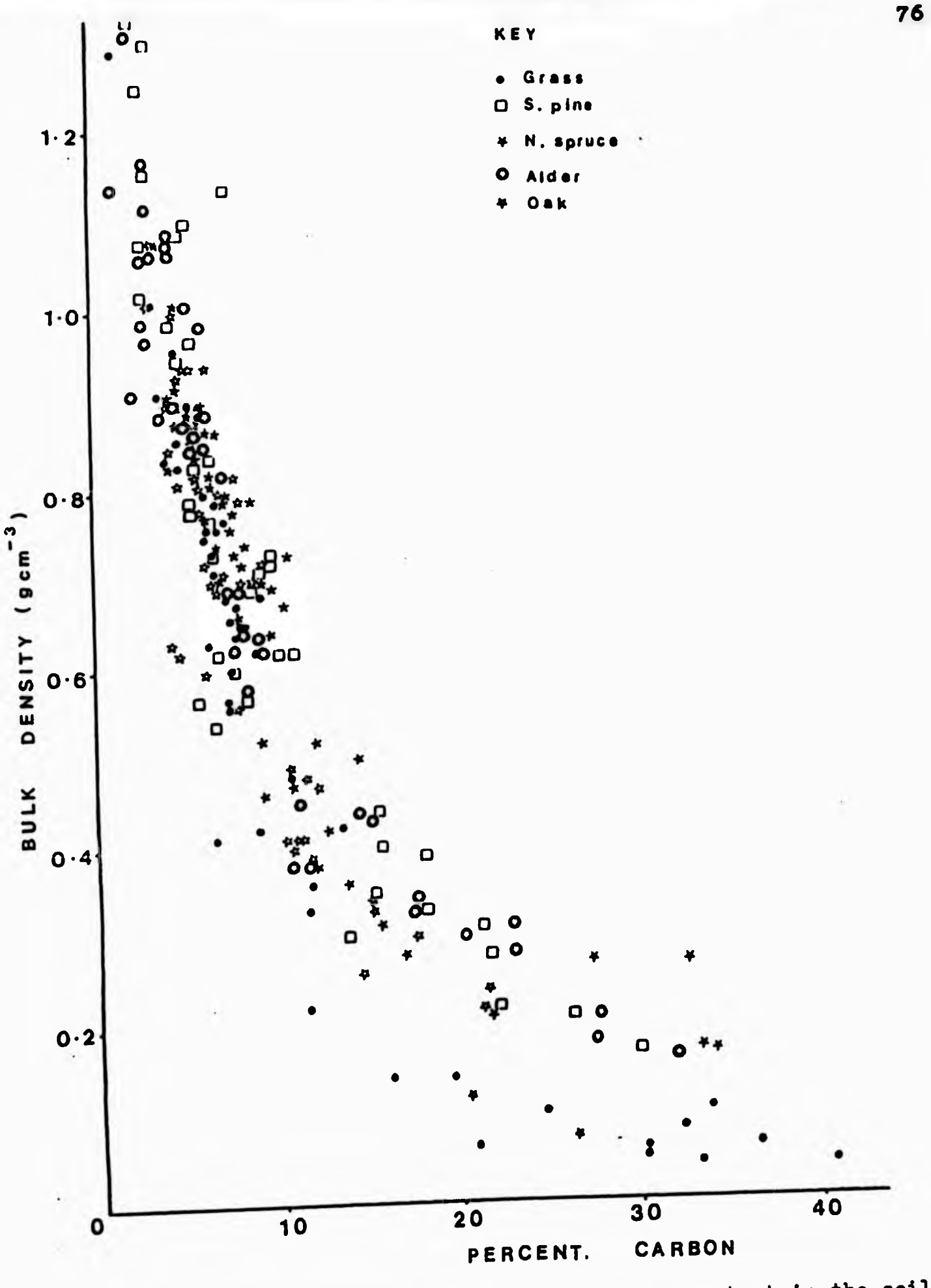


Fig 5.3 Change in bulk density with percentage carbon content in the soil under pure tree stands and the grassland site in block II.

The best model for the curves was obtained using an exponential relationship.The data sets were compared by analysis of covariance, after the relationships were expressed in a linear form by taking $\log_e$ of the y axis (Fig 5.4).The results of this analysis showed a clear difference between the BD/%C relationships obtained for oak and grassland plots compared with those for the alder, N.spruce and S.pine plots.There were no significant differences with respect to either parallelism or elevation within these two groups, but marked differences occurred between the groups($p<0.001$).Although organic carbon content is often the best predictor for soil bulk densities (Alexander, 1980), many other factors such as moisture, sand, silt and clay content also have an influence.At Gisburn, variations in the %C/BD relationships probably arise due to differences in soil moisture content related to the canopy type.Interception loss from conifer crops can proceed at three times the rate for grass(Ford, 1984), and is usually greater for evergreen than for deciduous trees(Nutter, 1978).Consequently the grassland site is likely to be much wetter than the tree stands.

Of the two deciduous trees plots planted, the oak has not grown as well as the alder and its canopy is more open. Thus the soil under the oak plot is probably not subject to the same transpirational loss as the alder plots, and the soil moisture content is likely to be similar to that of the grassland plot. As the bulk density is affected by the moisture content, particularly in highly organic soils (Greacen and Sands, 1980), these differences in moisture content may explain why samples from the grassland and oak plots with high percentage carbon contents had lower bulk densities, than samples from other plots with corresponding carbon contents. The relationships between bulk density, percentage carbon and percentage moisture were further examined as part of the seasonal sampling programme (Chap. 5.4.4.)

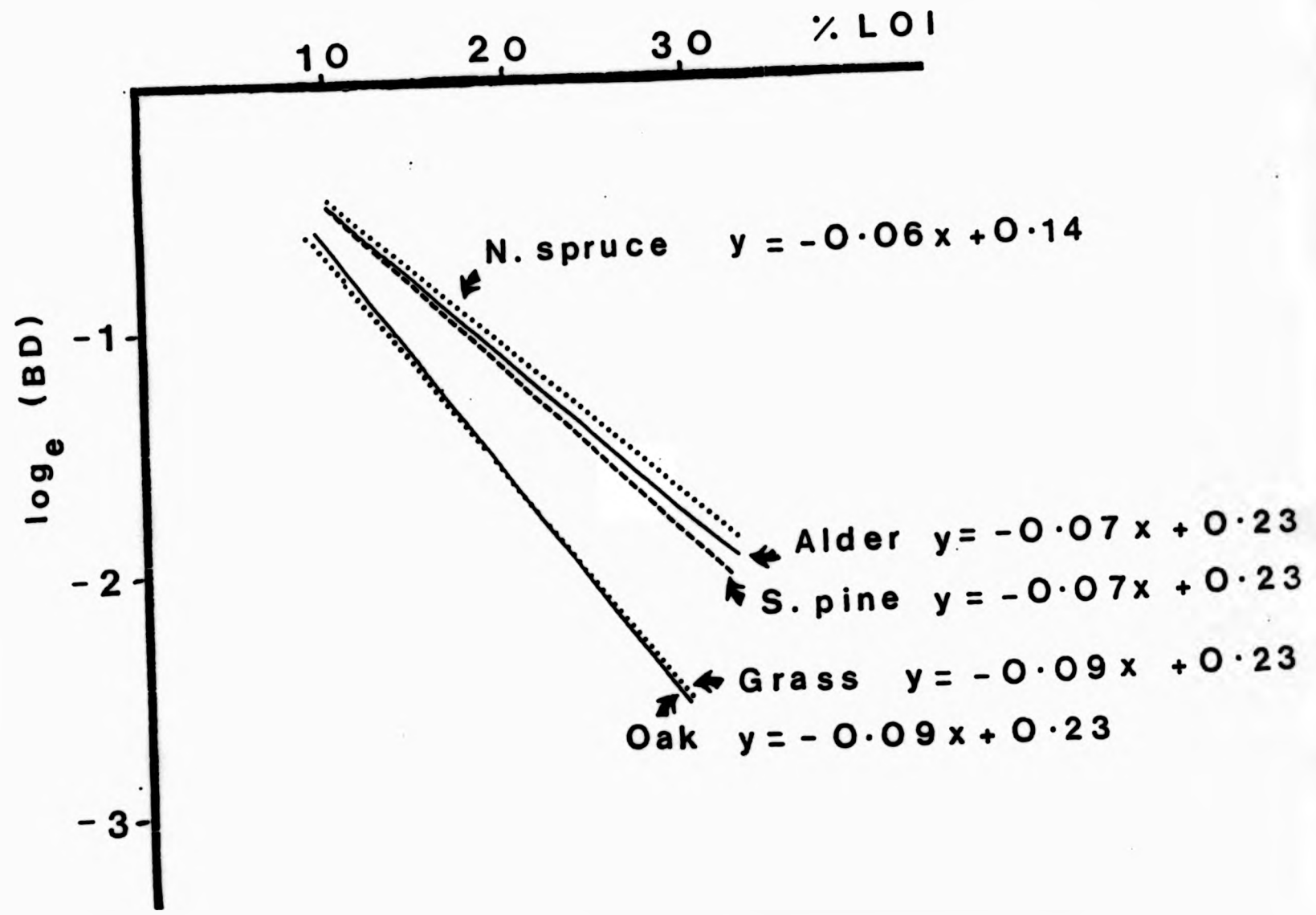


Fig 5.4 Relationship between loss-on-ignition (LOI) and $\log_e$ bulk density for soil under pure tree stands and the grassland site in block II.

5.2 Investigation of organic carbon content in the surface soils of all three blocks.

Comparison between species and blocks was initially performed using analysis of variance of a randomized block design.Significant heterogeneity of variance between treatments was detected which could not be removed by transforming the data. However analysis of variance is fairly robust to departures from homogeneity of variance provided the number of replicates per treatment are equal, (Scheffé, 1959), which they were in this experiment.Due to the significant interaction between blocks and species, comparisons of means (Fig 5.5 and Appendix 2) were done on each block separately.

The results obtained for block II in January 1984 were similar to those from the previous September, except that the carbon content of the alder litter layer had declined from 12(±0.7) to 5(±0.6) $TCha^{-1}$ which reflects the rapid decomposition of certain components of the forest floor, particularly the leaves.

The only consistent trend within all three blocks was that there was significantly more carbon in the litter layer under S. pine than under N. spruce and alder. There were no differences between the spruce half of the mixtures, neither in the litter layer nor in the 0-5 cm soil, even though marked differences in the earthworm population, nitrogen mineralization rates and phosphorus status had been found in these stands (Brown and Harrison,1982). These earlier results indicated that there were differences in the rate of carbon turnover in the mixed N. spruce stands, but there appears to have been no effect on the size of the soil organic matter pool.

Several between block differences were detected, in particular the carbon content of the 0-5cm soil of the grassland plot in block II was significantly less than in the other two blocks.This indicates that the apparent increase in the organic matter in the 0-5 cm soil of the tree plots relative to the grassland soil, in the preliminary study was not characteristic of the whole experiment.

It is apparent from these results, that due to within block heterogeneity, the use of blocking has not helped the data interpretation.If the soil had been surveyed prior to setting up the experiment, each block could have been planted on a more homogeneous site than has actually happened(Fig 2.1).An additional problem, is that the site is sloping and the blocks were established down the slope, whereas it would have been better to orient the blocks at right angles to the gradient(Cellier and Correll, 1984).

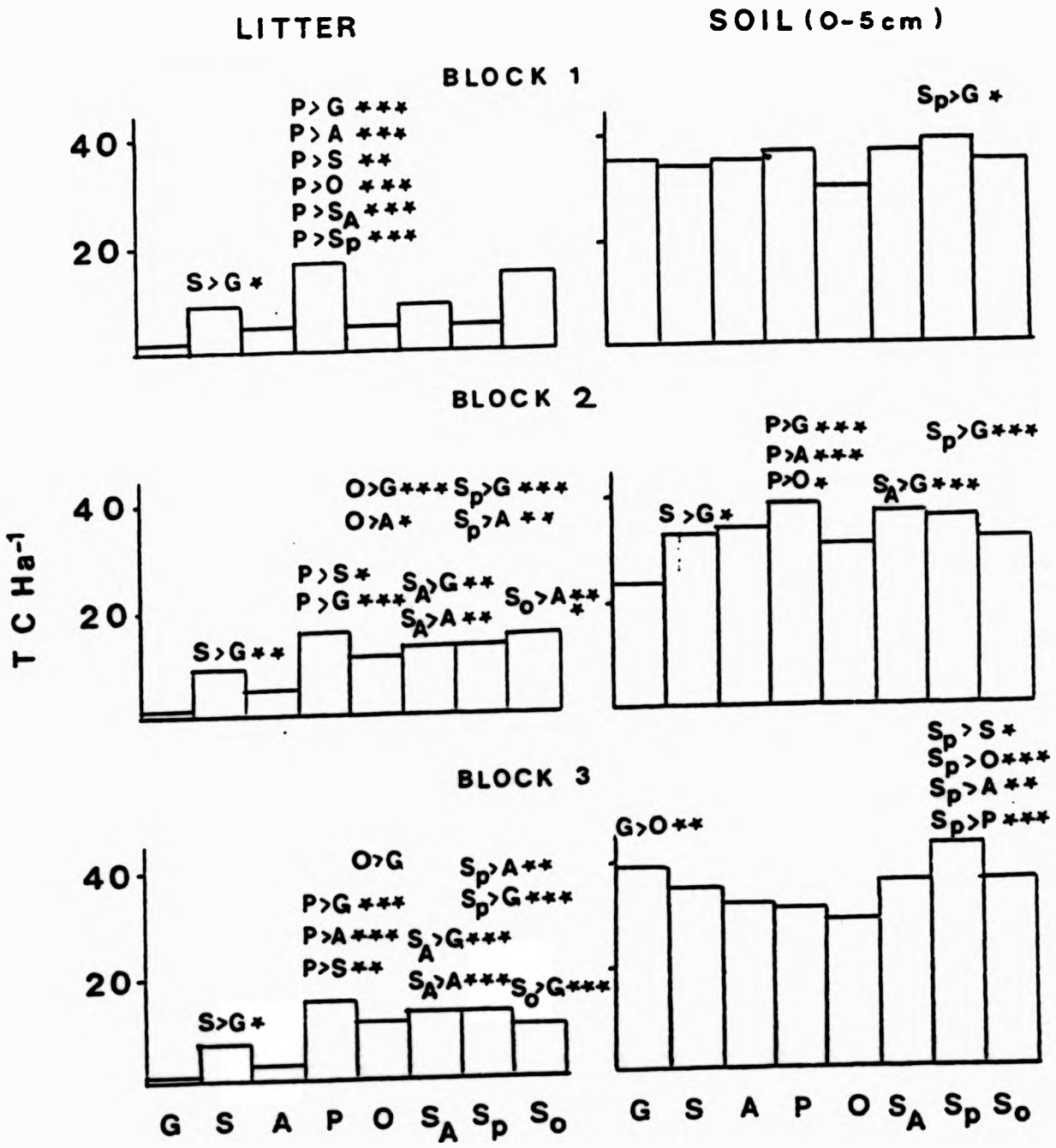


Fig 5.5 Comparison of mean carbon content ($TCha^{-1}$) in all three blocks of the Gisburn experiment.(G=grass; S=N.spruce; A=alder; P=S.pine; O=oak; S_A=N.spruce mixed with alder; Sp=N.spruce mixed with S.pine; So=N.spruce mixed with oak).

5.3 Changes in carbon content of soil and forest floor with age of Sitka spruce stand.

Table 5.3 Mean carbon content with coefficients of variation of the 0-15cm soil and litter layer of the Sitka spruce age series.

Year planted	0-15cm soil		Litter	
	TC per ha	(CV%)	TC per ha	(CV%)
1970	35	(33)	72	(42)
1968	63	(16)	69	(38)
1967	52	(11)	92	(30)
1965	42	(25)	63	(33)
1956	54	(15)	76	(22)
1953	72	(19)	83	(30)

The soils within stands had high variability (Table 5.3 and Appendix 3) showing the importance of adequate sample replication. There was no evidence of any trend in soil carbon content with stand age. Due to the large numbers of samples that had to be analysed, the 0-15cm soil cores were not separated into different depths, which meant that any change in the surface soil may have been masked by the large background of organic matter within the rest of the core.

In order to test this possibility, a further sampling programme was carried out in November 1984, the results of which are shown in Table 5.4.Analysis of variance confirmed the conclusion drawn from the previous sampling, that there was no detectable change in total soil carbon content within the age series.

Table 5.4 Mean carbon content with coefficients of variation of the 0-5cm soil in different aged stands of Sitka spruce.

Year planted	TC ha^{-1}	(CV%)
	0-5cm soil	
1961	22	(17)
1960	20	(17)
1967	20	(12)
1958	23	(9)
1953	22	(18)
1952	22	(13)
1951	22	(17)

Analysis of the litter layer (Table 5.3) indicated that the forest floor had developed rapidly during the initial stages of afforestation, as a steady state had already been reached only 13 years after planting. The presence of this equilibrium indicates that litter decomposition equalled litter input within the Sitka spruce stands. Conditions within the Gisburn forest appear to favour the growth of Sitka spruce, even when the stands were not fertilized (Chap. 5.5). Similar results (Carey, 1982) were observed for Sitka spruce grown in Ireland, where the rate of litter build up was linked with the vigour of the stand, and better tree growth was associated with less accumulation.

5.3.1 Effect of fertilization on the carbon content of the soil and forest floor in Sitka spruce stands.

The presence of a stand of unfertilized Sitka spruce within the boundary wall of the Experiment, allowed an assessment to be made of the potential effect of fertilization on the carbon content of the soil and forest floor.

Table 5.5 Mean carbon content with coefficients of variation of the 0-15cm soil and litter layer of the unfertilized Sitka spruce and stands within the Gisburn experiment, sampled in November 1983.

Species	0-15cm	Litter
	TC per ha (CV%)	TC per ha (CV%)
N.spruce	110 (9)	14 (41)
S.pine	105 (10)	21 (52)
Alder	96 (19)	19 (36)
Oak	104 (9)	5 (65)
Interface	100 (7)	12 (28)
Sitka spruce	84 (19)	13 (34)

The soils under the unfertilized Sitka spruce stand had similar carbon contents to those under the tree stands within the Gisburn experiment(Table 5.5).There was little difference between the soil carbon content of the fertilized(Table 5.3) and the unfertilized Sitka spruce stands, but the fertilized stands had significantly more litter($p<0.001$). Brix(1981) found that fertilization increased foliar mass of Douglas fir and that needle retention was decreased, this process could explain the greater development of the forest floor under the fertilized stands.

5.4 Seasonal sampling

Seasonal fluctuations in soil properties have been reported by various authors (Balzar,1979; Lockman and Molloy,1984).Total organic carbon content in the soil and litter layer was monitored seasonally, as changes in these pools may indicate that there are differences in the organic matter turnover rate.Inputs into the organic matter pools from litterfall and roots(Deans,1979) also vary with time.Aerial litter inputs were estimated from litter traps; root inputs were not measured, as accurate root estimation is an extremely time-consuming process, but the possible impact of fine root turnover is discussed in relation to the other results.

The pH, C/N ratios, moisture content and bulk density of the soil cores were measured to examine whether seasonal changes in these properties varied according to canopy type. Changes in the moisture content,particularly in organic soils, affect the soil bulk density, as dry organic soils expand on wetting (Greacen and Sands,1982).These changes in soil bulk density must be taken into account when discussing variations in total carbon content, as these results were expressed on a volume rather than a weight basis. Seasonal sampling in the pure plots was carried out over an eighteen month period, but was discontinued in the N.spruce/S.pine mixture after 12 months, as a severe gale early in 1984 destroyed a large area of the plot though windthrow.

5.4.1 Carbon content

The data was initially analysed using a 2-way analysis of variance which suggested that there were significant differences in the carbon content of

both the forest floor and soil at different times and between stands. There was no evidence of any interaction indicating that the different stands showed fairly similar trends with time.The results are illustrated diagrammatically in Figs 5.6a and 5.6b and are shown more fully in Appendix 4.1. Most analyses were performed using untransformed data except in the N. spruce/S. pine interface, where increased heterogeneity of variance necessitated the use of a logarithmic (base 10) transformation.

Kendall's test for randomness was applied (Kendall, 1973) to see whether or not observed fluctuations were random in nature.The results of this test showed that changes in the carbon content of the 0-5cm soil under alder, N.spruce and N.spruce mixture occurred randomly as did those in the forest floor of the N.spruce/S.pine interface.The forest floor under alder showed little fluctuation thoughout the sampling period, whilst all the coniferous stands peaked in August 1983, with another peak under the pure conifers in May 1984.

The lack of seasonal peaks in the forest floor of the alder stands was surprising, in view of the highly seasonal nature of the alder litterfall (Fig 5.7). The results indicate that a shorter time interval between sampling periods was necessary to detect changes in carbon content in the litter layer of the alder stand, since the leaves of alder decayed very rapidly. The pattern of carbon content in the litter layer under the different canopies of the mixed plot, followed each other closely until the beginning of 1984. The diverging trends may be a result of disturbance of the forest floor during removal of windthrown trees.

The variation in the carbon content of the forest floor and soil thoughout the season, may be partially explained by examining the change in the other parameters measured ie litterfall, moisture, bulk density, although many other factors such as microbial populations and root turnover are also involved.

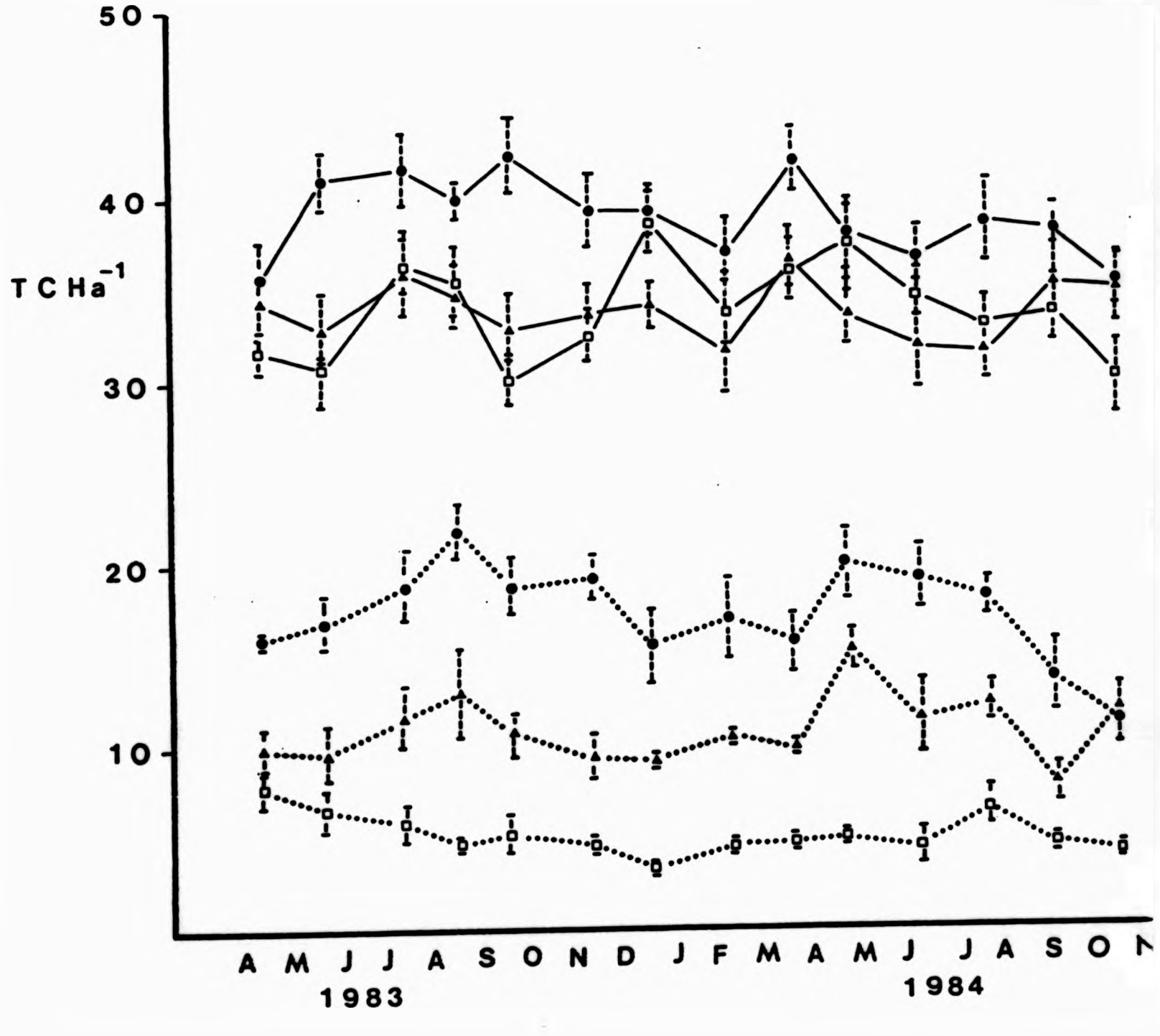


Fig 5.6a Change in carbon content with time in the litter and soil of pure stands of Scots pine, Norway spruce and alder.(Solid lines represent 0-5cm soil;dotted lines represent the litter).

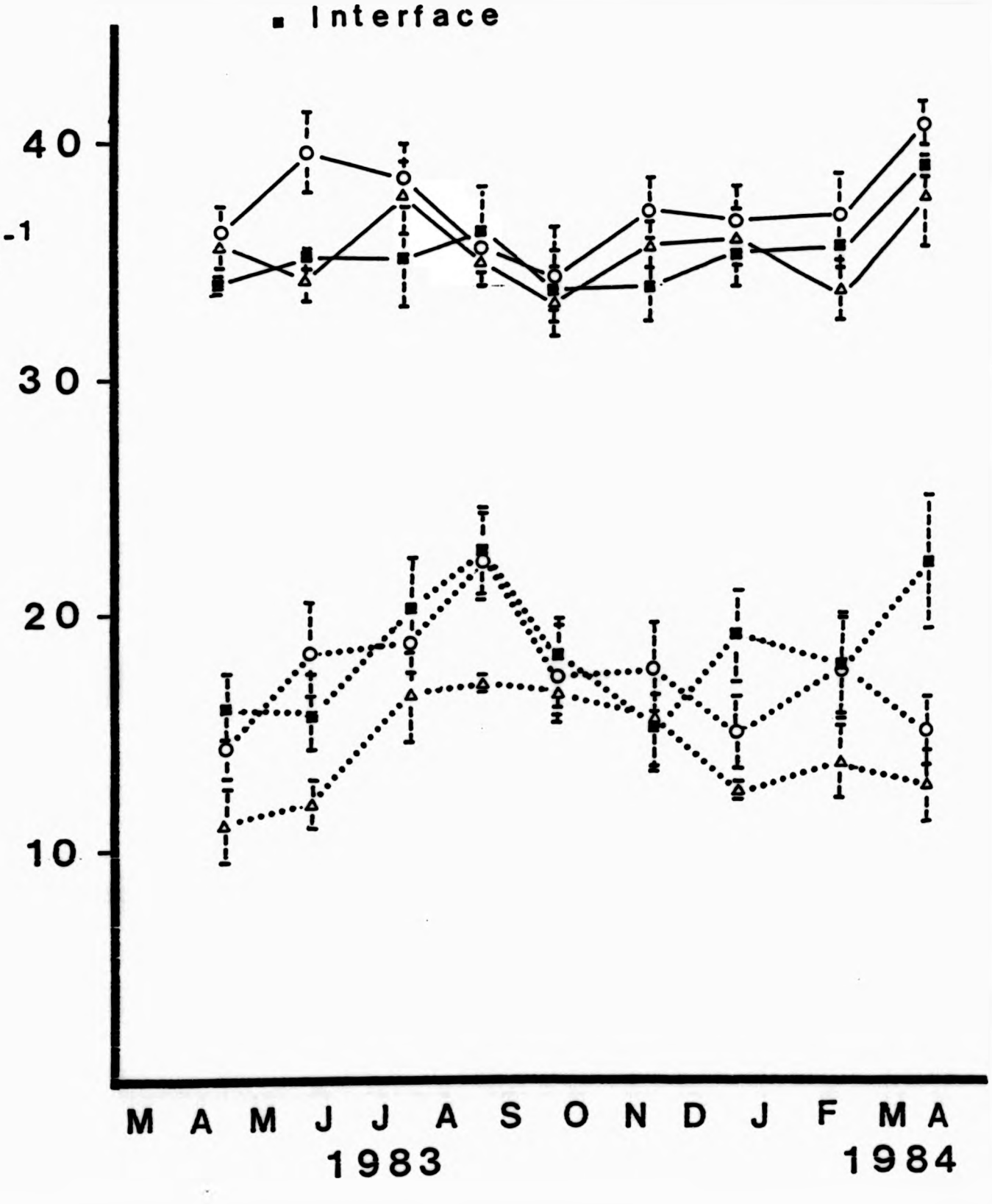


Fig 5.6b Change in carbon content with time in the litter and soil of the Norway spruce/Scots pine mixture.(Solid lines represent the 0-5cm soil; dotted lines represent the litter).

5.4.2 Litterfall

The deciduous tree species had a large leaf litter input in late autumn, with small inputs earlier in the year of leaf bud scales and reproductive structures(Fig 5.7).The biomass of the alder litterfall was probably underestimated, as the fallen leaves were often full of holes and some decomposition may have occurred within the litter traps, since these were only emptied once every six weeks.The speed at which alder leaves decompose is indicated by the fact, that there was no peak in the forest floor carbon content after the major period of litterfall. There was however, a peak shortly after the main litter input in the 0-5cm soil probably indicating that leaf litter carbon was rapidly incorporated into the soil.Contributions to this December peak may also have come from root death, and dieback of the herbaceous understory present in the alder stands.Litterfall from the coniferous trees exhibited no clear seasonal trend, although Miller(1974) reported that the pattern of litterfall under S.pine was distinctly seasonal, whilst that of N.spruce was aseasonal.

In order to compare approximate yearly litter inputs under the different stands, litter inputs were summed over a 12 month period (Table 5.6), the raw data is shown in Appendix 4.2.

Table 5.6 Litter inputs as estimated from litter trap data collected from 28th April 1983 to 14th May 1984.

Species	Litterfall (TC ha^{-1})
Norway spruce	2.72
Scots pine	2.89
Oak	1.25
Alder	1.68

Over the 12 month period examined, the litterfall from the conifers was similar, as was that from the two deciduous species, but almost twice as much coniferous litter was produced. Under comparable conditions, coniferous and deciduous trees often produce similar amounts of litter (Miller, 1974).

The disparity at Gisburn may reflect differences in the growth rates of the coniferous and deciduous trees, as after canopy closure, leaf fall parallels stem volume increment (Miller,1984). Equally, however, the method of sampling the aerial litterfall was probably inaccurate, as there were only five litter traps per plot, covering 0.2% of the area of each stand. In addition, conifers do not shed their needles on an annual basis, so the 18 month period over which litter was collected, would not give a very good estimate of annual litter production by the conifers.

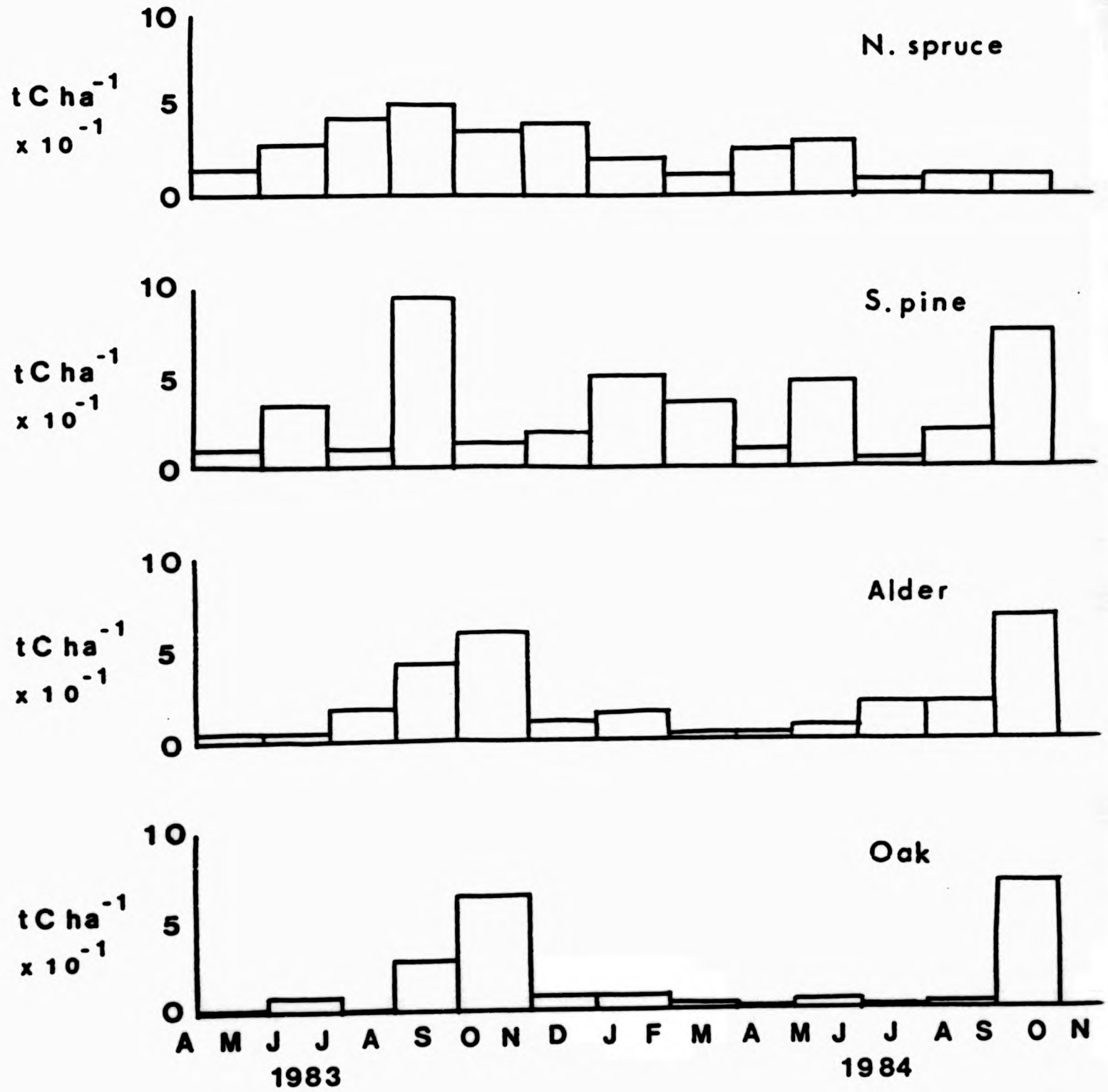


Fig 5.7 The patterns of litterfall in pure stands of Norway spruce, Scots pine, alder and oak from April 1983 - November 1984.

5.4.3 Soil moisture content

The % moisture content of all the coniferous plots had dropped dramatically by late summer 1983 (Figs 5.8a, 5.8b and Appendix 4.3) due to an unusually long spell of dry weather. The drop in moisture content under the alder stands was not so marked, possibly because the evapotranspirational loss from this plot was less than that from the coniferous plots, since the tree biomass was much less (Table 5.9). Nutter, (1979) found that waterflow from conifer plantations was 20% less than from deciduous plantations, which he attributed to greater interception in the former stands. In coniferous stands, the majority of the feeder roots are concentrated within the top few centimetres of soil and within the forest floor, and soil moisture content is a major factor in determining their viability (Deans, 1979). Peaks in the carbon content in the litter layer of the coniferous stands occur in July/August, 1983 and April/May, 1984, which correspond to the sharp drop in soil moisture content, implying that these peaks might be due to root death. Similar results were not recorded in alder plot since these trees root deeper than conifers at Gisburn, and also because the soil did not suffer such marked fluctuations in moisture content.

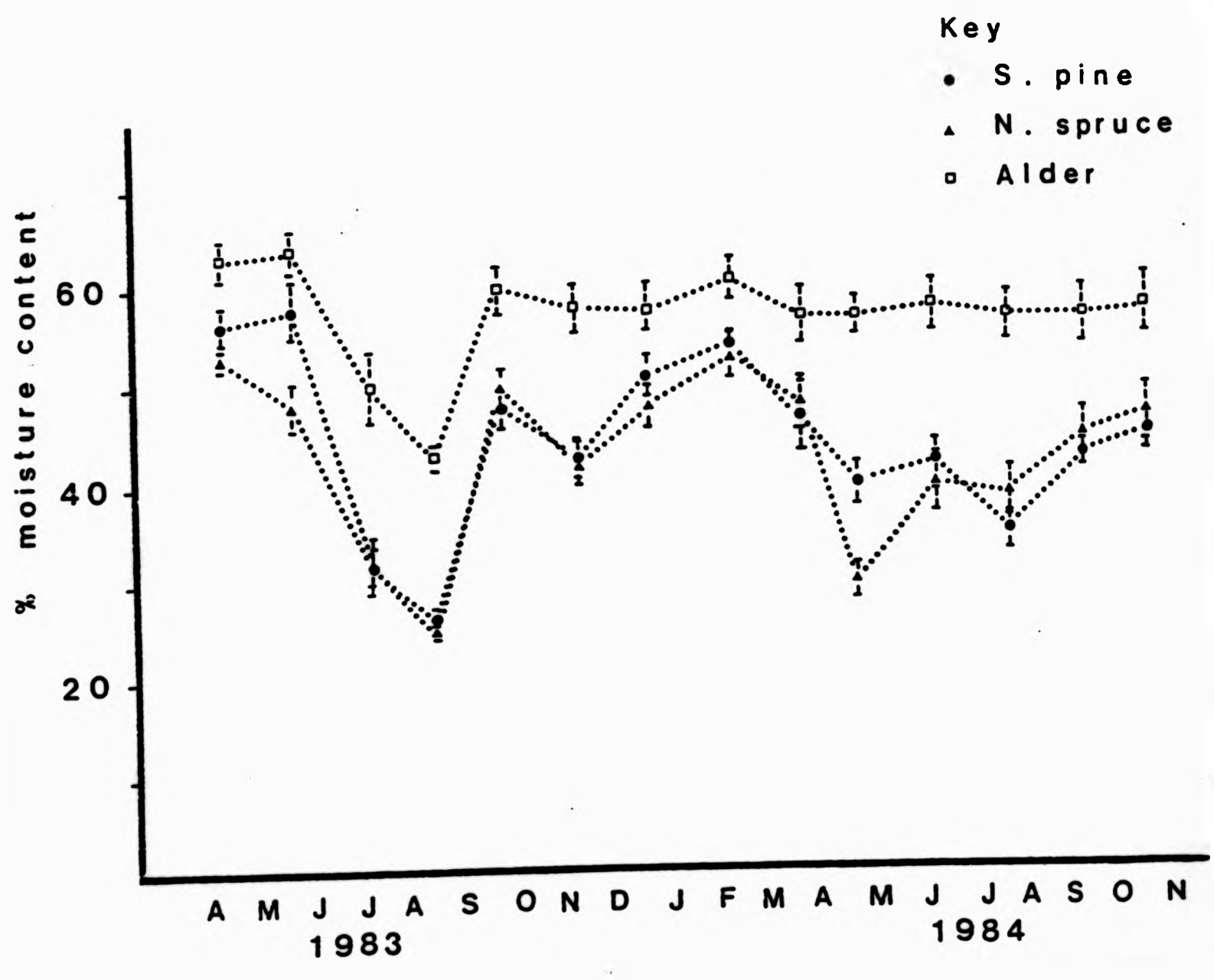


Fig 5.8a Change in percentage moisture content with time in the 0 -5cm soil of pure stands of Scots pine, Norway spruce and alder.

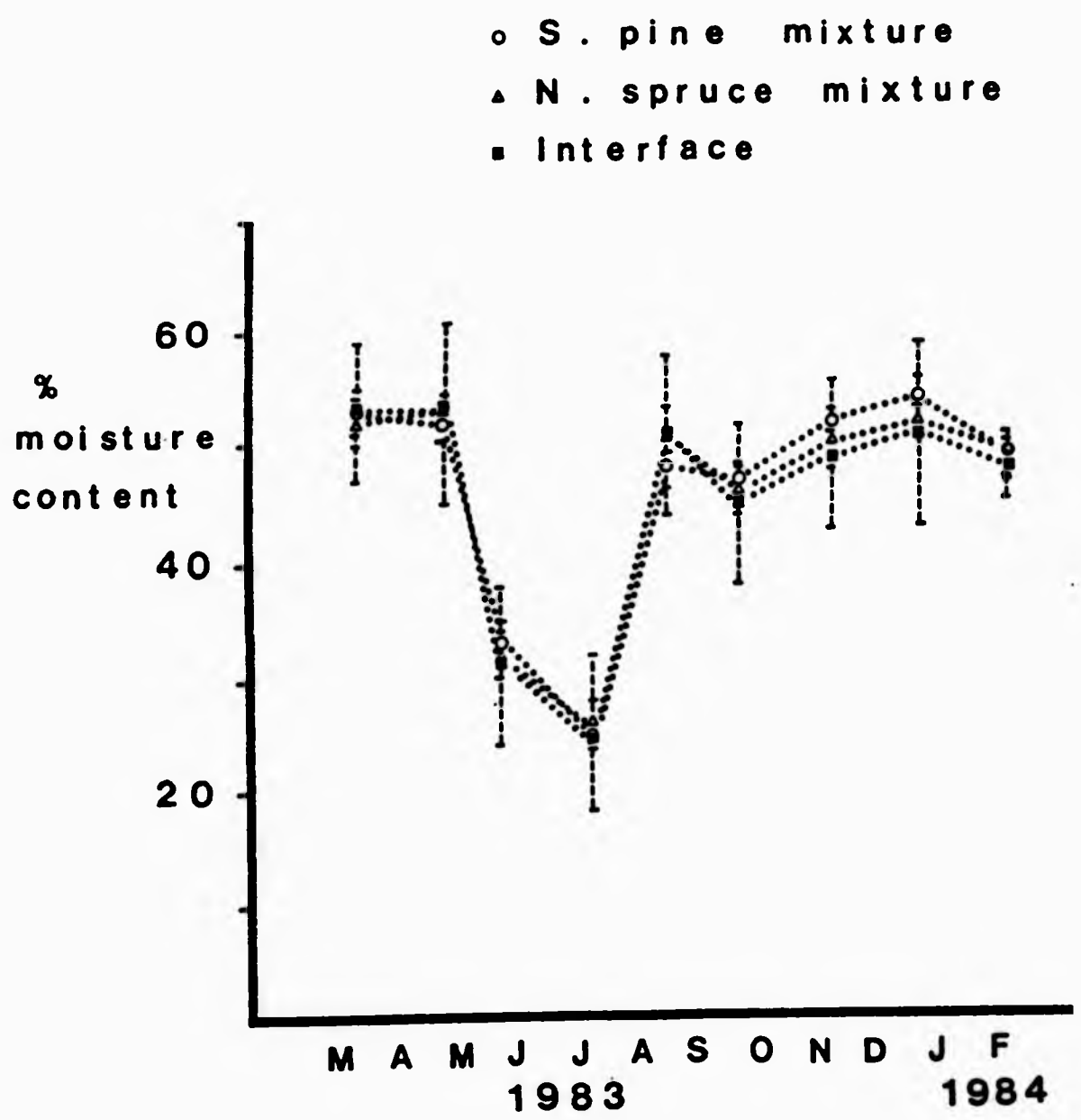


Fig 5.8b Change in percentage moisture content with time in the 0-5 cm soil of the Norway spruce/Scots pine mixture.

5.4.4 Bulk density.

The soil bulk density showed marked seasonal fluctuations in both the pure and mixed plots (Fig 5.9a and 5.9b and Appendix 4.4). A 2-way analysis of variance revealed that the bulk density of the alder plot was consistently lower than that of the coniferous species, which contrasts data obtained by Grieve (1978), who found that soils under coniferous stands had lower bulk densities than soils under deciduous trees. The lower bulk density was probably due to the higher moisture content in the soil under the alder stand (Fig 5.8a). The relationship between bulk density, % moisture and % C content in individual stands was examined, but apart from the alder plot, poor relationships were obtained (Table 5.7), probably due to the limited spread in the data as only the 0-5cm soil was examined. A multiple regression analysis was applied to the data obtained from the alder plot, to examine how much of the variance of the bulk density could be explained by changes in % carbon and % moisture content.

As can be seen from Table 5.8, a large amount of the variation in the bulk density can be explained by changes in % carbon and % moisture on their own. However, a greater per cent of the variation could be explained by combining the two parameters.

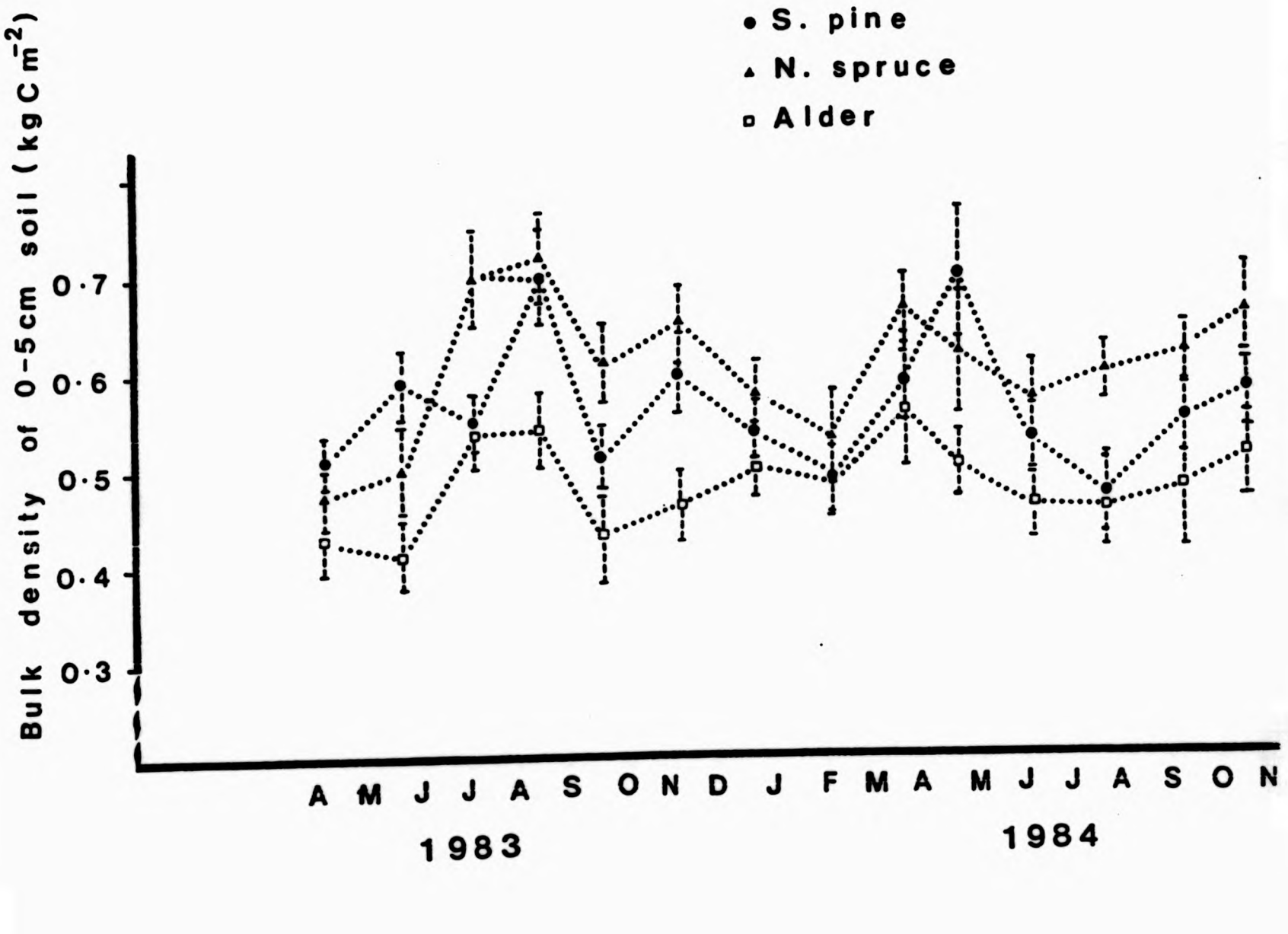


Fig 5.9a Change in bulk density with time in the 0-5cm soil of pure stands of Scots pine, Norway spruce and alder.

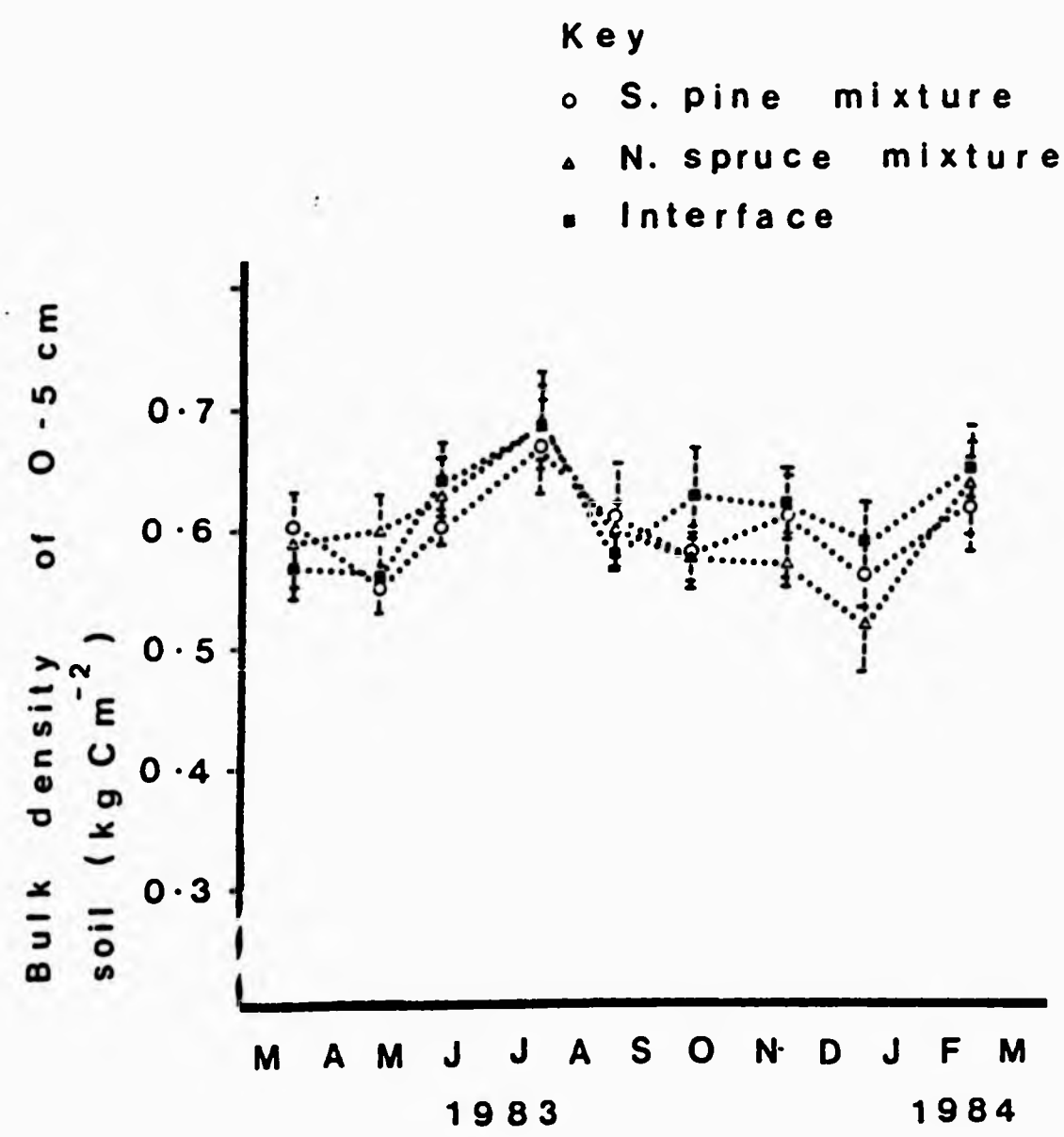


Fig 5.9b Change in bulk density with time in the 0-5cm soil of the N.spruce/S.pine mixture.

Table 5.7 Regression relationships between bulk density(y), % carbon (x) and % moisture(z) in the 0-5cm soil under the pure stands.(*** = $p < 0.001$, ns = not significant).

Species	Regression equation	
Alder	$y = 1.053-0.048x + 0.0007x^2$	$r^2 = 0.76$ ***
	$y = 0.645 + 0.0085z - 0.0002z^2$	$r^2 = 0.71$ ***
N.spruce	$y = 0.592 + 0.0012x$	$r^2 = 0.001$ ns
	$y = 0.743 - 0.0031z$	$r^2 = 0.052$ ns
S.pine	$y = 0.561 + 0.0004x$	$r^2 = 0.002$ ns
	$y = 0.644 - 0.0018z$	$r^2 = 0.11$ ns

Table 5.8 Bulk density as function of % carbon and moisture for soil under alder Tests of variances atributable to regression and additional terms.

Source of variance	df	F ratio	r^2
% Carbon (C)	1, 138	387.56***	73.6
Moisture (M)	1, 138	309.80***	69.0
C, M	2, 137	315.13***	81.9
M after C	1, 137	64.47***	
C, C^2	2, 137	222.20***	76.1
C^2 after C	1, 137	15.66***	
C, M, C^2	3, 136	228.21***	83.1
C^2 after C, M	1, 136	10.53***	
C, M, C^2, M^2	4, 135	170.74***	83.0
M^2 after C, M, C^2	1, 135	0.57ns	

*** $p<0.001$

5.4.5 pH.

The soil pH showed no significant variation over time or under the different tree stands (Fig 5.10 and Appendix 4.5), the average value being approximately 3.5.

This result was surprising, in view of the fact, that previous work (unpublished) had indicated that there was a clear seasonal pattern. The reason for this anomaly (Farr, 1972) may be because soils in this study were air-dried prior to pH measurement, whereas in the earlier study, measurements were made on field moist soils. The pH of the soil had dropped from the average value of pH 4.7 reported at the start of the Experiment(Brown, pers. comm). This low pH indicates that mull-like soil conditions are unlikely to form in the plots, since the soil conditions are unsuitable for Lumbricus terrestris, and the presence of this species is regarded as an essential feature for the formation of crumb structure in woodland soils(Satchell,1980).

A drop in soil pH as a result of afforestation with N. spruce, S. pine and alder was not unexpected, as both the conifer species and alder, are known soil acidifiers (Miles, 1978; Franklin et al, 1968)

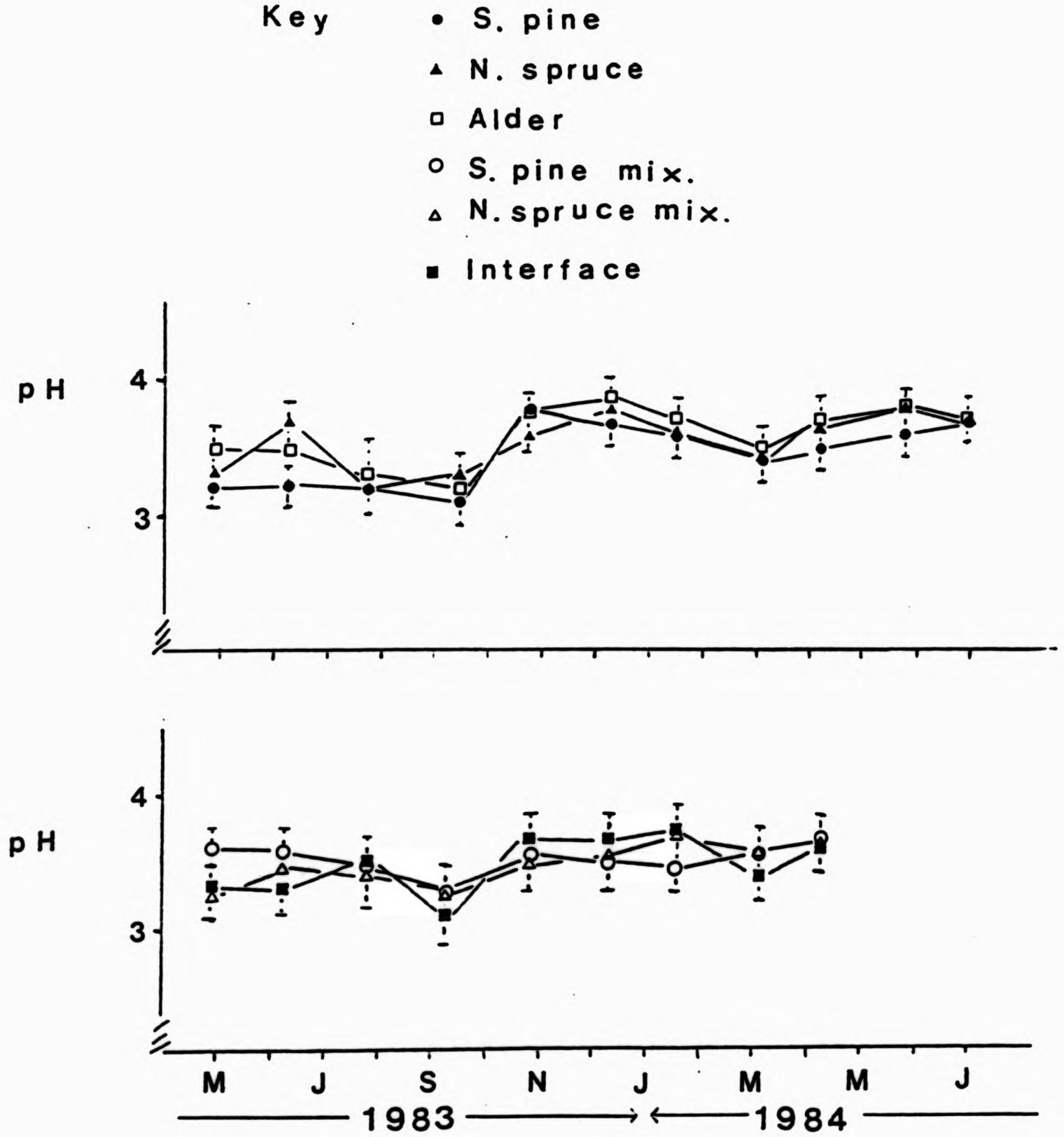


Fig 5.10 pH of the 0-5cm soil under pure stands of Scots pine,Norway spruce and alder and the Norway spruce/Scots pine mixture.

5.4.6. C/N ratio

The mean value for the C/N ratio in the 0-5cm soil with coefficient of variation, summed over the first nine sampling periods were:

	C/N ratio(%CV)
Alder	14.1 (32)
S.pine	16.7 (16)
N.spruce	16.4 (12)
N.spruce half of N.spruce/S.pine mixture	16.9 (27)

(The raw data is shown in Appendix 4.6)

There was significant heterogeneity of variance, but as the data sets were balanced with no missing values, a 2-way analysis of variance could be applied (Scheffé, 1959). The analysis showed that there was no seasonal change in the C/N ratios, but that the alder soil had significantly lower C/N ratios. This change was expected since alder at Gisburn is nodulated, and there are many reports of alder improving soil nitrogen status (Tarrant and Trappe,1971).

Bollen et al (1967) looked at seasonal changes in the C/N ratios of the AII horizon of a silty clay loam soil afforested with pure alder, pure conifers and a mixed stand of conifer and alder in the Pacific Northwest of America. The C/N ratios showed little fluctuation over the season, but the C/N ratios varied markedly in the different stands from 19-26, 19-22 and 15-17 for conifers, the mixed stands and alder respectively. The similarity of the C/N ratios at Gisburn indicates that the trees have made little impact on the original soil organic matter.

5.5 Tree biomass.

The above ground tree biomass was estimated to allow a better comparison of the relative productivity of the stands, as all previous estimates of stand performance (Chap. 2.3.1) have been based on the height of the six best trees per plot. The tree biomass data from the pure stands of alder, S.pine and N.spruce were also used in the construction of a simple carbon cycling model (Chap. 5.6).

The regression equations developed from the actual height of girth measurements are given in Table 5.9. The majority of the species gave good relationships apart from Scots pine, where all the trees were similar in height (7-14m) but had a wide range in DBH (8-27cm). (The raw data is given in Appendices 5.1 and 5.2).

Table 5.9 Regression equations relating tree DBH in cm. (x) to height in metres (y) for different tree species. (*** $p < 0.001$)

Species	Regression equation	
Norway spruce	$y=2.02 + 0.46x$	$r^2=0.77$ ***
Alder	$y=0.45 + 0.99x - 0.03x^2$	$r^2=0.79$ ***
Scots pine	$y=3.14 + 0.79 - 0.02x^2$	$r^2=0.53$ ***
Oak	$y=0.25 + 1.03x - 0.04^2$	$r^2 = 0.89$ ***
Sitka spruce	$y=3.48+0.52x$	$r^2 = 0.73$ ***

Tree biomass (Table 5.10) was estimated in accordance with the equation given in Chapter 4.2.2, assuming that the above ground carbon content of a

whole plant is approximately 47% (Westlake, 1963).

The results for tree biomass obtained from simple regression equations as described in this study are unlikely to be truly representative of the actual tree biomass, since correlation coefficients relating tree D.B.H. to height were relatively low, especially in the S. pine stand. Another factor which must be taken into account, was the assumption that the volume of individual trees conformed to that of a paraboloid. Cannell (1984) showed that the woody biomass of trees could be estimated from the product of its basal area, mean tree height and wood specific gravity, but a form factor must also be taken into account.

This form factor varies markedly from 0.4-0.5 for sparsely branched trees eg conifers, to 0.7-0.8 for trees which are heavily branched eg deciduous trees. In addition, the specific density used in the biomass estimate was based on a moisture content of 15 %, consequently these density values do not reflect those found in living trees. Due to the large number of approximations used, the biomass estimates, do not give a realistic estimate of the actual tree biomass at Gisburn.

Table 5.10 Above ground biomass and carbon content of the various tree stands expressed in T ha^{-1}.

Species	No. of trees per plot	Biomass T ha^{-1}	C Content T C ha^{-1}
Norway spruce	240	25.9	12.2
Scots pine	169	38.4	18.0
Oak	311	8.1	3.8
Alder	188	9.5	4.5
Mixed			
Norway spruce mix	87	5.4	2.5
Scots pine mix	107	14.6	6.9
Total in mixture	194	20.0	9.4
Unfertilized			
Sitka spruce	369	131	61.6

The biomass estimates were based on data collected prior to the serious withthrow in the mixed plot, although some trees had already been lost. The Scots pine stand had produced the greatest biomass within the experiment even though the plot had been thinned in 1974 and had suffered the worst windthrow of any of the pure stands.

The experimental coniferous plots had produced considerably more biomass than the deciduous trees, however, this was far outweighed by the much greater production of the Sitka spruce. Ovington (1962) noted a similar discrepancy in growth rates between neighbouring plantations of deciduous and coniferous trees; 47 year old stands of Douglas fir, Scots pine and oak had total above ground weights (including forest floor and ground flora) of 264, 177 and 121 x 10^3kg per ha respectively.

5.6 Carbon cycling model

In order to assess the overall differences in the quantitative and dynamic differences in carbon turnover in the three plots that have been most intensively studied ie alder, N.spruce and S.pine, a simple carbon cycling model was constructed. The model consisted of three compartments (Fig 5.11) and was based on the assumption, that in terms of total carbon content, the stands were in a steady state. Although this was not strictly true, there has been no detectable increase in soil organic matter, based on loss-on- ignition data (Brown unpub.) since 1955, and results from the Sitka spruce age series (Table 5.3) indicated that the forest floor was likely to be in equilibrium.

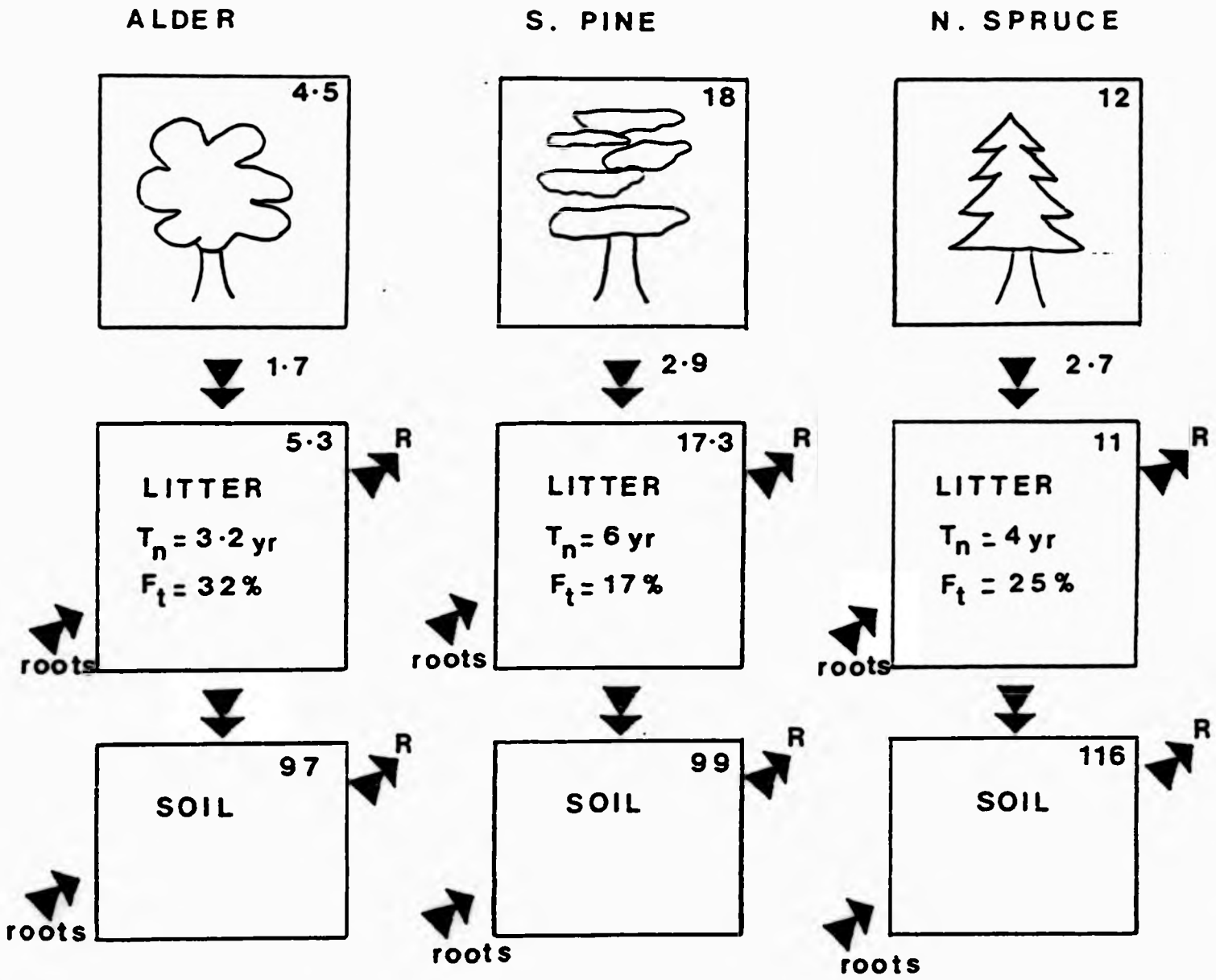


Fig 5.11 Simple carbon cycling model for pure stands of alder, S. pine and N. spruce, the litter layer and top 20cm of soil. (Values in the top right hand corner of boxes rep. pool sizes (T Cha^{-1}); R = respiratory losses;T_n = residence time (yr);Ft = fractional annual turnover).

5.6.1 Assumptions used in model construction.

a)Pool size

The size of the forest floor pool was estimated by taking the mean biomass from a 12 month period during the seasonal sampling programme (28/4/83-14/5/85). The soil organic matter pool and above ground tree biomass had been calculated previously (Fig 5.1 and Table 5.10).

b) Pool fluxes

The residence time for the forest floor was calculated using the equation:

$$Tn = \frac{\text{forest floor stock}}{\text{annual litter input}}$$

Fractional annual turnover, Ft, = 1/Tn x 100

The above formula only gave a rough approximation of the residence time, since it assumes that the forest floor was in a steady state, which was unlikely to be the case at Gisburn. The measure of annual litter input was based on the estimated aerial litterfall, and did not take into account root input. Bowen (1984) in a recent review article concluded that fine root turnover might be a more significant factor in nutrient cycling than is litterfall. The decomposition of fine roots is extremely rapid (Fogel and Hunt, 1983), so that although the throughput of root material is high, it only makes a small contribution to the litter and soil carbon pools. The results from the radiocarbon enrichment studies (Chap. 5.7.5.2) tended to confirm this last point, as little 'bomb' carbon had been incorporated into the topsoil.

The radiocarbon analyses indicated that transfer of material by eluviation from the forest floor into the soil organic matter pool and out again were probably negligible. The soil organic pool formed a distinct layer above the clayey subsoil, and was consequently poorly drained, in addition Gosz et al (1976) found that losses of organic matter in drainage water were extremely small relative to respiratory losses. The radiocarbon enrichment studies also indicated that there was only limited movement of recent material down the soil profile.

Soil respiratory losses were studied at Gisburn on a seasonal basis in 1978(Brown,unpub.). Although there were marked variations throughout the year, there was no significant difference between the species when the data was expressed on an annual basis. Only a few studies have attempted to partition respiration (Witkamp 1969; Edwards and Sollins 1973; Coleman, 1973), but as the distribution of respiration between roots, soil and litter varied according to the ecosystem studied, it was impossible to estimate the respiratory losses for the carbon model.

5.6.2. Discussion of the model analysis.

The major differences among the three stands investigated lay in the sizes of the above-ground biomass and forest floor pools. As mentioned earlier (Chap 5.5), conifers usually attain a much greater biomass than deciduous species when grown in this country. In all the plots of the present study, the forest floor biomass was roughly equivalent to the above-ground tree biomass, whereas Ovington (1962), in a review of quantitative ecology in woodland ecosytems, found that in many tree stands the above ground biomass was usually considerably greater than the forest floor biomass. This is probably a reflection of the poor growth of all trees within

the Experiment, as slow growth on peaty gley soil has been associated with greater litter accumulations, than when the trees grow well (Carey,1982).

The forest floor under alder had the highest turnover rate, since alder leaf litter has a lower C/N ratio than coniferous litter, rendering it more susceptible to decomposition. The calculated residence time for the forest floor under N.spruce was shorter than that for the S.pine, which was suprising as the microbial activity as measured by cotton strip decomposition (Brown, 1977) was much greater under S.pine.
However, Wittich (1939) reported that S. pine needles decomposed more slowly than N. spruce needles, whilst Mattson and Koutler-Andersson (1941) reported that the needles of both species decomposed at the same speed. The calculated residence times for the forest floor appear to be very short, as Kendrick (1959) estimated that S. pine needles spent approximately 6 months in the L layer, 2 years in the F_1 and 7 years in the F_2 before being humified, and Meyer (1962) estimated that it took 17 and 31 years in the H_1 and H_2 layers respectively for total mineralization of N. spruce needles. Vogt et al (1983) estimated that the various litter components in a 23 year old Abies amabilis stand, required 6-15 years for 99% decomposition to occur based on aerial inputs, but that this estimate was reduced by 75% when the fine root input was taken into account.
The carbon cycling model constructed for Gisburn does not provide a realistic picture of carbon turnover, since the values used in the mean residence time equation were only rough estimates. The two main points brought out by this simple model analysis are, that regardless of tree species, tree growth has been poor, and secondly, that in terms of total carbon content, the trees have had little impact on the original grassland soil.

Chapter 5.7 Interpretation of carbon isotope data

5.7.1 General considerations

The experimental complexity and time consuming nature of natural ^{14}C measurement restricted the total number of radiometric analyses that could be employed in this investigation.Consequently it was important, first of all to ascertain the extent to which the available ^{14}C enrichment data were truly representative of 1) the individual tree plots sampled and 2) the defined organic components of the total soil carbon pool.

In a long established woodland soil, which was assumed to be in equilibrium, Harkness et al(1985) found that the spatial variation of ^{14}C enrichment within the site was comparable with analytical precision (±0.5%) achieved in radiometric analysis.This ideal situation could not be anticipated for the Gisburn tree plots, since insufficient time had passed for the soil to have attained a natural equilibrium for carbon turnover.

During the period in which the various tree stands were introduced i.e. 1953 till 1968 (for the Sitka spruce stands), a natural ^{14}C deficiency due to radioactive decay was predominant in the grassland site (Fig 5.15), with a characteristic decline with depth in the soil profile (Ladyman, 1982).The pattern and more significantly, the depth of ploughing would therefore effectively define the initial ^{14}C enrichment of the freshly turned topsoil.The progressive uptake of the massive pulse of 'bomb' ^{14}C by the parent grassland between 1953 and 1968 was so gradual, that this can be effectively discounted in terms of its having imparted a significant difference to the initial ^{14}C enrichment of the soils prepared for planting over that period.

5.7.1.1 Assessment of within site variance

The ^{14}C enrichment values measured for two independent aliquots of bulk soil from the Gisburn plots and the unfertilized Sitka spruce stand are compared in Table 5.11.In the 2nd. series, the ^{14}C enrichment values for the total soil were calculated from the component fractions, as these had been separated quantitatively.

While the data for the grassland site was remarkably constant between all the component pairs, it was obvious that within the tree plots, there was a greater within site variability.However, with the notable exception of the alder plot, the general trends in the data were maintained, thus allowing the required semi-quantitative application of ^{14}C enrichment as a tracer for the relative changes induced by tree growth.The disparity of results for the alder plot were thought to be caused by inadequate separation of recent organic material from the mineral soil in the first fractionation series.

Table 5.11 Comparison of ^{14}C enrichment values recorded for the Gisburn plots and the unfertilized Sitka spruce stand.

Plot (Organic fraction)	C-14 Enrichment (Δ‰ ± 1σ)		
	1st series	2nd series	Mean
S.pine (Total C)	-91±5	-103±8	-97±10
S.pine (Organic debris)	-67±8	-50±10	-59±13
S.pine (fulvic)	-96±8	-	-96±8
S.pine (humic)	-3±5	-62±8	-33±10
S.pine (humin)	-122±5	-144±5	-133±8
Interface (Total C)	-104±4	-124±8	-114±9
Interface (Organic debris)	-	-56±10	(-56±10)
Interface (fulvic)	-26±7	-	(-26±7)
Interface (humic)	-55±6	-70±8	-57±10
Interface (humin)	-92±5	-163±5	-128±8
N.spruce (Total C)	+12±4	-25±8	-7±9
N.spruce (Organic debris)	-	+163±13	(+163±13)
N.spruce (fulvic)	+57±8	-	(+57±8)
N.spruce (humic)	-4±6	-35±8	-20±10
N.spruce (humin)	-14±6	-56±6	-35±9

Table 5.11 continued

Plot (Organic fraction)	C-14 Enrichment (Δ‰ ±1σ)		
	1st series	2nd series	Mean
Alder (Total C)	-4±4	-72±8	?
Alder (Organic debris)	-	+43±11	(+43±11)
Alder (fulvic)	-55±9	-	(-55±9)
Alder (humic)	-4±6	-67±8	?
Alder (humin)	+30±6	-108±5	?
Grass (Total C)	+28±4	+32±8	+29±9
Grass (organic debris)	+105±6	+93±6	+99±9
Grass (fulvic)	+137±8	-	(+137±8)
Grass (humic)	+85±4	+76±6	+81±8
Grass (humin)	+20±4	+6±6	+13±8
Sitka spruce (Total C)	-26±4	-46±8	-36±9
Sitka spruce (Organic debris)	-	+12±12	(+12±12)
Sitka spruce (fulvic)	+39±8	-	(+39±8)
Sitka spruce (humic)	+6±6	-19±8	-7±10
Sitka spruce (humin)	-80±4	-72±5	-76±7

Definition of fractions :

'fulvic' -borax soluble, acid soluble

'humic' - borax soluble, acid insoluble

'humin' - borax insoluble

5.7.1.2 Assessment of inter-site variance

This evaluation requires the comparison of plots under identical culture i.e. as represented by the Sitka spruce age series(Table 5.12).In this grouping it was noticeable that all organic components monitored for the 1956 plantation exhibit ^{14}C enrichment values that were depressed relative to those in the plots established previously and subsequently. However, the distribution pattern of ^{14}C enrichment among the component fractions remained comparable in each age stand. The '1956 anomaly' probably reflects the preparation of an older topsoil by slightly deeper ploughing, and as such does not detract from the interpretational value of the data.

Table 5.12 Comparison of ^{14}C enrichment values recorded by Sitka spruce age sequence in 1984.

Year	^{14}C enrichment (Δ ‰ $\pm 1\sigma$)			
	Debris	Borax soluble	Borax insoluble	Total carbon
1953	+65±6	+55±8	-27±6	+7±10
1956	+49±8	-5±6	-101±5	-63±10
1965	+171±10	+123±9	+10±6	+48±12
1967	+228±7	+98±6	+11±6	+63±10
1968	+207±10	+152±10	+96±6	+118±13

5.7.2 Ratio of borate extractable:non-extractable carbon

The ratio of borate extractable:non-extractable carbon was fairly constant for the tree plots in the Gisburn experiment (Table 5.13). The exceptions were soil from the alder plot which was higher, and the grassland soil which had a lower ratio.

Table 5.13 Carbon content (wt. %) in fractions relative to the original bulk soil.

Sample	Borax soluble	Borax insoluble	Ratio sol.:insol.
S.pine	2.5	5.14	0.49
Alder	2.56	4.19	0.61
N.spruce	2.23	5.17	0.43
Interface	2.12	6.3	0.33
Grassland	3.71	12.8	0.29
Sitka spruce(unfert.)	2.24	5.47	0.41

In the Sitka spruce plots there was a marked increase in the ratio of soluble/insoluble carbon (Fig 5.12), even though in terms of total carbon (Table 5.4), there was no change with stand age.The results for the grassland have been added to the graph, as these were the most likely to be representative of the initial site conditions.Data from the unfertilized Sitka spruce plot fits in with that of the fertilized stands, indicating that there has been a change in the chemical nature of the soil organic matter, which is linked with the length of time of afforestation.

The initial fractionation procedure of separating the borate soluble

extracts into acid soluble and acid insoluble components also indicated that the trees had influenced the soil organic matter chemistry. The relative contributions to the total soil carbon in the 0-5cm depth increment for the acid soluble; acid insoluble and non-extractable components was equivalent to 0.1;0.3;0.6 for the tree plots, whereas the corresponding distribution for the grassland site was somewhat different being 0.02;0.31;0.67. If the ratio of acid soluble:acid insoluble borate fractions can be regarded as equivalent to the fulvic:humic acid ratios, then it would appear that the trees have induced a change in the chemical nature of the soil organic matter, since the humus of forest soils are usually characterized by a higher ratio of fulvic to humic acids, than are grassland soils (Stevenson, 1982).

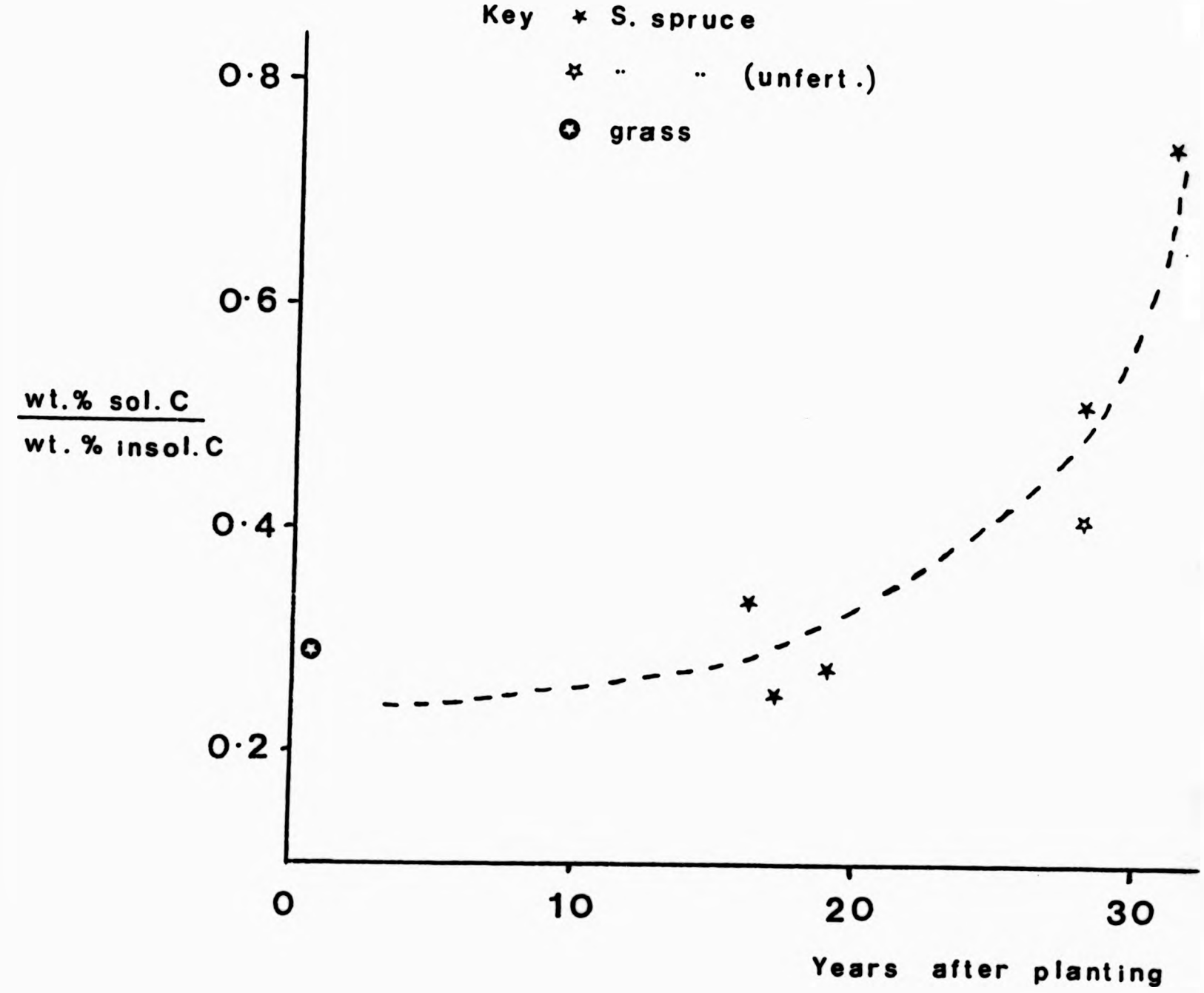


Fig 5.12 Ratio of borax soluble:borax insoluble carbon under stands of Sitka spruce of various ages.(Dotted lines rep. approximate trend with age).

5.7.3 Distribution of ^{14}C

5.7.3.1 Gisburn plots

The ^{14}C enrichments for the experimental plots and the unfertilized Sitka spruce stand are summarized in Fig. 5.13. There was a generally consistent pattern of ^{14}C enrichment among the component organic fractions i.e. organic debris>borax soluble>borax insoluble. This gives a clear indication of the corresponding pathway of biological degradation as defined by borate separation, and highlights the slow rate of decomposition of some plant remains as the determining stage in the turnover of soil carbon. The borax soluble and insoluble components of the N.spruce and grassland soils were more enriched than the corresponding fractions for the alder, S.pine and N.spruce/S.pine interface. The former plots were known to be the least biologically active with respect to decomposition of cotton strips (Brown, 1977) and would therefore tend to accumulate carbon relative to the other plots, thus giving a higher enrichment value. Similar results were found by Rafter and Stout (1970), who studied pasture and beechwood ecosystems, the former site was more productive and this was associated with less ^{14}C enrichment than the forest site.

The enrichment data for the unfertilized Sitka spruce stand lay in the middle of those of the Gisburn experiment, indicating that the rate of organic matter turnover was intermediate between that of the 'more' active and 'less' active stands.

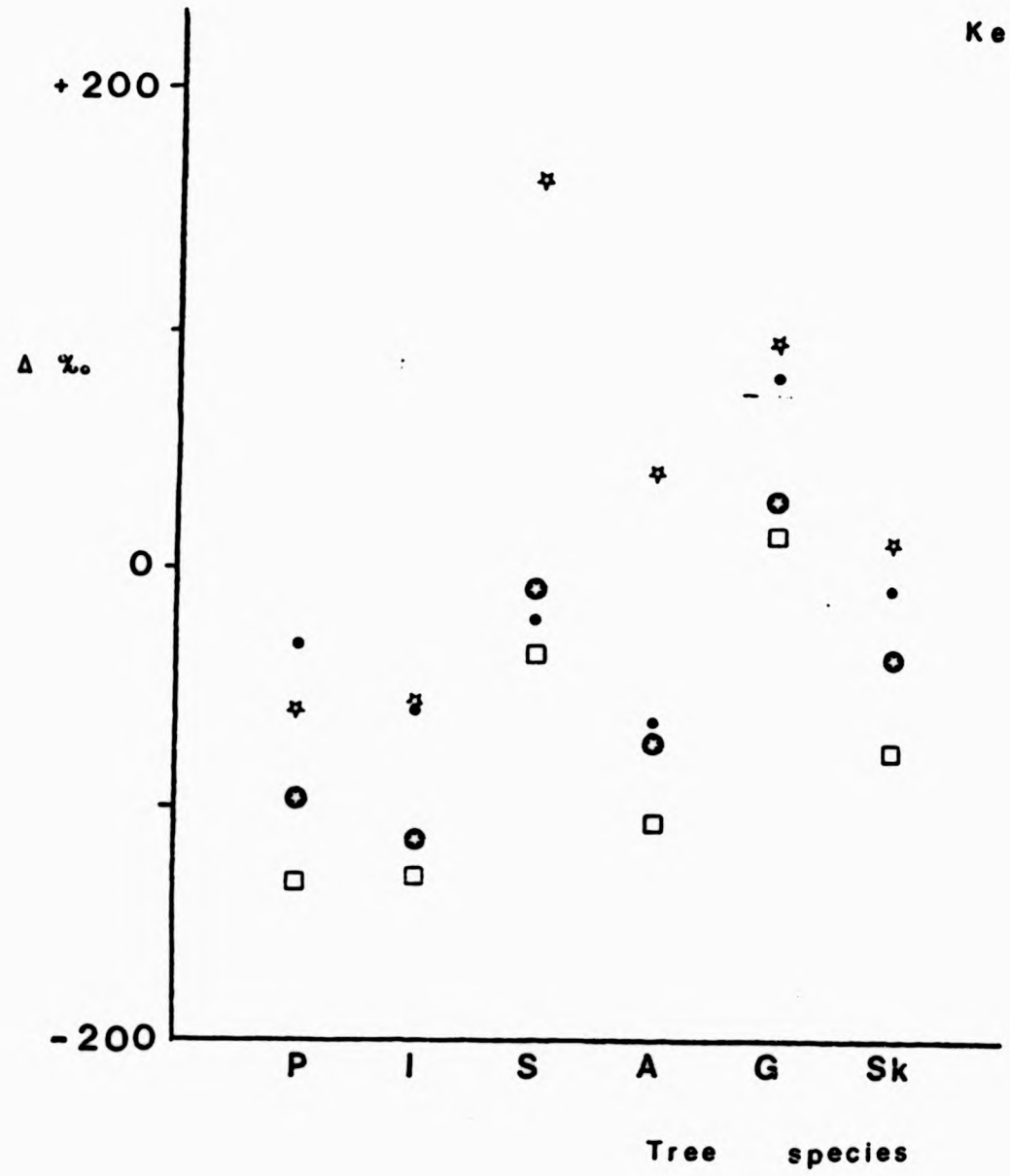


Fig 5.13 Distribution of ^{14}C in the total soil and the components fractionated by sodium borate. (P=S.pine; I=Interface of S.pine/N. spruce mixture; S=N.spruce; A=alder; G=grass;Sk=Sitka spruce (unfert)).

5.7.3.2 Fertilized Sitka spruce stands

The results for the Sitka spruce stands are given in Fig 5.14. The pattern of enrichment between the component fractions was the same as that observed in the Gisburn plots(Fig 5.13).

It is noticeable, that although the ^{14}C concentration at all sites and in all component fractions of the soil organic matter were much greater than that characteristic of the total parent grassland at the time of planting (Ladyman,1982), the oldest stands remained the least enriched in ^{14}C. This pattern shows a predominant and persistent influence of atmospheric ^{14}C transferred to the soil organic pool within a few years of initial planting.

It might be expected that the soils of the older stands would have a higher enrichment of ^{14}C relative to the younger stands, since the older trees were planted prior to the peak in the atmospheric 'bomb' carbon. However, this peak was only transitory, compared with the length of time the trees were growing in the '^{14}C deficient' atmosphere.

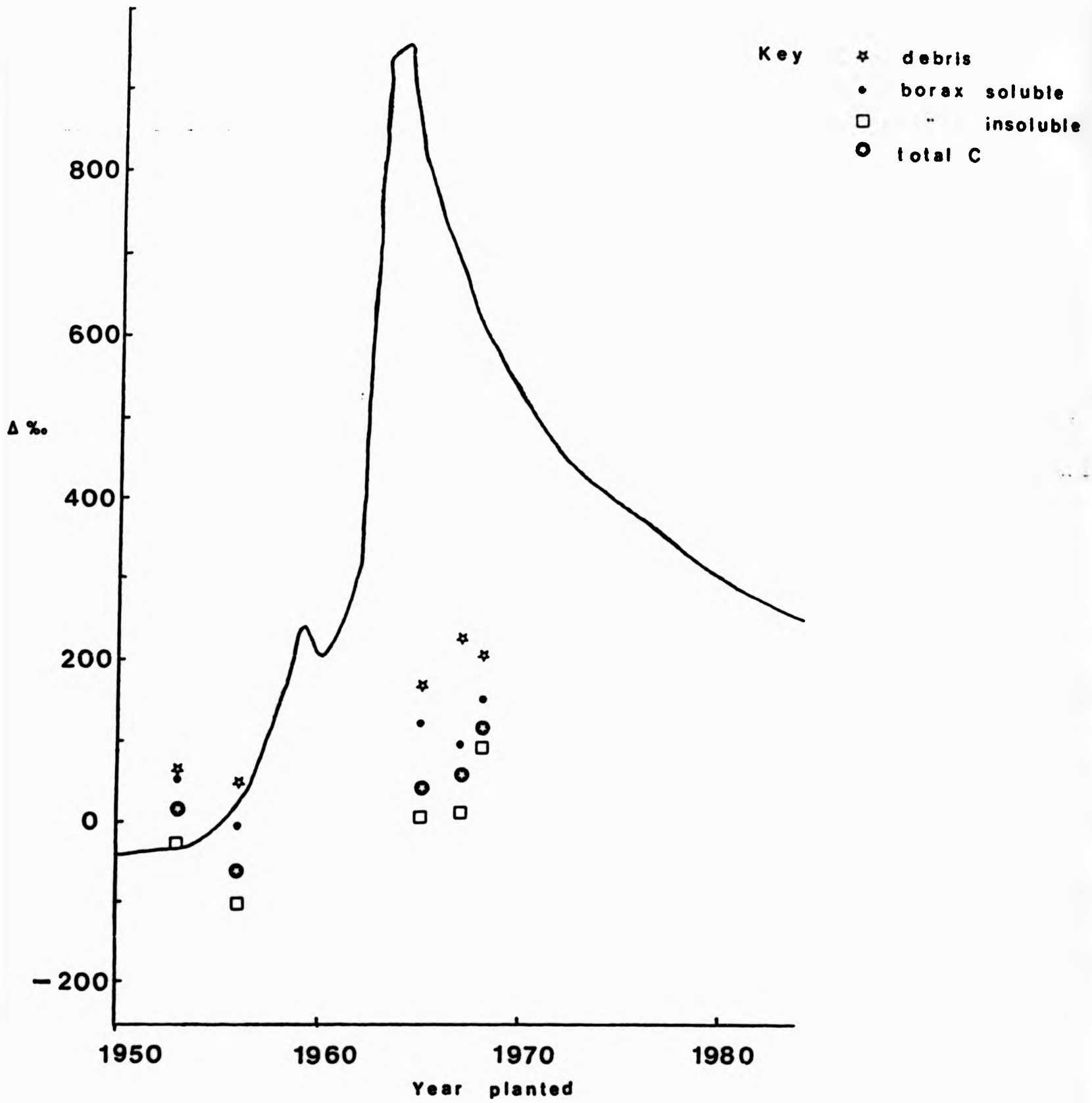


Fig 5.14 ^{14}C enrichment of the total soil and borate fractions from the various aged Sitka spruce stands. The solid line represents atmospheric 'bomb' ^{14}C .

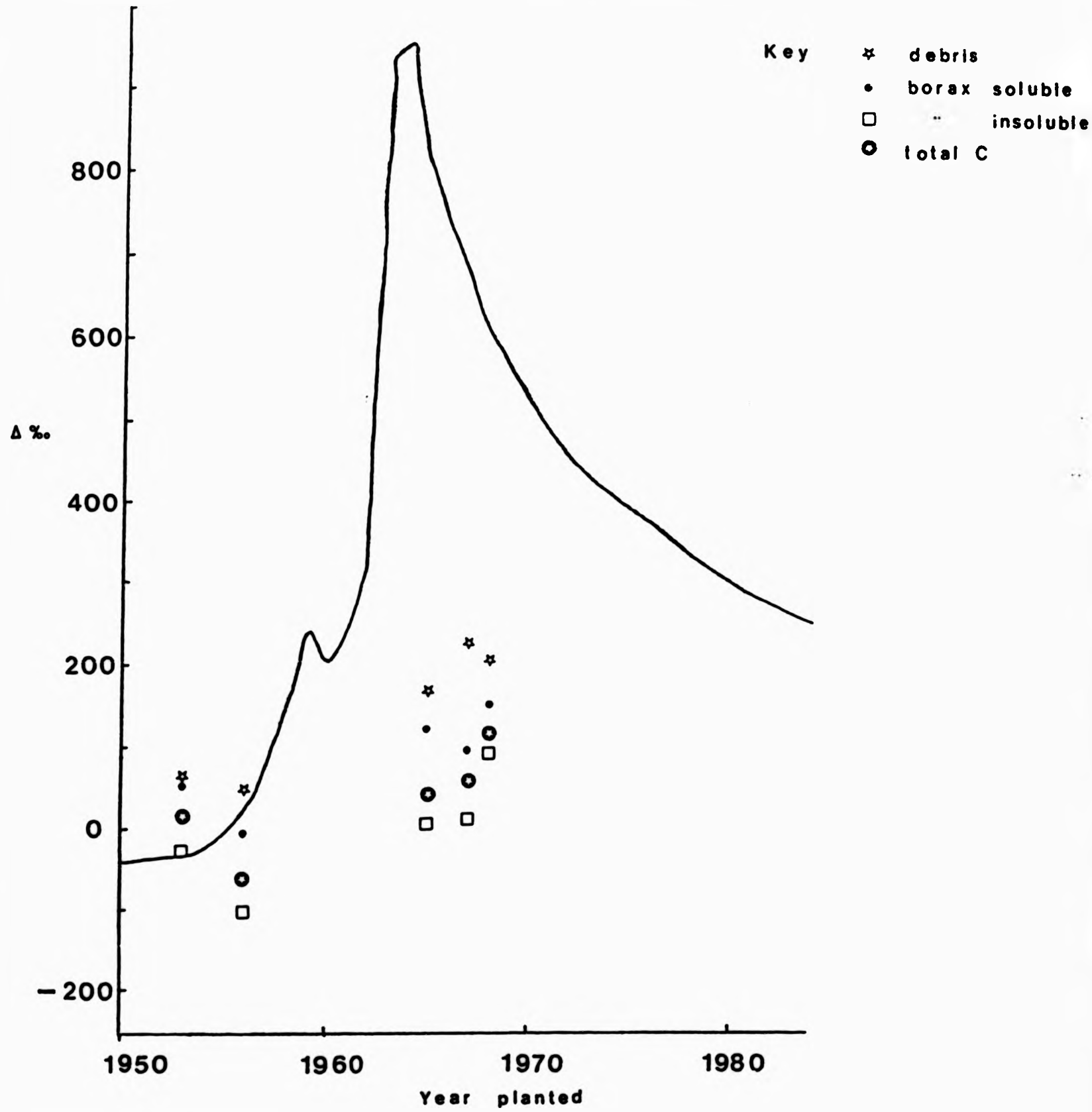


Fig 5.14 ^{14}C enrichment of the total soil and borate fractions from the various aged Sitka spruce stands. The solid line represents atmospheric 'bomb' ^{14}C .

5.7.4 Stable isotope ratios, $^{13}C/^{12}C$

There was no evidence of any fractionation of the $^{13}C/^{12}C$ stable isotope ratios, with respect to tree species, depth in the soil profile or with chemical fractionation(Table 5.14), although such variations have been reported elsewhere(Stout et al,1975).Differences between the plots have probably not occurred, because all the plant species under investigation have Calvin pathways during photosynthesis, so that the ^{13}C values in the vegetation lie between -20 % and -30% .Even if, species differences in fractionation had occurred, they would be difficult to detect, since the effect of the plant is determined by the proportion of its increment to the total mass of organic matter; and since the annual accretion of organic matter at Gisburn is negligible relative to the total amount of organic material in the soil profile, then any effect on the ^{13}C values would be small.

Table 5.14 Comparison of stable isotope ratios ($\delta^{13}C_{PDB}$) from total soil and fractionated soil, and at different depths down the soil profile, in pure stands of S.pine, N.spruce and alder and from the grassland.(Soil profile data was measured in 1981(Brown, unpub.)).

Sample	S.pine	N.spruce	Alder	Grassland
Borate soluble	-26.2	-27.5	-28.5	-27.4
Borate insoluble	-27.9	-27.0	-27.7	-28.3
Rootlets	-27.5	-27.4	-28.9	-27.7
Litter	-29.4	-29.4	-29.9	-28.5
0-2cm	-28.2	-27.8	-28.4	-27.8
2-8.5cm	-28.2	-28.6	-28.6	-28.8
8.5-15cm	-28.4	-28.9	-28.4	-28.7

5.7.5 Comparison of 'bomb' ^{14}C enrichment values with other studies: a)Meathop woodland; b)1981 values for the Gisburn experiment.

5.7.5.1 Meathop woodland

A recent long term study (Harkness et al, 1985) in a Lake District woodland has shown that there was a delay before the atmospheric peak in 'bomb' ^{14}C was reflected in the soil (Fig 5.15), and that this delay in incorporation increased with increasing depth in the soil profile. 'Bomb' ^{14}C enrichment values have been measured for the Gisburn grassland plot, since 1955(Ladyman, 1982) and these have been added to the Meathop data in Fig 5.15.Although these sites are not directly comparable, since Meathop is a long established oak woodland in equilibrium , a similar delayed increase in the 'bomb' ^{14}C content of the 0-5cm grassland soil

was observed. Harkness et al proposed a selective microbial humification, particularly of woody material, to explain the delay in the peak transfer of 'bomb' ^{14}C but this hypothesis is obviously not applicable to a grassland site.An alternative possibility, is that it takes several years before an increase in 'bomb' ^{14}C can be detected in the soil, because of the presence of a large background pool of organic matter, which dilutes the recently added carbon.This process would be more marked in highly organic soils such as the peaty gleys at Gisburn, and could explain the greater delay in the increase in 'bomb' ^{14}C in the grassland soil relative to the Meathop soil. Another contributory factor to the delayed appearance of the peak in the Gisburn soil, might be because a substantial amount of carbon fixed by the grass may be derived from the soil, rather than from the atmosphere. Monteith et al (1964) reported that 20% of the carbon dioxide fixed by barley can come from the soil.Some evidence for this process is gained by looking at the enrichment values for the litter samples collected from the grassland site in 1977 and 1981 (Fig 5.15), these have values which fall below the atmospheric ^{14}C enrichment, indicating that carbon low in ^{14}C has been incorporated into the grass. This contrasts data for the litter enrichment values from the Meathop woodland, where the results indicated that the carbon dioxide fixed by the trees was derived from the atmosphere.There was no evidence of a downward transfer of 'bomb' ^{14}C below 5cm in the grassland site, such transfers are likely to be small in this soil, since it is poorly draining and there are no deep burrowing earthworms, to aid the incorporation of recent organic material into the soil.

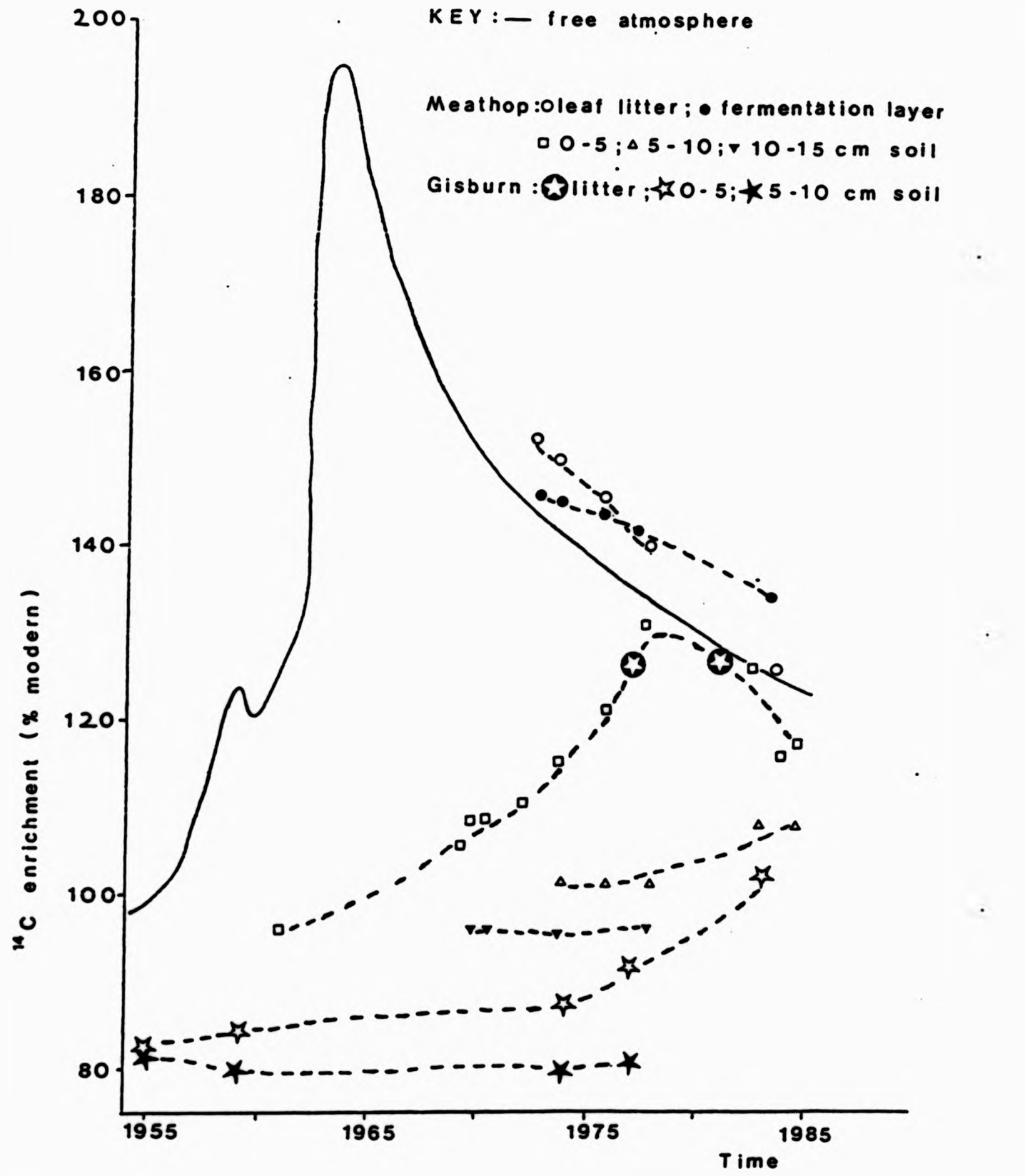


Fig 5.15 Comparison of measured and modelled ^{14}C enrichment values for a Lake District oak woodland after Harkness et al(1985 in press), with additional data from the Gisburn grassland.

5.7.5.2 Comparison of the results obtained for the Gisburn experiment in 1981 and 1983.

Previous results (Brown, unpub.) from soil samples collected under the pure tree stands and the grassland are shown in Table 5.15 . Unfortunately it was not possible to compare the results from 1981 and 1983 directly, since the previous samples were taken from different depths and ^{14}C enrichment decreases exponentially with depth (O' Brien and Stout, 1978).

Table 5.15 ^{14}C enrichment values (error = ±1σ) from the bulk soil and litter samples collected in 1981.

Species	Sampling depth in soil profile			
	Litter	0-2cm	2-8.5cm	8.5-15cm
Grass	+271	+85	-148	-235
N.spruce	+529	+142	-152	-206
S.pine	+533	+115	-159	-201
Alder	+472	+167	-171	-212

It is noticeable, however, that the 0-2cm soil under grass in 1981 was less enriched than under the trees, whilst in 1983, the reverse situation was true for the 0-5cm soil.This anomaly may have arisen because of differences in the way recent carbon is added to the soil under grass relative to the trees. Consequently the resultant exponential distribution of 'bomb' ^{14}C would be different and the curves might cross over in the top few centimeters of soil (Fig 5.16), therefore the result obtained would depend on the depth examined.

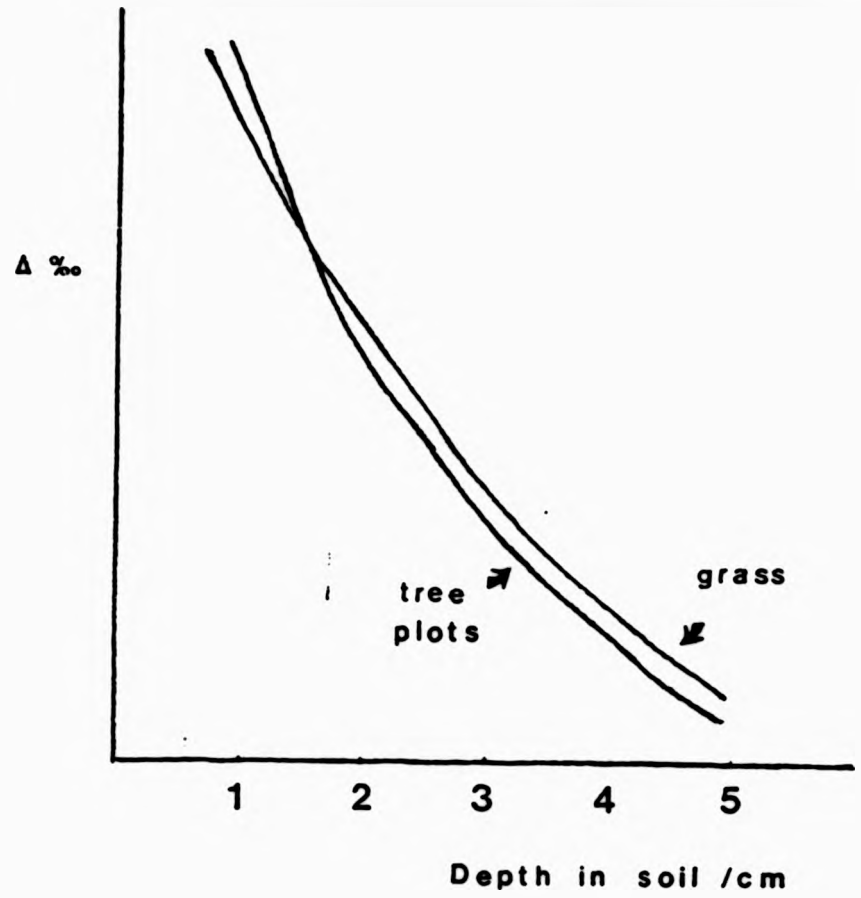


Fig 5.16 Hypothetical differences in ^{14}C enrichment distributions under the grassland and tree plots at Gisburn.

An alternative possibility based on Fig 5.15 is that the levels of 'bomb' ^{14}C in the soil under the Gisburn tree plots have peaked before the grassland soil, so that samples taken in 1981 and 1983 are at either side of the cross-over point, but this can only be speculation in the absence of other data.

The ^{14}C enrichment values for the forest floor of the alder plot were somewhat lower than for the other tree species, this was expected, since the model analysis (Chap. 5.5) indicated that alder had the fastest turnover time. The ^{14}C enrichment values for the forest floor under the Gisburn tree plots were considerably higher than those from Meathop (Fig 5.15), showing that some components of the forest floor were more than 10 years old, even though, in the Gisburn stands, there was only a limited input of woody material, usually in the form of reproductive structures or

small twigs. The similarity of the forest floor ^{14}C enrichment values indicated that all the litter types had reached a similar end-point in the decomposition process, which was governed by the microbial populations present in the soil, and their ability to degrade the more resistant litter fractions.The differential enrichment of the forest floor and top 0-2cm soil, confirmed the previously mentioned point, that there was little mixing of material down the soil profile.

Chapter 5.8 Gel filtration

Gel filtration analysis was carried out, to examine whether there were any differences in the molecular size distribution of soil extracts from under the various treatments, and to try and relate changes to soil organic matter turnover and pedogenesis. The absorbance measurements (Figs 5.17 and 5.18) made on the Sephadex fractions of the borate soluble material, showed that after the initial exclusion peak, the bulk of the material was eluted in a broad band which is characteristic of the polydisperse nature of soil extracts (Posner, 1963).Differences between the fractionation patterns occurred in the intermediate and high molecular weight material; the low molecular weight fractions had similar absorbance distributions regardless of tree species.

The most appropriate way of comparing results of this nature is to examine the ratio of high molecular weight material to low molecular weight material.Swift et al, (1970) proposed a long term humification process, or slow oxidative degradation to explain the physical and chemical changes associated with decreasing humic acid molecular weight within a given soil extract, such that, an increase in the ratio of low molecular weight to high molecular weight material was linked to an increase in humification.

Table 5.16 Ratio of high molecular weight material(A) to low molecular weight material(B) in the borate soluble organic matter after fractionation on Sephadex G-75.

Sample	A:B	Sample	A:B
Alder	1:2.2	Sitka spruce(1968)	1:2.1
Interace	1:2.2	(1967)	1:2.2
S.pine	1:2.5	(1965)	1:1.9
N.spruce	1:3.0	(1956)	1:2.1
Oak	1:3.2	(1953)	1:3.0
Grass	1:3.4	(unfert)	1:2.2

The results (Table 5.16) showed that the extracts under N.spruce, oak, grass and the oldest Sitka spruce plot had higher ratios of low molecular weight to high molecular weight material than the other stands. The presence of a greater amount of the low molecular weight to high molecular weight material under these four stands, indicated that the borate soluble material in these extracts was 'more humified', relative to the other plots. The soils taken from the Gisburn experimental stands with the 'less humified' soil extracts were those which were known to be the most biologically active, with respect to the decomposition of cotton strips(Brown, 1977). In these soils, cycling of the organic matter would be relatively rapid, so that the soil pool is constantly being replenished with recently decomposed material.As results from the measurement of 'bomb' ^{14}C enrichment showed that much of the recent organic material was extracted by the sodium borate (Table 5.6), the more active soils should be characterized by 'less humified' soil extracts, which was in fact the case.

Similar results were reported by Goh and Williams(1982) who studied changes in the molecular weight distribution of soil organic matter in a soil chronosequence. They found that with increased soil development, which was associated with improved organic matter turnover, the proportion of organic matter in the larger molecular weight sizes decreased together with a corresponding increase in the intermediate molecular weight range. The oldest site, however, had a greater proportion of larger molecules, because organic matter cycling was retarded due to the much wetter conditions and low soil pH at this site.

The majority of the Sitka spruce stands had molecular weight distributions similar to the more biologically active sites in the Experimental layout. The 'more humified' soil extract for the oldest Sitka spruce stand could indicate that the turnover rate of the soil organic matter had slowed under this stand, but without additional information, the difference could equally be attributed to initial site heterogeneity in soil conditions.

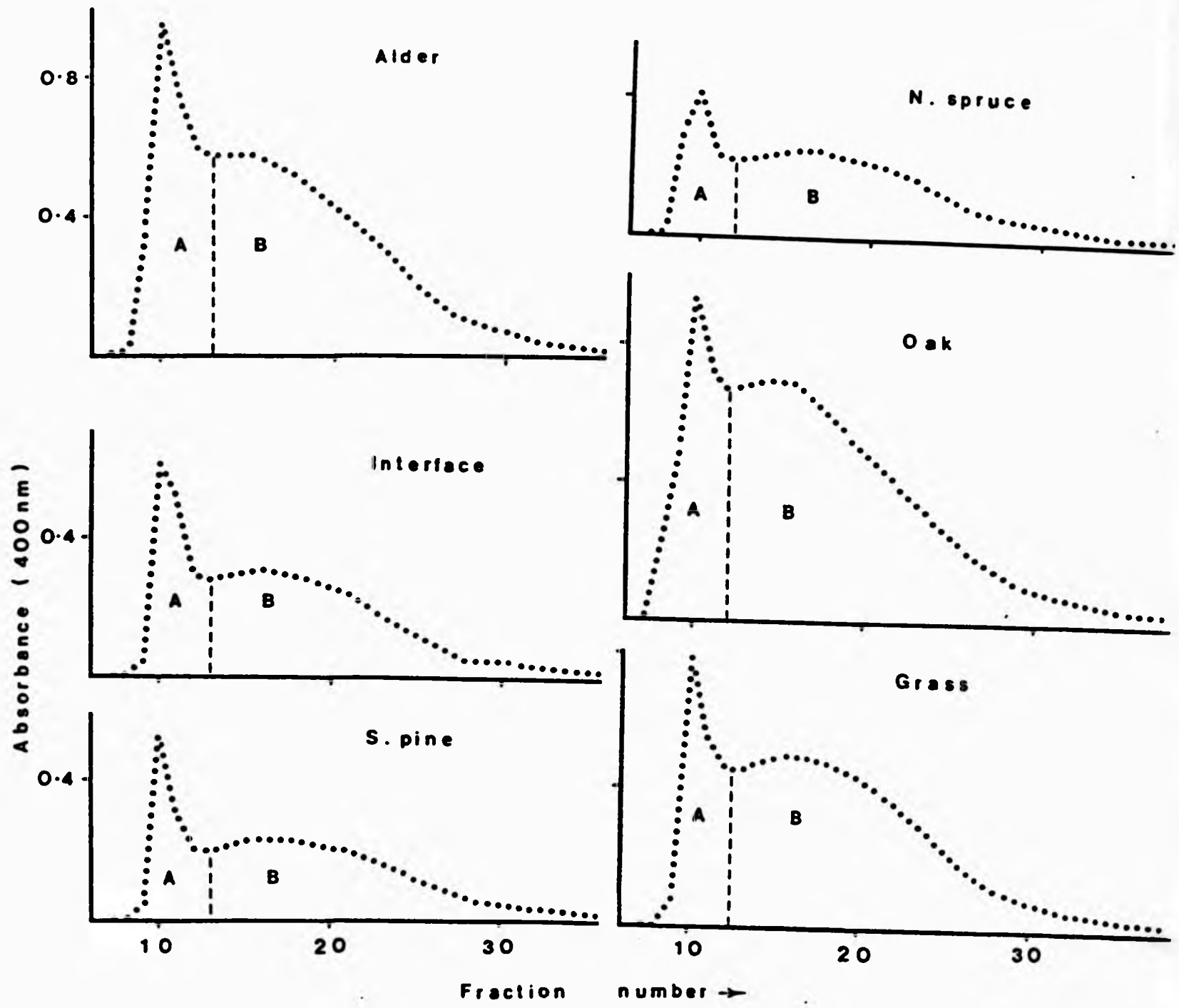


Fig 5.17 Absorbance (400nm) of borate soluble organic matter fractions separated on Sephadex G-75 obtained by extracting 0-5cm soil from the Gisburn experiment

A, high molecular weight fractions (mol. wt. ≥50,000 nominal)

B, lower molecular weight fractions (mol. wt. ≤ 50,000 nominal)

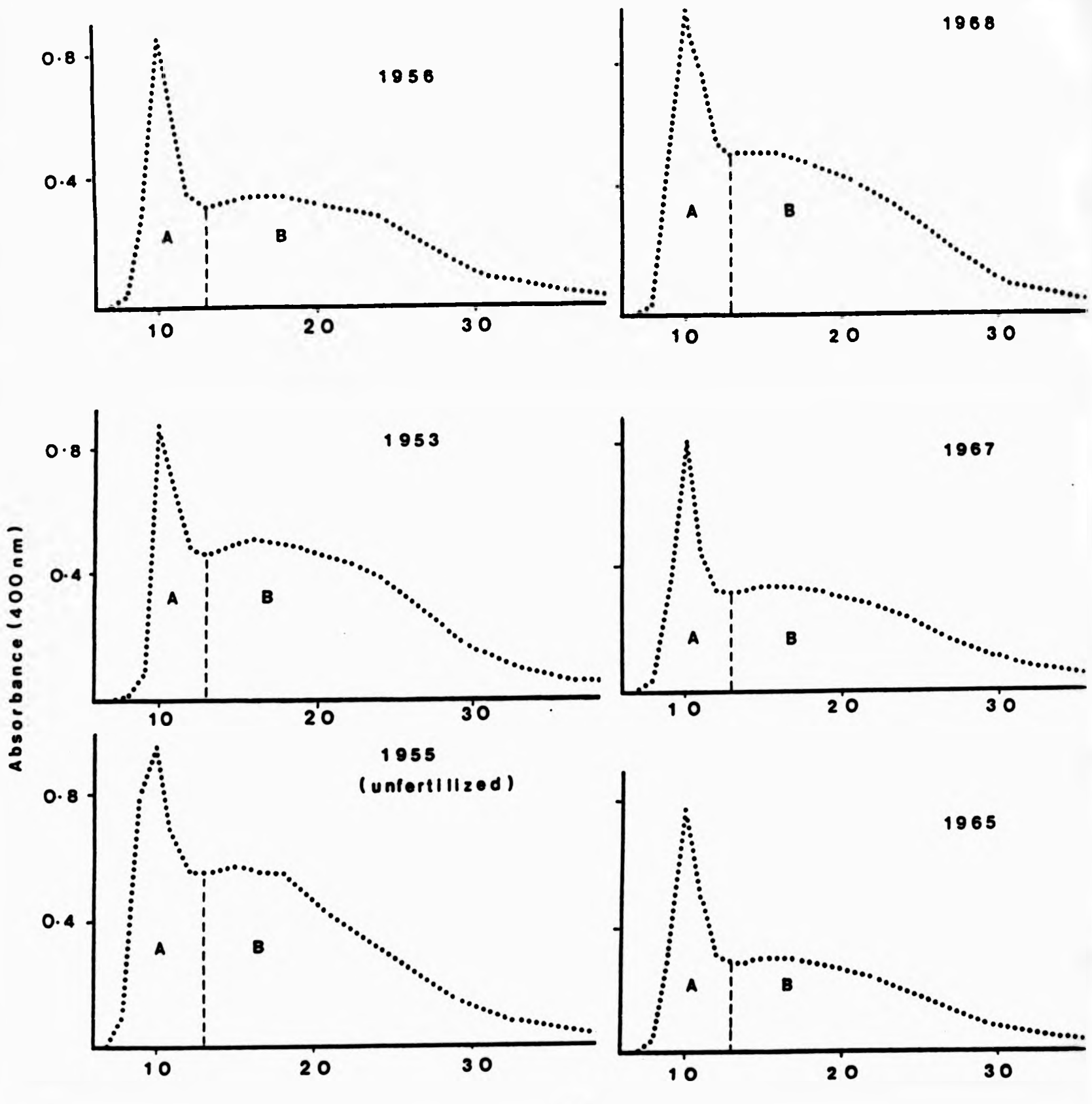


Fig 5.18 Absorbance (400nm) of borate-soluble organic matter fractions separated on Sephadex G-75 obtained by extracting 0-5cm soil from Sitka spruce stands.

A, high molecular weight fractions (mol.wt. ≥ 50,000 nominal)

B, low molecular weight fractions (mol. wt. ≤ 50,000 nominal)

Chapter 5.9 Nuclear magnetic resonance spectroscopy

The NMR spectroscopy was carried out in accordance with the method described by Newman and Tate(1984).Despite the fact, that the samples were scanned for 72 hours, no peaks were detected.

The reason for the lack of signal from the soil extracts is not easily explained, as the samples had 2-3 times the amount of carbon per mil, that is normally required for a spectra to be produced. It is possible that either the sodium borate itself, or some soil component extracted from the soil interfered with any signal produced from the extracts. Unfortunately there was insufficient time during the course of this study to discover the reasons for the lack of signal, but this problem would merit further investigation, given the potential of NMR spectroscopy for examining chemical changes in soil organic matter.

Chapter 6 Conclusions

6.1 Sampling

In order to achieve the aims of this study, briefly summarized as : "an examination of the effects of afforestation over time and between species on the quantitative, qualitative and dynamic nature of soil organic matter", it was necessary first of all to collect "representative" soil samples from the plots under investigation. It is not sufficient to take only one sample to represent that of a whole area, because soil is not a static medium, but a three dimensional body that is continuously variable both in time and space.

The first major problem that must be overcome when commencing a project of this type, is to decide the number of replicates that are needed to obtain a realistic estimate of the value of the soil property under investigation. Previous work at Gisburn had indicated that at least ten replicates were necessary to allow for random variation in the soil chemical properties that had been measured. Organic matter content is often less variable than other soil properties (Ball and Williams,1968) so the initial sampling programme was carried out by taking ten replicate cores. Statistical analysis of the results showed that quite small differences in the carbon content between the experimental plots could be detected (Fig 5.1).

The qualitative studies of the soil organic matter were too time consuming and the Radiocarbon studies too expensive for more than one analysis to be made, so replicate cores were bulked prior to the analysis. The results from the "bomb" carbon enrichment studies (Table 5.11) indicated that this approach was generally successful, but must

be used with caution in more variable sites.

6.2 Quantitative and qualitative studies

Three of the four main objectives of this study were based on the possible effects of afforestation on the total amount of organic matter both above and within the soil profile, the fourth examined qualitative changes. The original objectives are restated and the conclusions drawn from the results are given below :

1) To define the change in soil organic carbon content due to afforestation with different tree species.

This part of the study initially looked at the distribution of total carbon down the soil profile under the pure stands of N. spruce, oak, S. pine and alder relative to the grassland plot in Block 2. Only small differences between the plots were found, and these were limited to the 0 - 5 cm soil and litter layer. These results together with the similarity of pH values observed under all stands (Chapter 5.4.5), indicate that the general trends observed in Europe (Miles,1985) that conifers tend to cause acidification and a redistribution of organic matter compared with broad leaved trees do not apply at Gisburn. Lack of a "species effect" may be mainly due to the relatively short time that the stands have been growing, and also because the site does not favour the growth of the species planted within the experimental layout.

The second part of this objective examined whether the differences observed in the surface soil of Block 2 were reflected throughout the experiment as a whole, and whether differences could be detected in the mixed N. spruce plots. Marked differences in earthworm

populations, nitrogen mineralization rates and phosphorus status had been found in the N. spruce plots when mixed with alder and S. pine relative to pure N. spruce (Brown and Harrison, 1982). The only consistent trend observed between species was that there was significantly more carbon in the litter layer under S.pine relative to N. spruce and alder. There were no differences detected in the mixed plots, indicating that the previously observed differences in biological activity in the mixed plots have not affected the size of the organic matter pools. Any differences in the organic carbon content of the soil under the various species may have been masked by the presence of the large background pool of organic matter present at the start of the experiment. The inherent within block variability particularly in block 1, would also mean that consistent between treatment effects would be difficult to detect.

2) To examine the dynamic nature of the organic matter pool through analysis of seasonal change and modelling.

The seasonal sampling study showed that the carbon content of both the litter and soil did fluctuate over the sampling period, but that there was no clear seasonal pattern. The main sources of carbon input are from aerial litterfall and root death. The alder plot showed a marked seasonality in litterfall, but this was not reflected in the carbon content of the forest floor. This indicates that sampling was too infrequent, and the fresh alder litter was broken down and respired in less than six weeks. Peaks in the carbon content of the soil under the conifer plots coincided with a sharp drop in the % moisture content of the soil, indicating that this increase in carbon may have

been due to root death (Deans,1979)

The model analysis of carbon cycling in the experimental plots at Gisburn was too simplistic to give a realistic estimate of carbon turnover. The main points brought out by the analysis were that the distribution of total carbon between the tree biomass and forest floor indicated that tree growth was poor, and that in terms of total carbon content the trees have had little impact on the original grassland organic matter.

3) To assess the change in total organic carbon content in the soil and litter layer produced by one tree rotation.

This part of the research project was important, because it examined the potential effect on the soil of commercially managed tree plantations. The conclusions drawn from the results were that there has been no increase in soil organic carbon under an age sequence of Sitka spruce, and that the forest floor, once formed appeared to be in equilibrium. These results for the forest floor are similar to those found by Carey (1982) at sites favourable to the growth of Sitka spruce in Ireland. There was no evidence of a build up of organic matter in the topsoil, as has been observed in some Sitka spruce stands (Page,1968). In fact, despite good tree growth in these stands, they appear to have made little impact on the original soil organic matter.

4) To examine the qualitative changes in soil organic matter and to relate these to species and temporal effects.

Qualitative studies were used to try to identify long term changes in soil organic matter, especially with respect to tree species and as

indices for soil development. The use of sodium borate proved to be fairly successful as a soil extractant in this study, as relatively crude extracts could be used for gel filtration and radiocarbon enrichment studies. It is apparent that it may not be suitable for NMR spectroscopy, as it was not possible to obtain any spectra from highly concentrated samples. There was insufficient time to ascertain why the sodium borate extracts did not produce NMR spectra, but this clearly is an area worthy of further study.

The radiocarbon enrichment studies indicated that the sodium borate extracted the most recent carbon, this was important as the original idea of using soil extracts was to try and separate the more recent carbon from the "old" background pool of grassland organic matter, since previous work at Gisburn had shown little variation in the "bomb" carbon enrichment of bulk soil samples (Table 5.15).

The increase in extractability of the soil carbon with increasing stand age indicated that changes in the chemical nature of the soil organic matter had occurred, which were linked to the increasing period of afforestation, even though there had been no change in the total carbon content of the soil.

Both the radiocarbon enrichment studies and the gel filtration experiments indicated that organic matter turnover was fastest in the soils of alder, S. pine and the N. spruce/S. pine interface relative to the pure N. spruce, oak and grassland soils. This is in agreement with previous results at Gisburn (Brown 1977;Brown and Harrison 1982). Although the gel filtration studies did reveal differences in the biological activity of the Gisburn plots, they were fairly small, and there was little variation in extracts from the Sitka spruce stands. As

it would be extremely difficult to interpret such data without additional background information, this technique would appear to have limited value in future studies of this nature.

One of the most interesting findings from the radiocarbon enrichment studies, was that the soil under the fertilized Sitka spruce stands was characterized by carbon incorporated into the soil at the time of planting, even after 30 years of afforestation. The oldest stand remained the least enriched in "bomb" carbon, despite being planted prior to the peak in the atmospheric "bomb" carbon. However, this peak was only transistory, compared with the length of time that the trees were growing in the ^{14}C 'deficient' atmosphere.

The Gisburn grassland showed a similar delayed incorporation of the atmospheric peak of "bomb" carbon to that found in the Meathop woodland soil (Harkness et al, 1985). This indicates that the delayed pulse in the soil can not be due to the selective microbial decay of lignified material as suggested by the authors of the Meathop study, but to some other process.

Nuclear magnetic resonance spectroscopy appears to have great potential in the study of long term soil changes. As this analysis has only been applied to soil studies comparatively recently, there are still many problems to overcome particularly with respect to sample preparation. There was insufficient time to ascertain why the concentrated sodium borate soil extracts did not produce NMR spectra, but clearly this is an area worthy of further study.

6.3 General Conclusions

The general pedogenic trends associated with coniferous and broadleaved trees in Europe are that conifers tend to cause or accelerate podzolisation, whilst deciduous stands seem to maintain higher topsoil pH values and retard podzolisation (Miles,1985). These trends were not observed at Gisburn in the present study.

At Gisburn, the tree species examined appeared to have little effect on the soil in terms of total organic matter content, and the forest floor, once established, rapidly reached an equilibrium. There was no evidence of a repositioning of organic matter within the soil profile, which usually accompanies soil acidification under conifers. This lack of species effect may be due to the relatively short time period that the soils have been afforested, and also because tree growth has been poor. However, the presence of a large background pool of organic matter prior to planting, and the inherent soil variability, may have masked any changes in the total organic matter that have occurred.

The qualitative studies proved to be more informative, and showed that changes in the chemical nature and turnover of the soil organic matter had taken place. The change in extractability of the soil organic matter with sodium borate, taken from the age sequence of Sitka spruce stands, indicated that the chemical nature of the soil organic matter was being gradually altered. There was an increase in the ratio of soluble/insoluble carbon associated with the increasing length of time under afforestation. As the radiocarbon enrichment studies have indicated that organic matter turnover is already extremely slow, any long term changes in the chemical nature of the organic matter, which

may lead to slower turnover rates as a result of afforestation merit further study. Such changes in the chemical structure of the soil organic matter, could have important implications for the success of future tree rotations, if these differences affect the soil's ability to supply nutrients to trees.

There have been several studies (Tarrant et al, 1983;O'Carroll, 1978) which have shown that the use of mixed stands can enhance tree growth, by improving soil nutrient supply. Similar results were obtained from the Gisburn Experiment, where N. spruce has attained greater top heights when grown in mixture, especially with S. pine, than when it is grown in pure stands. The results from the radiocarbon and gel filtration studies, indicated that the improved growth of N. spruce in the mixed stands is a result of faster cycling of organic matter and hence a better nutrient supply. These results have important implications for the management of future rotations of tree stands. It may become more economic to plant mixed tree stands, if tree growth can be maintained without the need for repeated applications of expensive fertilizers. Reduction in the use of fertilizers, particularly water soluble nitrate fertilizers, would be beneficial, as it would lower the risk of contaminated water supplies. Planting mixed stands may also help prevent the soil deterioration that has been observed under pure coniferous stands in Europe.

It is important that further research should be carried out, into the potential effects of tree species on the nature of the soil organic matter and its ability to supply nutrients. In Britain, there is only a limited amount of land that can be used for afforestation, and it is

vital that this resource is managed carefully, so that the soil does not deteriorate irrevocably with successive generations of trees.

REFERENCES

Adams, S.N. 1974. Some relations between forest litter and growth of Sitka spruce on poorly drained soils. J. Appl. Ecol., 11, 761-765.

Alexander, E.B. 1980. Bulk densities of California soils in relation to other soil properties. Soil Sci. Soc. Am. J., 44, 689-692.

Allen, S.E. et al. 1974. Chemical analysis of ecological materials. Oxford, Blackwell Scientific.

Avery, B.W. and Bascombe, C.L. 1974. 'Soil Survey Laboratory Methods'. Soil Survey Technical Monograph No. 6.

Baker, R.A. 1970. Trace organic contaminant concentration by freezing. IV. Ionic effects. Water Res., 4, 559-573.

Ball, D.F. 1964. Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. J. Soil Sci., 15, 84-92.

Ball, D.F. and Williams, W.M. 1968. Variability of soil chemical properties in two uncultivated brown earths. J. Soil Sci. 19, 379-391.

Balzar,C. 1979. Zeitabhangige Anderungen bodenchemischer Kenndaten eines Parabraunerdeprofils im Wienerwald.(Time-dependent changes in the soil chemical characteristics of a parabraunerde profile in the Vienna Woods). Centralblatt fur das Gesamte Forstwesen. 96, 226-241.

Barron, P.F. 1980. Cross-polarization ^{13}C NMR spectroscopy of whole soils. Nature, 286, 585-586.

Benham, D.G. 1985. A freeze concentrator for dewatering aqueous samples. Lab. Practice, 34, 126-128.

Bollen, W.B. et al. 1967. Influence of Red Alder on fertility of a forest soil. Microbial and Chemical Effects. Res. Bull. Ore. For. Res. Lab. No. 12, 1-60.

Bowen, G.D. 1984. In 'Nutrition of forest trees in plantations'. Ed. Bowen, G.D. and Nambiar, E.K.S. Academic press Inc.(London) Ltd. 147-180.

Brix, H. 1981. Effects of thinning and nitrogen fertilization on branch and foliage production in Douglas-fir. Can. J. For. Res. 11, 502-511.

Brown, A.H.F. 1977. The Gisburn Experiment. Effects of different tree species on the activity of soil microbes. Annu. Rep. Inst. Terr. Ecol. 1977, 41.

Brown, A.H.F. and Harrison, A.F. 1982. Effects of tree mixtures on earthworm populations, and N and P status in Norway spruce (Picea abies) stands. New Trends in Soil Biology. Proc. VIII. Intl. Colloquium of Soil Zoology, Louvain-la- Neuve (Belgium). Aug. 30-Sept. 2nd, 1982.

Cameron, R.S. et al. 1972. Molecular weight and shape of humic acid sedimentation and diffusion measurements on fractioned extracts. J. Soil Sci., 394-408.

Candler, R. and Van Cleve, K. 1982. A comparison of aqueous extracts from the B horizon of a birch and aspen forest in interior Alaska. Soil Sci., 134, 176-180.

Cannell, M.G.R. 1984. Woody Biomass of Forest Stands. For. Ecol. Man. 8, 299-312.

Carey, M.L. 1982. Pinus radiata forest floors: factors affecting organic matter and nutrient dynamics. N.Z.J. For. Sci., 12, 36-48.

Carey, M.L. and Farrell, E.P. 1978. Production, Accumulation and Nutrient content of Sitka spruce litterfall. Ir. For., 33, 35-44.

Ceccanti, B. et al. 1978. Fractionation of humus-urease complexes. Soil Biol. Biochem., 10, 39-46.

Cellier,K.M. and Correll, R.L. 1984. In 'Nutrition of forest trees in plantations'. Ed. Bowen, C.D. and Nambiar, E.K.S. Academic press Inc. (London) Ltd., 439-462.

Challinor, D. 1968. Alteration of surface soil characteristics by four tree species. Ecol., 49, 286-290.

Christman, R.F. and Minear, R.A. 1971. Organics in Lakes, in 'Organic compounds in Aquatic Environments'. 119-43. Ed. S.P. Faust and J.V. Hunter. Marcel Dekker Inc., N.Y.

Christensen, B.T. 1982. The effect of afforestation on C and N in the soil at Gisburn. A pilot study. Merlewood R and D Paper, No. 89.

Christensen, B.T. and Malmos, P.A. 1982. Loss-on-ignition and carbon content in a beech forest soil profile. Holarct. Ecol., 5, 376-380.

Coleman, D.C. 1973. Compartmental analysis of 'total soil respiration': An exploratory study. Oikos, 24, 361-366.

Dawson, J.O. et al. 1983. Changes in soil nitrogen concentrations around Alnus glutinosa in a mixed, short-rotation plantation with hybrid Populus. Can. J. For. Res., 13, 572-576.

Deans, J.D. 1979. Fluctuations of the soil environment and fine root growth in a young Sitka spruce plantation. Plant Soil, 52, 195-208.

Determann, H. 1968. 'Gel Chromatography, Gel Filtration, Gel Permeation, Molecular Sieves. A Laboratory Handbook', Springer-Verlag, New York.

Dubach, P. and Mehta, N.C. 1963. The Chemistry of soil humic substances. Soils Fert., 26, 293-300.

Edwards, N.T. and Sollins, P. 1973. Continuous measurements of carbon dioxide evolution from partioned forest floor components. Ecol., 54,406-412.

Farr, E. 1972. An investigation of laboratory and field methods of determining the pH of soil suspensions. J. Sci. Fd. Agric., 23, 1089-1097.

Floate, M.J.S. 1970. Plant nutrient cycling in hill land. Hill Farming Research Organisation Report No. 5, 15-34.

Fogel, R. and Hunt, G. 1983. Contribution of mycorrhizae and soil fungi to nutrient cycling in a Douglas-fir ecosytem. Can. J. Forest. Res., 13, 219-232.

Ford, E.D. 1984. In 'Nutrition of forest trees in platations'. Ed. Bowen, G.D. and Nambiar, E.K.S. Academic press Inc. (London) Ltd., 17-52.

Forrest, W.G. and Ovington, J.D. 1970. Organic matter changes in an age series of Pinus radiata plantations. J. Appl. Ecol., 7, 177-186.

Frankland, J.C. et al, 1963. Spatial and seasonal variations in soil, litter and ground vegetation in some Lake District woodlands. J. Ecol 51, 97-112.

Franklin, J.F. et al. 1968. Chemical soil properties under coastal Oregan stands of alder and conifers. In : Biology of Alder (eds. J.M. Trappe,J.F. Franklin, R.F. Tarrant and G.M. Hansen), p 157-172. Pacific Northwest Forest and Range Experiment Station, Portland, Oregan.

Gascho, G.J. and Stevenson, F.J. 1968. An improved method for extracting organic matter from soil. Soil Sci. Soc. Amer. Proc., 32, 117-119.

Gerasimov, I.P. and Chichagova, O.A. 1971. Some problems in the radiocarbon dating of soil. Soviet Soil Sci., 5, 519-527.

Gilmore, A.R. 1977. Change in a reforested soil associated with tree species and time. II. Soil organic content and pH in hardwood plantations. For. Res. Rep., Dep. For., Uni. Illinois (1977) No. 77-1, 3pp.

Gilmore, A.R. 1980. Changes in a reforested soil associated with tree species and time. V. The organic content and pH of the soil in hardwood plantations after twenty-three years. For. Res. Rep., Dep. For., Univ. Illinois (1980) No. 80-4, 2pp.

Goh, K.M. and Molloy, B.P.J. 1978. Radiocarbon dating of paleosols using soil organic matter components. J. Soil Sci., 29, 567-573.

Goh, K.M. and Pullar, W.A. 1977. Radiocarbon dating techniques for tephras in central North Island, New Zealand, Geoderma, 18, 265-278.

Goh, K.M. and Reid, M.R. 1975. Molecular weight distribution of soil organic matter as affected by acid pretreatment and fractionation into humic and fulvic acids. J. Soil Sci., 26, 207-222.

Goh, K.M. and Williams, M.R. 1982. Distribution of carbon, nitrogen, phosphorus, sulphur and acidity in two molecular weight fractions of organic matter in soil chronosequences. J. Soil Sci., 33, 73-87.

Gosselink, J.G. et al. 1984. Relationship of organic carbon and mineral content to bulk density in Louisiana marsh soils. Soil Sci., 137, 177-180.

Gosz, J.R. et al. 1976. Organic matter and nutrient dynamics of the forest and forest floor in the Brook Forest. Oecologia (Berl.) 22, 305- 320.

Greacen, E.L. and Sands, R. 1980. Compaction of forest soils. A review. Aust. J. Soil Res., 18, 163-189.

Grieve, I.C. 1978. Some effects of the plantation of conifers on a freely drained Lowland soil, Forest of Dean, UK. For., 51, 21-28.

Grieve, I.C. 1980. Some contrast in soil development between grassland and deciduous woodland sites. J. Soil Sci., 31,137-145.

Hall, B.R. and Folland, C.J. 1970. Soils of Lancashire. Bull. Soil Surv. Gt. Brit.

Harkness, D.D. and Millar, B.F. 1980. Possibility of climatically induced variations in the ^{14}C and ^{13}C enrichment patterns as recorded by a 300-year-old Norwegian pine. Radiocarbon 22, 291-298.

Harkness, D.D. and Wilson, H.W. 1972. Some applications in radiocarbon measurement at the S.U.R.R.C. Proc. 8th. Int. Conf. Radiocarbon Dating, Lower Hutt City, N.Z. 18-25 Oct. 1972, 1, B102.

Harkness, D.D. et al. 1985 The temporal distribution of 'bomb' ^{14}C in a forest soil. In press.

Harrington, C.A. and Deal, R.L. 1982. Sitka alder, a candidate for mixed stands. Can. J. For. Res., 12,108-111.

Hatcher, P.G. et al. 1980. Use of solid state ^{13}C NMR in structural studies of humic acids and humin from Holocene sediments. Org. Geochem., 2, 87-92.

Holmsgaard, E. et al. 1961. Bodenbildung,Zuwachs und Gesundheitzustand von Fictenbestanden erster und zweiter Generation. 1. Nord Seeland.Quoted Stone, E.L. 1975. Effects of species on nutrient cycles and soil change. Phil. Trans. Royal Soc. London, B271, 149-162.

House of Lords Select Committee on Science and Technology 1981. Scientific Aspects of Forestry, I and II (2nd Report). London. HMSO.

Howard, P.J.A. 1966. The carbon- organic matter fractions in various soil types. Oikos, 15, 229-236.

Jenkinson, D.S. 1970. The accumulations of organic matter in soil left uncultivated. Rep. Rothamsted exp. Stn. for 1970, Pt. 2. Harpenden, Herts., 113-137.

Jones, E.W. 1965. Pure conifers in Central Europe- a review of some old and new work. J. Oxf. Univ. For. Soc.(Ser.5) no. 13, 3-15.

Jorgensen, J.R. et al. 1980. Nutrient changes in decomposing loblolly pine forest floor. Soil Sci. Soc. Am. J., 44, 1307-1314.

Kalembasa, S.J. and Jenkinson, D.S. 1973. A comparitive study of titrimetric and gravimetric methods for the determination of organic carbon. J. Sci. Fd. Agric., 24, 1085-1090.

Kendall, M.G. 1973. Time-series. Griffin, London.

Kendrick, W.B. 1959. The time factor in the decomposition of coniferous leaf litter. Can. J. Bot. 37, 907-912.

Kovalev, L.S. 1969. Effect of the admixture of Birch and Caragana on the breakdown of forest litter and the growth of Pine in plantations in the forest-steppe of the Central Chernozem Regions. Lesnoi Zhurnal, 3, 166-168.

Ladd, J.N. 1969. The extinction coefficients of soil humic acids fractionated by Sephadex gel filtration. Soil Sci. 107, 303-306.

Ladyman, S.J. 1982. Natural isotope abundances in soil studies. P.h.D. thesis. University of Strathclyde.

Ladyman, S.J. and Harkness, D.D. 1980. Carbon isotope measurement as an index of soil development. Radiocarbon, 22, 885-891.

Libby, W.F. 1946. Atmospheric helium three and radiocarbon from cosmic radiation. Phys. Rev., 69, 671.

Lockman, R.B. and Molloy, M.G. 1984. Seasonal variation in soil test results. Commun. in Soil Sci. Plant Anal., 15, 741-757.

Lousier, J.D. and Parkinson, D. 1979. Organic matter and chemical element dynamics in an aspen woodland soil. Can. J. Forest Res., 9, 449-463.

Maciolek, J.A. 1962. Limnological organic analysis by quantitative wet oxidation. U.S. Fisheries and Wildlife Service Research Rep. no. 60.

Malcolm, D.C. 1979. Some effects of the first rotation on site properties. Ir. For., 36, 76-88.

Mattson, S. and Koutler-Andersson, E. 1941. The acid-base condition in vegetation, litter and humus. I Acids, acidoids and bases in relation to decomposition. K LantbrHogst. Annlr., 9, 1-26.

Meyer, F.H. 1962. Comparative microbiology and micromorphology of humus formation in stands of beech and spruce on basaltic brown earth. Z. Pfl-Ernahr. Dung. Bodenk. 93, 234-243.

Mielikainen, K. 1980 Manty-Koivusekametsikoiden rakenne ja kehitys.Summary: Structure and development of mixed pine and birch stands. Commun. Inst. For. Fenn., 99, 1-82.

Mihai, G.I. 1969. Quoted in Miles, J. 1985. The pedogenic effects of different species and vegetation types and the implications for succession. J. Soil Sci. 36, 571-584.

Millar, C.S. 1974. in 'Biology of plant litter decomposition'. Ed. Dickinson, C.H. and Pugh, G.J.F. Vol. 1., 105-128.

Millar, H.G. 1984. in 'Nutrition of plantation forests'. Ed. Bowen, G.D. and Nambiar, E.K.S. Academic press (London), 53-78.

Millar, H.G. et al. 1979. Nutrient cycles in pine and their adaption to poor soils. Can. J. Forest Res., 9, 19-29.

Miles, J. 1978. The influence of trees on soil properties. Inst. Terr. Ecol. Ann. Rep. 1977,7-11.

Miles, J. 1985a. Soil in the ecosystem. In:Ecological Interactions in the Soil Environment (ed. A.H. Fitter),pp 407-427. British Ecological Society Special Publication No. 4. Blackwell Scientific Publications, Oxford.

Miles, J. 1985b. The pedogenic effects of different species and vegetation types and the implications of succession. J. Soil Sci. 36, 571-584.

Monteith, J.L. et al. 1964. Crop photosynthesis and the flux of carbon dioxide below the canopy. J. Appl. Ecol., 1, 321-337.

Mullins, C.E. and Hutchinson, B.J. 1982 The variability introduced by various subsampling techniques. J. Soil Sci., 33, 547-561.

Nakhla, S.M. and Delibrias, G. 1967. Utilisation de carbone-14 d'origine thermonucleoire pour lelud de la dynamique du carbone dans le sol. Proc. Symp. Radioactive dating and low level counting. Monaco. pub. I.A.E.A. Vienna, 169.

Newbould, P.J. 1967. Methods for estimating the Primary Production of Forests. I.B.P. Blackwell Scientific Publications. Oxford and Edinburgh.

Newman, R.H. and Tate, K.R. 1984. Use of alkaline soil extracts for ^{13}C nmr characterization of humic substances. J. Soil Sci. 35, 47-54.

Nutter, W.L. 1978. In 'The Ecology of Even-aged Forest Plantations'. Eds. Ford, E.D. et al. Proc. Int. Union For. Res. Org. Edinburgh Sept. 1978., 47-54.

O'Brien, B.J. 1984. Soil organic carbon fluxes and turnover rates estimated from radiocarbon enrichments. Soil Biol. Biochem., 16, 115-120.

O'Brien, B.J. and Stout, J.D. 1978. Movement and turnover of soil organic matter as indicated by carbon isotope measurements. Soil Biol. Biochem., 10, 309-317.

O'Carroll, N. 1978. The nursing of Sitka spruce. 1. Japanese larch. Ir. For., 33, 60-65.

O'Carroll, N. 1982. The nursing of Sitka spruce. 2. Nitrogen-fixing species. Ir. For., 39, 17-29.

Ovington, J.D. 1950. The afforestation of the Culbin Sands. Ecol., 38, 308-319.

Ovington, J.D. 1951. The afforestation of the Tentsmuir Sands. Ecol., 39, 363-375.

Ovington, J.D. 1962. Quantitative ecology and the woodland ecosystem concept. Adv. Ecol. Res. 1, 103-192.

Page, H.J. 1930. Quoted Stevenson, F.J. 1982. 'Humus Chemistry. Genesis, Composition, Reactions. Wiley, 1982.

Page, G. 1968. Some effects of conifer crops on soil properties. Comm. For. Rev. 47, 52-62.

Paul, E.A. et al. 1964. Investigations of the dynamics of soil humus utilizing carbon dating techniques. 8th Int. Cong. Soil Sci. Bucharest, Romania, 201-208.

Pines, A. et al. 1973. Proton enhanced N.M.R. of dilute spins in solids J. Chem. Phys., 59, 569-590.

Posner, A.M. 1963. Importance of electrolyte in the determination of molecular weights by 'Sephadex' gel filtration, with especial reference to humic acid. Nature, 198, 1161-1163.

Pyatt, D.G. 1970. Soil groups of upland forests. Forest Record, Forestry Commission, London 71.

Rafter, T.A. and Stout, J.D. 1970. Radiocarbon measurements as an index of the rate of turnover of organic matter in forest and grassland ecosystems in New Zealand. Nobel Symposium, 12, 401-417.

Roletto, E., et al. 1982. Gel filtration and absorption spectroscopic investigations on humic substances from organic fertilizers. Plant Soil, 66, 383-390.

Reilley, C.N. and Sawyer, D.T. 1961. 'Experiments for instrumental Methods'. McGraw-Hill Book Co., New York.

Satchell, J.E. 1980. Potential of the Silpho Moor experimental birch plots as a habitat for Lumbricus terrestris. Soil Biol. Biochem., 12, 317-324.

Scheffe, H.A. 1959. The analysis of variance. Wiley.

Scharpenseel, H.W. 1972. Natural radiocarbon measurement on soil organic matter fractions and on soil profiles of different pedogenesis. 8th. Int. Conf. Radiocarbon Dating, Lower Hutt City, N.Z. 18-25 Oct. 1972., 2, 382-393.

Schnitzer, m. and Preston, C.M. 1983. Effects of acid hydrolysis on the ^{13}C NMR spectra of humic substances. Plant Soil, 75, 201-209.

Schnitzer, M. and Skinner, S.I.M. 1968. Gel filtration of fulvic acid, a soil humic compound. In 'Isotopes and radiation in soil organic-matter studies.' I.A.E.A., Vienna, 1968, 41-53.

Sims, J.R. and Haby, V.A. 1971. Simplified colorimetric determination of soil organic matter. Soil Sci., 112, 137-141.

Sokal, R.R. and Rohlf, F.J. 1969. Biometry. W.H. Freeman and Co.

Steel, R.G.D. and Torrie, J.H. 1980. Principles and Procedures of Statistics. A Biometrical approach. 2nd. Ed. McGraw-Hill Kogakusha, Ltd.

Stevenson, F.J. 1982. 'Humus Chemistry. Genesis, Composition, Reactions.' Wiley, 1982.

Stone, E.L. 1975. Effects of species on nutrient cycles and soil change. Phil. Trans. Royal Soc. London, B271, 149-162.

Stout, J.D. et al. 1975. The possible significance of isotopic ratios in paleoecology. In Quaternary Studies. Ed. R.P. Suggate and M.M. Cresswell. The Royal Soc. New Zealand, Wellington, 279-286.

Stout, J.D. and O'Brien, B.J. 1972. Factors affecting radiocarbon enrichment in soil and turnover of soil organic matter. Proc. 8th Int. Conf. Radiocarbon Dating, 2, 394-407.

Swift, M.J. et al. 1979. 'Decomposition in Terrestrial Ecosystems.' Studies in ecology:Vol. 5. Blackwell Scientific.

Swift, R.S. et al. 1970. Spectral characteristics of a humic acid fractionated with repect to molecular weight using an agar gel. Soil Sci., 110, 93-99.

Suess, H.E. 1955. Radiocarbon concentration in modern wood. Science, 122, 706-707.

Swift, R.S. and Posner, A.M. 1971. Gel chromatography of humic acid. J. Soil Sci., 22, 237-249.

Tarrant, R.F. et al. 1983. Managing red alder in the Douglas-fir region: some possibilities. J. For.,81 ,787-792.

Tarrant, R.F. and Trappe, J.M. 1971. The role of Alnus in improving the forest environment. Plant and Soil Special Volume, 1971, 335-348.

Tate, K.R. 1972. Radiocarbon dating in studies of soil organic matter-vegetation relationships. Proc. 8th. Int. Conf. Radiocarbon dating, Vol. 2, 408-419.

Tate, K.R. 1979. Fractionation of soil organic phosphorus in two New Zealand soils by use of sodium borate. N.Z.J. Sci., 22, 137-42.

Thompson, D.A. 1984. Ploughing of Forest Soils. Forestry Commission Leaflet 71. HMSO.

Thompson, T.R.E. 1972. Report on 'A soil survey of Gisburn Forest'.Soil Survey of England and Wales. (unpublished).

Tinsley, J. and Salam, A. 1961. Chemical studies of soil organic matter. 1. Extraction with aqueous solutions. J. Soil Sci., 12, 259-268.

Tinsley, J. and Walker, C.H. 1964. The composition of organic matter extracted from soils with formic acid. Trans. 8th Int. Cong. Soil Sci., 3, 149-160.

Turner, J. 1981. Nutrient cycling in an age sequence of western Washington Douglas-fir stands. Ann. Bot., 48, 159-169.

Van Goor, C.P. 1954. Quoted in Stone, E.L. 1975. Effects of species on nutrient cycles and soil change. Phil. Trans. Royal Soc. London, B271, 149-162.

Van Goor, C.P. 1967. In 'Colloquium on forest fertilization', 55-65, Int. Potash Inst. Jyvadskla, Finland.

Vogt, K.A. et al. 1983. Organic matter and nutrient dynamics in forest floors of young and mature Abies amabilis stands in Western Washington, as affected by fine root input. Ecol. Monogr., 53, 139-157.

Waksman, S.A. 1936. 'Humus' Williams and Wilkins, Baltimore, 1936.

Waring, R.H. and Franklin, J.F. 1979. Evergreen coniferous forest of the Pacific Northwest. Science, 204, 1380-1386.

Westlake, D.F. 1963. Comparison of plant productivity. Biol. Rev., 38, 385-425.

Wilson, M.A. 1981. Applications of nuclear magnetic resonance spectroscopy to the study of the structure of soil organic matter. J.Soil Sci., 32, 167-186.

Witkamp, M. 1969. Cycles of temperature and carbon dioxide evolution from litter and soil. Ecol., 50, 922-924.

Worobey, B.L. and Webster, G.R.B. 1981. Indigenous ^{13}C-NMR structural features of soil humic substances. Nature, 292, 526-529.

Wittich, W. 1939. Research on the process of litter decomposition on a soil with mull conditions. Forstarchiv. 15, 96-111.

APPENDIX 1 Preliminary sampling (October 1982) in Block II. Distribution of carbon (Kg C m^{-2}) down soil profile under pure stands of N. spruce, S. pine, oak, alder and the grassland site.

Litter

N. spruce	.75	1.26	1.27	1.56	.92	.74	.86	1.35	.97	.4
Alder	1.15	.97	1.14	1.5	.95	1	1.11	1.25	1.57	1.16
S. pine	2.11	2.16	1.72	1.38	1.96	1.92	1.99	2.4	1.47	
Oak	1.1	1.26	2.14	1.09	1.59	1.48	2.13	1.03	.7	1.7

0-2.5 cm

Grass	.67	.35	.36	.36	.33	.92	.46	.74	.6	.72
N. spruce	1.66	1.67	1.27	1.19	1.28	1.94	1.53	1.13	1.31	1.49
Alder	1.15	1.7	2.11	1.6	1.31	1.56	1.54	1.61	1.1	1.32
S. pine	1.76	1.46	1.11	1.87	1.59	1.42	1.37	1.61	1.33	
Oak	1.16	1.24	1.4	1	1.28	.65	.52	1.23	1.66	1.34

2.5-5.0 cm

Grass	.99	1.03	.6	1.38	1.17	.84	.68	1.25	1.52	1.14
N. spruce	1.22	1.99	1.35	1.86	1.42	2.07	1.65	1.24	1.45	1.51
Alder	1.31	1	1.72	1.56	1.33	1.49	1.3	1.45	1.36	1.68
S. pine	.76	1.76	1.24	1.11	1.29	1.67	1.91	1.84	1.67	
Oak	1.22	1.49	1.13	1.39	.79	1.52	1.37	1.43	1.1	.98

5.0-10.0 cm

Grass	2.48	3.26	2.67	2.43	2.89	2.19	2.67	2.62	3.04	2.8
N. spruce	2.62	3.09	3.09	3.33	2.81	3.46	3.66	2.75	2.5	3.15
Alder	2.6	1.8	2.78	2.78	2.68	2.44	2.29	2.86	2.53	3.19
S. pine	1.67	2.92	1.92	2.55	2.46	3.81	2.63	3.64	2.65	
Oak	2.43	2.73	2.36	3	2.29	2.31	2.46	2.56	2.68	1.41

10.0-15.0 cm

Grass	2.28	2.83	2.58	2.06	2.84	2.1	2.83	2.5	2.68	2.29
N. spruce	2.65	2.82	3.14	2.75	2.58	3.43	3.76	2.06	2.56	2.96
Alder	1.7	1.46	2.95	2.17	2.28	2.61	1.89	2.49	2.61	3.29
S. pine	1.52	2.91	2.51	2.21	2.76	3.19	2.44	.34	2.11	
Oak	2.53	2.56	2.14	3.41	3.6	2.49	2.44	1.95	2.44	2.07

15.0-20.0 cm

Grass	2.47	2.55	2.63	1.82	2.82	1.81	1.06	1.92	3.02	2.61
N. spruce	2.35	2.43	2.59	3.02	2.01	3.67	3.03	2.43	1.99	2.66
Alder	1.48	1.91	2.29	2.54	1.57	1.83	1.15	2.12	1.46	2.28
S. pine	1.48	1.68	1.74	1.95	2.07	4	1.61	1.02	2.64	2.02
Oak	2.35	2.45	1.71	3.07	3.39	1.95	2.52	1.94	1.98	1.94

APPENDIX 2 Distribution of organic carbon content (Kg C m^{-2}) in the litter layer and surface soils from the pure tree stands, N. spruce half of the N. spruce mixed stands and the grassland site from all three blocks (sampled February 1983)

Key to sample code (eg G1L)

1st digit rep. tree stand
2nd digit is the sample no.
3rd digit rep. depth in soil profile
(L - Litter; 1 - 0-2.5cm; 2 - 2.5-5.0cm)

G - Grass
S - N. spruce
A - Alder
P - S. pine
O - Oak

SP - N. spruce half of N. spruce/S. pine mixture
SA - N. spruce half of N. spruce/Alder mixture
SO - N. spruce half of N. spruce/Oak mixture

BLOCK I

		A2L	0.275	031	1.494	SA5L	0.370
G1L	0.093	A21	1.180	032	1.392	SA51	1.348
G11	2.076	A22	1.286	04L	0.729	SA52	1.877
G12	3.286	A3L	0.593	041	1.492	SA6L	0.630
G2L	0.000	A31	1.988	05L	0.663	SA61	1.640
G21	1.080	A32	1.839	051	1.486	SA61	1.466
G22	1.746	A4L	0.424	052	1.269	SA7L	0.458
G3L	0.185	A41	1.813	06L	0.107	SA71	2.252
G31	1.979	A42	1.547	061	0.990	SA72	2.253
G32	2.182	A5L	0.265	062	0.964	SA8L	0.457
G4L	0.088	A51	1.571	07L	0.373	SA81	2.309
G41	1.924	A52	1.414	071	1.315	SA82	2.349
G42	1.932	A6L	0.268	072	1.604	SA9L	0.550
G5L	0.224	A61	1.334	08L	0.669	SA91	2.399
G51	1.319	A62	1.394	081	1.807	SA92	1.838
G52	1.174	A7L	0.486	082	1.543	SA0L	0.000
G6L	0.212	A71	1.515	09L	0.000	SA01	1.940
G61	0.824	A72	1.670	091	1.788	SA02	1.393
G62	1.615	A8L	0.526	092	1.762	SO1L	1.247
G7L	0.103	A81	1.943	00L	0.299	SO11	1.354
G71	1.499	A82	1.601	001	1.310	SO12	1.559
G72	2.161	A9L	0.625	002	1.264	SO2L	1.534
G8L	0.297	A91	2.072	SP1L	0.385	SO21	1.354
G81	1.346	A92	1.611	SP11	2.033	SO22	0.000
G82	2.125	A0L	0.336	SP12	1.444	SO3L	2.152
G9L	0.423	A01	0.755	SP22	1.572	SO31	1.839
G91	2.030	A02	2.671	SP21	1.278	SO32	2.331
G92	1.955	P1L	1.796	SP22	1.893	SO4L	1.735
G0L	0.162	P11	1.796	SP3L	0.971	SO41	1.987
G01	1.281	P12	2.034	SP31	1.548	SO42	2.113
G02	1.482	P2L	2.022	SP32	1.909	SO5L	0.969
S1L	0.489	P21	1.781	SP4L	0.513	SO51	1.678
S11	1.565	P22	1.983	SP41	1.490	SO52	1.483
S12	2.145	P3L	1.820	SP42	1.511	SO6L	1.470
S2L	0.901	P31	1.674	SP5L	1.046	SO61	1.335
S21	1.929	P32	1.987	SP51	2.169	SO62	2.292
S22	1.929	P4L	2.070	SP52	2.435	SO7L	1.536
S3L	0.992	P41	1.765	SP6L	1.222	SO71	1.921
S31	1.663	P42	1.501	SP61	1.457	SO72	1.978
S32	2.196	P5L	1.428	SP62	2.022	SO8L	0.367
S4L	1.947	P51	1.895	SP7L	0.629	SO81	1.759
S41	2.009	P52	2.095	SP71	1.430	SO82	1.835
S42	1.478	P6L	1.412	SP72	1.515	SO9L	0.998
S5L	1.168	P61	2.068	SP8L	0.877	SO91	1.381
S51	1.458	P62	1.689	SP81	1.819	SO92	1.262
S52	1.541	P7L	2.320	SP82	2.061	SO0L	2.991
S6L	0.477	P71	1.520	SP9L	0.636	SO01	1.596
S61	1.313	P72	1.798	SP91	2.363	SO02	1.629
S62	1.700	P8L	1.075	SP92	2.327		
S7L	0.691	P81	1.346	SP0L	1.147		
S71	1.225	P82	1.689	SP01	1.891		
S72	1.434	P9L	1.715	SP02	2.234		
S8L	0.186	P91	1.937	SA0L	0.402		
S81	1.714	P92	2.271	SA01	2.060		
S82	1.877	P0L	1.243	SA12	1.944		
S9L	0.831	P01	2.033	SA2L	0.854		
S91	1.046	P02	2.194	SA21	2.012		
S92	1.644	O1L	0.525	SA22	1.753		
S0L	1.362	O11	1.474	SA3L	0.383		
S01	1.847	O12	1.435	SA31	1.938		
S02	1.838	O2L	0.517	SA32	2.167		
A1L	1.147	O21	1.769	SA4L	1.075		
A11	2.579	O22	1.965	SA41	2.267		
A12	0.000	O3L	0.373	SA42	1.369		

APPENDIX 2 (continued)

BLOCK II

		A2L	0.589	031	1.096	SA42	1.800
G1L	0.000	A21	1.749	032	1.470	SA5L	0.742
G11	0.788	A22	1.592	04L	1.358	SA51	1.718
G12	1.386	A3L	0.299	041	2.067	SA52	2.870
G2L	0.281	A31	1.181	042	1.436	SA6L	1.155
G21	1.206	A32	1.163	05L	1.538	SA61	1.874
G22	1.285	A4L	0.304	051	1.582	SA62	1.624
G3L	0.037	A41	1.500	052	1.308	SA7L	0.666
G31	1.138	A42	1.859	06L	1.418	SA71	1.569
G32	1.288	A5L	0.321	061	1.356	SA72	1.351
G4L	0.042	A51	1.856	062	1.515	SA8L	1.783
G41	0.738	A52	1.459	07L	1.253	SA81	2.228
G42	0.991	A6L	0.331	071	1.686	SA82	1.697
G5L	0.109	A61	1.788	072	1.645	SA9L	0.909
G51	0.810	A62	1.672	08L	1.122	SA91	2.128
G52	1.251	A7L	0.621	081	1.623	SA92	1.940
G6L	0.248	A71	2.088	082	1.565	SA0L	1.928
G61	0.859	A72	1.855	09L	0.174	SA01	1.362
G62	1.436	A8L	0.523	091	1.403	SA02	1.893
G7L	0.000	A81	1.794	092	1.564	S01L	0.850
G71	1.119	A82	1.457	00L	1.421	S011	1.913
G72	1.452	A9L	0.503	001	1.795	S012	1.540
G8L	0.106	A91	2.150	002	1.464	S02L	0.666
G81	1.105	A92	2.103	SP1L	1.949	S021	1.459
G82	1.628	A0L	0.846	SP11	2.204	S022	0.319
G9L	0.068	A01	1.650	SP12	1.724	S03L	4.739
G91	1.693	A02	1.862	SP2L	1.040	S031	1.871
G92	1.316	P1L	1.600	SP21	1.016	S032	1.621
G0L	0.000	P11	1.859	SP22	2.160	S04L	1.712
G01	1.258	P12	1.745	SP3L	0.991	S041	2.037
G02	1.564	P2L	1.171	SP31	1.334	S042	1.477
S1L	0.546	P21	2.176	SP32	1.812	S05L	0.667
S11	1.336	P22	1.749	SP4L	1.610	S051	1.942
S12	1.453	P3L	1.765	SP41	1.993	S052	2.122
S2L	0.967	P31	2.264	SP42	1.808	S06L	0.952
S21	1.916	P32	2.139	SP5L	1.325	S061	1.880
S22	1.921	P4L	1.855	SP51	2.057	S062	1.619
S3L	0.186	P41	1.837	SP52	1.626	S07L	1.490
S31	1.843	P42	2.468	SP6L	1.533	S071	1.534
S32	2.269	P5L	2.207	SP61	1.728	S072	1.597
S4L	1.490	P51	2.217	SP62	1.664	S08L	1.566
S41	1.549	P52	2.142	SP7L	0.597	S081	1.759
S42	1.255	P6L	1.789	SP71	1.762	S082	1.680
S5L	1.173	P61	2.072	SP72	1.630	S09L	0.728
S51	1.215	P62	2.647	SP8L	0.853	S091	1.531
S52	1.610	P7L	1.037	SP81	2.034	S092	1.253
S6L	1.415	P71	1.919	SP82	2.563	S00L	1.142
S61	1.668	P72	1.850	SP9L	1.288	S001	1.728
S62	2.246	P8L	0.965	SP91	1.939	S002	1.468
S7L	0.756	P81	1.640	SP92	1.995		
S71	1.612	P82	1.723	SP0L	1.338		
S72	1.462	P9L	1.536	SP01	2.399		
S8L	0.367	P91	1.989	SP02	1.553		
S81	1.705	P92	1.650	SA1L	1.119		
S82	1.739	P0L	1.759	SA11	2.036		
S9L	0.897	P01	1.897	SA12	1.344		
S91	1.651	P02	1.430	SA2L	2.042		
S92	1.802	01L	0.710	SA21	1.818		
S0L	0.920	011	1.211	SA22	1.990		
S01	1.381	012	1.478	SA3L	1.207		
S02	1.864	02L	1.082	SA31	1.474		
A1L	0.604	021	1.784	SA32	1.636		
A11	1.650	022	1.512	SA4L	1.187		
A12	1.879	03L	0.994	SA41	1.682		

APPENDIX 2 (continued)

BLOCK III

		A2L	0.177	031	1.468	SA42	2.090
G1L	0.158	A21	1.827	032	1.380	SA5L	1.933
G11	2.514	A22	1.614	04L	1.842	SA51	1.496
G12	2.240	A3L	0.174	041	1.205	SA52	1.579
G2L	0.032	A31	1.648	042	1.600	SA6L	1.453
G21	1.389	A32	1.804	05L	2.248	SA61	1.677
G22	2.089	A4L	0.487	051	1.487	SA62	1.798
G3L	0.068	A41	2.000	052	1.360	SA8L	0.729
G31	1.384	A42	1.560	06L	0.710	SA71	1.864
G32	1.433	A5L	0.465	061	1.289	SA72	1.936
G4L	0.064	A51	1.386	062	1.591	SA8L	1.304
G41	2.347	A52	1.519	07L	1.546	SA81	1.598
G42	3.034	A6L	0.755	071	1.866	SA82	1.598
G5L	0.074	A61	1.475	072	1.424	SA9L	1.653
G51	1.960	A62	1.138	08L	0.739	SA91	0.518
G52	2.470	A7L	0.520	081	1.325	SA92	1.934
G6L	0.071	A71	1.629	082	1.380	SA0L	1.288
G61	1.571	A72	1.242	09L	0.938	SA01	1.351
G62	2.647	A8L	0.000	091	1.237	SA02	2.323
G7L	0.051	A81	1.215	092	1.149	S01L	1.154
G71	1.523	A82	1.113	00L	1.213	S011	1.668
G72	1.659	A9L	0.212	001	1.441	S012	1.008
G8L	0.067	A91	1.527	002	1.249	S02L	0.974
G81	2.155	A92	1.222	SP1L	1.483	S021	6.325
G82	2.120	A0L	0.160	SP11	2.511	S022	1.278
G9L	0.000	A01	1.995	SP12	2.753	S03L	0.545
G91	1.616	A02	1.587	SP2L	1.905	S031	1.714
G92	1.895	P1L	1.712	SP21	2.333	S032	1.666
G0L	0.082	P11	1.517	SP22	1.590	S04L	0.966
G01	1.272	P12	1.482	SP3L	2.063	S041	0.995
G02	2.108	P2L	1.759	SP31	2.287	S042	1.392
S1L	1.466	P21	1.312	SP32	3.034	S05L	0.609
S11	1.721	P22	1.686	SP4L	0.933	S051	1.724
S12	1.547	P3L	1.817	SP41	1.825	S052	1.402
S2L	0.684	P31	1.661	SP42	1.488	S06L	0.780
S21	1.838	P32	1.304	SP5L	0.991	S061	2.129
S22	1.747	P4L	1.418	SP51	3.156	S062	1.864
S3L	0.529	P41	1.719	SP52	2.160	S07L	0.220
S31	2.024	P42	1.219	SP6L	0.453	S071	1.394
S32	1.811	P5L	0.793	SP61	1.923	S072	1.649
S4L	0.340	P51	1.497	SP62	1.966	S08L	1.521
S41	2.039	P52	1.863	SP7L	1.639	S081	1.875
S42	1.558	P6L	1.441	SP71	1.939	S082	1.902
S5L	0.592	P61	2.096	SP72	2.461	S09L	1.593
S51	1.920	P62	1.582	SP8L	1.651	S091	1.846
S52	1.689	P7L	1.135	SP81	2.015	S092	1.776
S6L	0.702	P71	2.109	SP82	1.637	S00L	1.138
S61	1.621	P72	1.347	SP9L	0.781	S001	1.138
S62	1.161	P8L	2.100	SP91	1.989	S002	1.008
S7L	1.111	P81	0.913	SP92	2.332		
S71	1.595	P82	1.610	SP0L	1.148		
S72	1.447	P9L	2.107	SP01	2.277		
S8L	0.591	P91	1.986	SP02	1.726		
S81	1.783	P92	1.295	SA1L	0.928		
S82	1.684	P0L	0.666	SA11	1.931		
S9L	0.542	P01	1.468	SA12	2.191		
S91	2.185	P02	1.329	SA2L	2.135		
S92	1.515	[illegible]	0.966	SA21	1.972		
S0L	0.781	011	1.755	SA22	1.509		
S01	1.554	012	1.436	SA3L	1.189		
S02	2.282	02L	0.354	SA31	2.358		
A1L	0.487	021	2.161	SA32	1.774		
A11	2.282	022	1.543	SA4L	0.864		
A12	2.144	03L	0.000	SA41	2.036		

APPENDIX 3 Carbon content (Kg C m^{-2}) of soil and forest floor in different aged stands of Sitka spruce (sampled June 1983)

1965 (Plot 1)		1965 (Plot 2)	
0-15 cm soil	Litter	0-15 cm soil	Litter
6.8	8.6	5.6	2.3
3.9	7.5	8.1	0.8
5.4	7.5	5.5	0.9
5.9	6.3	5.0	1.5
5.5	5.6	5.3	2.1
5.7	7.5	6.1	0.9
6.2	7.2	5.8	1.4
4.9	8.4	5.5	1.3
5.0	5.2	5.4	1.4
5.9	5.2	6.4	1.5
4.8	4.8	10.4	2.3
4.5	6.5	6.1	1.0
5.5	9.4	5.1	1.0
3.0	7.6	5.4	0.9
5.6	10.5	4.8	1.1
6.1	9.6	5.6	2.2
4.0	8.7	4.2	1.0
6.0	9.2	5.0	1.0
5.4	6.3	3.9	2.0
4.3	6.4	5.3	1.2
5.9	7.7	7.1	0.6
6.0	7.7	5.3	0.5
4.9	8.2	5.4	0.5
4.2	6.7	6.4	0.7
5.6	8.7	4.8	1.8
6.2	9.3	4.9	2.0
7.0	7.1	4.8	1.1
6.5	7.5	3.3	2.2
5.4	8.8	3.9	2.5
	5.9	5.4	1.0

1967 (Plot 1)		1967 (Plot 2)	
0-15 cm soil	Litter	0-15 cm soil	Litter
2.8	7.2	4.9	4.9
4.0	7.8	5.6	3.7
4.6	5.8	3.8	5.9
4.2	6.7	3.5	5.1
3.0	9.3	3.4	6.9
2.7	5.8	3.6	5.1
3.7	4.9	5.7	5.9
3.2	3.9	6.1	5.8
3.9	4.1	5.5	8.7
3.2	5.9	5.3	10.2
3.4	5.3	4.6	5.5
3.1	3.6	4.1	5.5
3.9	4.7	3.8	4.5
3.3	7.2	4.5	8.6
3.7	6.0	7.2	6.5
3.2	4.4	5.1	9.6
3.3	6.2	4.8	13.9
2.2	7.1	5.0	4.9
4.6	6.8	4.8	6.6
4.8	4.8	4.4	7.4
4.0	5.2	6.3	6.2
3.4	2.8	5.9	14.9
4.1	5.4	3.8	6.4
2.7	7.0	4.2	5.2
3.2	4.8	6.0	7.0
3.4	6.6	4.3	6.7
3.6	7.6	5.7	5.9
3.1	5.9	4.5	4.9
3.1	7.0	4.6	5.1
2.8	6.8	3.6	6.0

APPENDIX 3 (continued)

1968 (Plot 1)		1968 (Plot 2)	
0-15 cm soil	Litter	0-15 cm soil	Litter
5.6	5.0	6.4	10.3
4.9	9.9	4.9	7.19
5.1	8.7	4.2	11.2
5.6	8.2	5.1	8.9
5.4	7.9	5.9	9.6
5.2	6.5	5.3	6.1
4.7	6.8	4.5	8.1
5.0	12.1	5.3	12.7
5.5	10.7	4.7	12.4
5.6	15.0	4.7	8.2
5.2	6.9	4.6	10.1
5.3	6.4	6.4	8.7
4.4	11.3	6.4	8.6
5.4	14.2	4.4	7.6
5.9	12.9	5.1	8.4
5.4	16.5	4.3	7.1
4.7	7.8	4.8	7.2
6.3	8.5	4.9	8.3
5.2	10.9	5.9	5.4
5.0	7.3	5.2	7.3
5.7	6.8	4.9	7.9
5.4	4.2	4.5	14.8
5.9	10.9	4.4	7.4
5.2	8.8	4.9	7.8
5.1	5.4	4.9	7.5
5.4	15.7	4.6	7.3
6.3	11.1	4.1	12.2
4.9	13.1	4.2	9.9
5.2	7.6	5.2	10.7
4.9		5.5	

1970 (Plot 1)		1970 (Plot 2)	
0-15 cm soil	Litter	0-15 cm soil	Litter
1.3	7.7	3.2	6.0
1.8	5.2	4.1	6.3
2.0	8.4	3.7	4.9
2.2	6.5	3.6	5.1
2.9	8.1	2.9	8.7
3.6	7.3	4.2	5.4
2.0	9.1	4.8	13.1
3.7	8.6	5.3	4.4
3.3	6.3	3.4	4.2
3.5	10.8	4.5	3.6
3.7	15.9	3.4	5.2
3.7	11.9	4.2	8.1
3.6	11.9	4.6	10.9
3.4	12.1	3.7	9.8
3.6	18.1	2.3	5.4
2.5	4.6	3.6	5.5
3.5	3.8	5.2	3.7
3.2	6.2	4.1	5.7
3.2	10.6	3.1	7.4
2.8	6.6	3.6	4.5
4.4	6.7	3.1	8.1
3.2	7.8	8.0	8.1
4.1	6.9	5.0	4.5
3.4	9.6	4.2	3.7
4.6	6.3	4.4	5.8
1.8	4.8	5.2	6.8
2.4	4.3	5.1	4.8
2.5	5.7	3.6	5.1
1.5	10.4	3.9	3.5
1.1	5.1		4.2

1953 (Plot 1)		1953 (Plot 2)	
0-15 cm soil	Litter	0-15 cm soil	Litter
8.9	17.2	9.7	8.9
10.2	11.0	11.7	7.3
9.7	8.7	10.5	8.5
13.9	8.9	10.2	11.1
10.2	9.7	7.0	10.2
8.7	10.0	10.0	7.3
9.2	11.3	9.8	8.6
10.4	11.9	10.8	6.5
9.2	8.5	10.7	9.6
8.4	13.0	11.2	6.8
5.2	9.9	12.7	7.5
12.4	8.4	8.7	9.6
9.6	11.3	13.1	7.8
7.5	7.4	9.9	9.5
5.0	11.6	8.7	6.9
7.9	7.7	10.5	11.8
6.6	8.9	8.2	7.8
5.9	9.8	10.0	12.1
7.0	9.2	11.5	9.7
7.2	8.9	11.4	8.9
6.3	9.4	8.4	6.2
7.7	10.1	12.8	6.6
5.7	9.6	9.4	10.3
7.5	9.1	9.7	9.2
8.7	6.9	13.4	10.6
7.0	8.2	8.8	8.2
8.7	9.9	9.9	5.9
9.4	8.5	10.8	7.2
6.7	6.7	8.8	5.9
	7.1	8.8	7.3

1956 (Plot 1)		1956 (Plot 2)	
0-15 cm soil	Litter	0-15 cm soil	Litter
5.7	8.9	8.0	6.4
8.7	8.5	9.6	6.8
6.6	8.4	7.4	6.3
7.9	6.9	7.1	6.6
7.4	6.3	8.9	5.9
8.1	6.8	8.1	6.7
9.6	8.2	8.4	5.4
6.2	12.3	8.6	6.3
6.9	10.3	7.4	6.9
4.7	10.4	7.2	7.4
9.4	13.5	6.4	6.8
6.6	10.7	7.7	6.7
8.0	7.9	8.4	6.3
5.7	12.7	9.7	5.2
6.9	9.0	5.6	7.0
6.2	8.5	7.8	6.1
4.0	14.7	8.8	5.4
4.7	9.3	6.6	6.9
4.9	8.7	5.9	7.6
5.2	8.2	4.7	8.2
5.8	8.9	5.6	6.6
7.6	11.5	7.7	6.4
6.9	7.8	7.9	6.1
7.3	10.7	7.1	7.8
7.7	12.8	8.2	6.1
6.5	12.5	7.3	8.1
5.9	10.6	7.4	5.5
8.4	8.7	5.4	6.6
7.1	12.8	8.4	7.2
5.4	12.9	8.0	6.5

4.1 Total carbon content (Kg C m^{-2}) in the litter layer and 0-5cm soil, in the pure stands of N. spruce, S. pine, alder and the N. spruce/S. pine mixture at six weekly time intervals.
(PM = S. pine half of mixture; SM = N. spruce half of mixture Interface is the interface between the S. pine and N. spruce blocks within the mixture.)

	28/04/83		09/06/83	
	Litter	0-5 cm soil	Litter	0-5 cm soil
N. SPRUCE	.753	2.449	.523	3.441
	.31	4.649	.683	2.674
	2.03	3.012	1.129	3.4
	1.256	3.795	.21	2.287
	1.638	3.453	.271	2.953
	.644	2.566	1.337	2.282
	.452	3.837	1.279	4.353
	1.029	2.844	1.323	3.886
	.831	3.537	1.24	3.59
	1.046	4.203	1.623	4.03
	1.318	3.653	2.006	4.939
	1.685	4.837	1.7	4.1
	1.491	3.03	1.624	3.895
	1.012	3.435	1.161	4.372
S. PINE	1.41	3.237	2.151	4.639
	1.727	4.23	1.314	4.421
	1.572	3.893	1.482	3.543
	1.687	2.599	2.574	4.232
	1.813	3.678	1.872	3.339
	2.148	3.173	1.027	3.667
	0	2.99	.316	3.718
	1.289	3.261	.602	3.007
	.827	2.811	1.203	3.608
	.419	3.336	1.168	3.955
ALDER	1.075	3.552	.634	2.644
	.359	3.382	.343	3.359
	.523	3.478	.621	2.31
	1.28	3.845	.639	2.77
	1.083	3.349	.863	3.033
	1.026	3.293	.265	2.376
	1.715	4.057	.963	3.874
	1.232	3.332	2.184	3.677
	1.431	3.743	3.048	3.78
	2.042	3.099	.559	4.714
	1.143	3.894	1.584	4.512
PM	1.527	4.172	2.298	3.826
	1.525	3.889	1.542	3.774
	1.715	3.489	2.571	3.345
	.538	3.39	1.681	4.73
	1.455	3.427	1.74	3.667
	.525	3.797	.894	3.658
	.851	3.67	1.635	3.592
	1.357	3.876	1.377	3.204
	.714	3.214	1.286	3.306
	.368	4.128	1.352	3.939
	1.052	3.544	1.229	3.292
SM	1.52	3.67	1.384	2.858
	1.06	2.567	.437	2.725
	1.539	3.594	1.27	3.688
	2.133	3.652	1.14	3.052
	1.607	4.808	.967	4.234
	1.913	4.836	1.6	5.1
	0.995	4.489	1.349	4.341
	1.929	5.371	1.284	4.778
INTERFACE	1.81	5.595	1.8	4.994
	1.26	4.666	1.827	5.412
	0.855	4.208	2.335	6.165
	1.405	4.505	2.223	5.997
	1.502	4.994	1.203	5.004
	2.655	6.461	1.287	4.93

	21/07/83		01/09/83	
	Litter	0-5 cm soil	Litter	0-5 cm soil
	.53	3.382	.468	2.68
	1.983	3.163	.771	2.676
	.916	2.079	2.991	3.658
	.598	3.124	1.138	4.329
N. SPRUCE			.214	4.151
	.905	4.398	1.2	3.695
	1.378	4.07	1.671	3.328
	1.63	4.065	1.59	3.108
	.927	3.047	1.35	3.527
	1.975	4.344	1.621	3.61
	.85	4.53	2.134	4.355
	2.608	4.557	2.037	4.233
	1.19	4.416	2.336	3.641
S. PINE	.66	4.228	2.412	4.333
	1.729	4.389	1.726	3.656
	1.673	3.121	1.434	3.757
	2.081	4.199	2.461	3.749
	3.35	4.128	3.191	3.509
	1.954	4.323	2.107	4.209
	1.589	4.92	2.13	4.608
	2.114	3.423	.332	3.022
	.448	3.258	.296	3.367
	.327	4.227	.712	3.62
	.527	3.493	.298	4.393
ALDER	.767	4.155	.453	3.72
	.674	3.685	.24	3.191
	.496	4	.915	3.681
	.172	3.389	.627	4.541
	.867	3.839	.715	2.948
	.419	2.901	.312	3.105
	1.327	3.321		
	1.371	3.864	1.854	3.42
	2.102	4.31	2.29	2.734
	1.421	4.472	2.694	3.435
	2.537	3.113	2.383	3.068
PM	1.663	4.178	2.664	3.864
	2.831	3.27	2.348	4.406
	1.942	3.363	1.44	4.014
	1.26	3.845	2.652	3.155
	1.959	4.571	1.245	3.736
	1.643	3.706	3.168	3.476
	1.906	3.517	1.182	3.788
	1.943	3.233	1.582	3.626
	1.919	3.558	1.934	3.784
	2.399	4.25	1.65	3.107
SM	1.246	4.674	2.046	2.894
	.266	3.451	1.541	3.601
	2.038	3.698	1.803	3.725
	2.794	3.383	1.529	3.498
	.81	4.333	2.162	3.218
	1.351	3.612	1.647	3.628
	2.206	5.792	2.119	6.193
	3.505	6.948	2.201	5.082
	1.704	5.717	1.814	4.724
INTERFACE	2.036	6.137	1.666	4.974
	1.938	4.494	2.528	6.229
	1.437	5.129	2.703	6.187
	2.035	5.183	2.067	5.24
	2.355	6.376	2.438	6.787
	1.222	5.207	2.933	7.116
	2.009	4.775	2.367	6.631

	12/10/83		28/11/83	
	Litter	0-5 cm soil	Litter	0-5 cm soil
N. SPRUCE	1.043	2.471	.845	3.448
	1.752	2.951	.881	3.565
	1.179	3.214	.691	3.098
	.402	3.21	1.455	2.825
	1.06	3.45	.822	2.286
	1.348	3.64	1.174	3.631
	.688	3.254	.67	4.053
	.989	3.41	1.793	3.719
			.362	4.03
	1.069	3.411	.804	3.205
	1.223	3.953	2.297	3.218
	2.437	3.864	1.447	4.982
	1.348	5.735	1.694	4.12
	1.229	5.089	2.083	3.031
S. PINE	2.246	4.494	1.755	4.21
	2.419	4.342	1.636	3.704
	1.933	3.914	1.73	3.676
	1.903	3.642	2.99	3.664
	2.397	3.853	1.93	4.353
	1.45	3.267	1.751	4.129
	1.306	4.255	.706	3.201
	.111	3.396	.126	3.188
	.852	2.895	.579	3.81
	.453	3.483	.95	4.061
ALDER	.401	2.509	.346	3.325
	.902	3.057	.731	2.331
	.444	3.48	.258	2.906
	.202	2.426	.489	3.563
	.201	2.983	.371	2.897
	1.499	3.376	.405	3.352
	.273	2.938		
	1.941	4.047	1.56	2.993
	.805	3.335	1.864	4.29
	1.382	2.774	1.989	4.783
	2.175	3.825	1.955	4.107
PM	2.19	3.32	.856	3.893
	1.264	3.785	2.776	3.548
	2.138	3.34	1.985	3.761
	1.894	2.829	2.257	3.541
	1.091	3.968	1.743	3.916
	2.562	3.286	.636	3.602
	1.371	3.466	1.074	3.37
	2.37	2.028	1.437	3.498
	1.268	3.435	1.958	3.646
	2.299	3.829	1.505	3.079
SM	1.76	3.047	1.663	3.615
	1.627	3.859	2.525	3.867
	1.839	3.292	1.356	3.521
	1.626	3.575	2.214	3.791
	1.151	3.699	1.401	3.264
	1.567	3.444	.49	4.222
	1.316	4.173	1.905	5.131
	2.169	6.1	1.035	3.821
	2.073	5.62	2.041	6.484
INTERFACE	1.879	4.703	1.387	4.797
	2.338	5.359	.714	3.968
	1.917	4.691	1.434	4.779
	1.75	5.411	1.694	4.447
	1.164	4.983	1.664	5.134
	2.596	7.021	1.231	5.213
	.887	3.938	2.184	5.673

	09/01/84		21/02/84	
	Litter	0-5 cm soil	Litter	0-5 cm soil
N. SPRUCE	.973	3.988	.846	2.913
	1.023	2.933	1.27	2.492
	.602	3.11	1.129	2.695
	1.193	3.719	.85	3.071
	1.283	3.91	.936	3.302
	.642	3.188	1.245	2.106
	1.191	3.383	.458	3.23
	.782	3.604	1.076	4.075
	1.022	3.428	1.327	3.945
	.639	4.137	1.538	3.74
	2.54	4.532		
	2.089	3.191		
			1.089	4.485
			1.661	3.983
	1.124	4.372	2.86	4.026
	.926	4.313	2.28	3.375
S. PINE	1.25	3.314	1.798	3.967
	.907	4.315	.977	3.955
	2.031	3.75	1.551	3.164
	1.402	3.95	1.451	2.955
	.959	3.911	.807	3.454
	2.13	3.767	2.76	3.817
	.784	3.348	.088	3.768
	.474	3.418	.252	3.186
	.124	3.773	.659	2.874
ALDER	.155	3.639	.462	2.454
	.255	3.544	.899	3.478
	.427	3.288	.532	2.91
	.429	4.867	.533	3.321
	.201	3.955	.347	4.465
	.035	3.943	.302	3.47
	.643	4.724	.53	3.863
		4.121	1.977	3.713
	1.392	3.448	2.091	2.334
	2.167	4.215	.66	3.904
	1.176	3.434	1.645	3.902
PM	.899	3.863	2.477	4.044
	1.729	2.845	2.589	3.263
	1.545	3.594	1.672	3.652
	2.162	4.159	2.372	4.239
	.469	3.611	1.504	3.961
	1.773	3.425	.848	3.909
	1.71	4.026		
	.613	3.548	.639	3.295
	1.166	3.301	1.431	2.738
	1.416	3.896	1.651	3.873
	.933	2.957	1.542	3.256
SM	1.375	3.077	1.759	4.023
	1.617	3.793	1.296	3.328
	1.32	4.025	1.7	3.664
	1.198	4.242	1.599	3.351
	1.224	3.279	1.703	2.977
	1.675	4.859	.309	3.276
	1.813	5.455	1.631	4.544
	1.772	5.08	1.391	5.121
	1.66	4.972	2.659	6.345
INTERFACE	1.853	4.613	1.308	4.664
	1.405	4.942	1.029	5.341
	1.199	6.343	1.419	4.411
	2.002	5.418	1.418	4.615
	1.784	7.337	2.255	5.822
	3.188	5.735	2.288	5.814
	2.513		2.437	6.82

	05/04/84		14/05/84	
	Litter	0-5 cm soil	Litter	0-5 cm soil
	.774	2.881	1.198	2.59
	.528	3.348	1.514	2.997
	1.078	3.664	1.145	2.906
	1.015	3.708	1.508	3.751
	1.018	4.341	1.817	2.855
N. SPRUCE	1.51	4.223	1.304	3.851
	.955	4.03	1.995	3.986
	1.463	3.616	1.114	3.313
	.784	3.489	1.773	3.512
	.691	3.357	2.058	3.483
	2.254	4.978	1.74	4.412
	1.815	5.259	1.455	4.767
	1.496	4.699	2.422	4.265
S. PINE	1.827	4.078	1.767	4.367
	2.232	3.058	3.546	3.289
	.903	4.491	1.601	3.739
			1.968	3.627
			1.412	3.515
			2.628	2.411
	1.296	3.809	1.585	3.739
	1.917	3.157	.739	3.472
	1.784	4.979	.526	3.812
	.45	3.77	.507	3.254
	.123	2.945	.439	4.885
	.162	3.862	.105	3.279
ALDER	.499	3.513	.172	3.253
	.526	4.549	.312	4.246
	.356	3.736	1.177	4.045
	.771	3.948	.608	3.338
	.557	3.352	.703	4.159
	.76	3.756		
	.521	3.081		
	.718	3.682		
	1.567	4.071		
	2.389	4.351		
PM	1.583	4.101		
	.736	4.065		
	2.006	4.437		
	1.085	3.471		
	1.798	4.343		
	1.811	4.385		
	1.041	3.592		
	1.013	4.256		
	.582	3.594		
	.957	3.8		
SM	1.04	4.595		
	1.176	2.77		
	1.65	4.264		
	2.164	3.534		
	1.628	3.486		
	1.736	3.34		
	1.122	4.097		
	.944	4.447		
	1.805	5.464		
	1.377	5.08		
	2.045	6.375		
	1.786	5.893		
	1.478	5.077		
	2.989	7.097		
	1.644	5.29		
	2.129	6.008		
	5.209	9.177		
	1.85	6.189		

26/06/84

	Litter	0-5 cm soil
	1.288	2.156
	2.409	1.79
	.958	2.991
	.842	3.724
N. SPRUCE	1.61	3.518
	.505	3.678
	.606	4.035
	1.826	3.76
	.708	2.579
	.78	3.65
	1.665	4.218
	2.807	4.419
	2.458	3.576
	1.143	3.013
S. PINE	1.541	3.233
	1.157	3.37
	2.61	3.421
	1.906	3.676
	1.725	3.906
	2.155	4.121
	.551	4.301
	.66	3.02
	1.096	3.653
ALDER	.07	3.733
	.231	3.898
	.451	3.475
	.361	3.14
	.463	3.231
	.044	3.597
	.713	2.709

18/09/84

	.728	3.468
	.855	3.244
	.974	3.133
	.781	2.922
N. SPRUCE	.35	3.477
	1.527	4.313
	.625	3.153
	.926	4.261
	.586	4.271
	.576	3.089
	1.618	3.353
	1.443	4.067
	.491	4.037
S. PINE	.466	3.887
	1.337	3.953
	1.896	4.346
	1.862	3.528
	.709	3.423
	1.926	3.772
	1.995	4.056
	.66	3.7
	.377	2.601
	.786	3.972
ALDER	.364	3.426
	.157	3.434
	.173	3.219
	.287	4.005
	.377	4.237
	1.064	2.568
	.526	2.597

07/08/84

Litter	0-5 cm soil
.816	2.486
1.04	2.69
1.281	2.272
1.395	3.273
1.926	3.107
1.347	4.029
1.541	3.329
1.16	3.318
.96	3.386
.946	3.638
1.93	4.482
1.818	3.062
1.969	3.181
1.42	3.514
1.767	3.927
2.207	4.549
1.704	3.198
2.37	3.869
1.326	5.448
1.87	3.521
.845	2.784
.527	3.389
.68	3.448
1.37	3.533
.256	3.378
.936	3.908
.834	3.863
.409	3.201
.481	3.213
.443	2.473

30/10/84

.365	2.75
.924	2.811
1.214	3.197
1.676	3.24
1.837	3.589
1.009	3.722
1.546	3.252
1.604	4.085
.79	3.92
1.218	4.621
.331	4.084
.508	3.258
1.032	3.227
1.016	3.136
1.864	4.364
1.611	4.12
1.281	3.698
1.735	3.19
.575	3.504
1.265	2.709
.715	3.893
.198	2.546
.068	2.932
.198	3.323
.499	3.437
.491	1.702
.497	2.88
.955	3.785
.273	3.302
.198	2.505

4.2 Total litterfall (Kg C m^{-2} x 10) collected in each of five litter traps in the pure stands of S. pine , N. spruce , alder and oak.

	N. SPRUCE	S. PINE	ALDER	OAK
	.12	.19	.01	.02
09/06/83	.12	.05	.15	.01
	.13	.17	.03	.01
	.14	.1	.02	.01
	.13	.09	.02	.01
	.25	.32	.09	.13
21/07/83	.37	.34	.06	.06
	.22	.58	.06	.06
	.27	.26	.07	.12
	.31	.32	.04	.03
	.22	.14	.26	.04
01/09/83	.62	.09	.17	.01
	.31	.09	.18	.01
	.76	.18	.14	.01
	.25	.11	.15	.03
	.3	.63	.25	.36
12/10/83	.7	.85	.35	.29
	.28	.97	.53	.22
	.34	1.29	.56	.37
	.92	1.03	.53	.23
	.23	.17	.7	.69
28/11/83	.33	.25	.68	.62
	.39	.08	.59	.87
	.4	.13	.53	.7
	.4	.23	.56	.39
	.45	.15	.21	.03
09/01/84	.26	.13	.02	.07
	.29	.24	.15	.08
	.45	.32	.05	.11
	.54	.13	.15	.08
	.19	.19	.23	.05
21/02/84	.17	1.33	.2	.03
	.22	.26	.02	.18
	.2	.16	.22	.03
	.27	.65	.11	.05
	.11	.26	.09	.02
05/04/84	.2	.75	.01	.03
	.12	.24	.03	.05
	.14	.18	0	.02
	.15	.41	.04	.02
	.24	.04	.06	.02
14/05/84	.22	.02	.03	.03
	.36	.3	.01	.03
	.33	.04	.01	.02
	.2	.05	.01	.01
	.29	.45	.09	.06
26/06/84	.23	.82	.1	.09
	.38	.49	.07	.07
	.36	.35	.06	.05
	.22	.34	.09	.06
	.12	.02	.12	.01
07/08/84	.06	.07	.12	.01
	.08	.07	.13	.02
	.07	.09	.18	.01
	.09	.07	.5	0
	.09	.2	.19	.01
18/09/84	.18	.19	.25	.01
	.16	.21	.2	.03
	.09	.27	.19	.01
	.08	.16	.25	.05
	.07	.68	.85	.79
30/10/84	.07	.85	.54	.8
	.15	.9	.69	.8
	.07	.69	.54	.5
	.12	.67	.72	.73

4.3 % moisture content of the 0-5cm soil samples collected from the pure stands of N. spruce, S. pine, alder and the N. spruce/S. pine mixture at six weekly time intervals.
(PM = S. pine half of mixture; SM = N. spruce half of mixture
I = interface between the S. pine and N. spruce blocks within the mixture.)

	28/04/83	09/06/83	21/07/83	01/09/83	12/10/83
P 1	65.47	54.14	38.11	37.66	35.42
P 2	66.31	00 00	49.25	24.22	48.28
P 3	57.73	73.19	32.13	22.14	51.66
P 4	54.02	66.06	22.87	22.44	43.73
P 5	62.02	63.13	18.98	25.11	44.74
P 6	51.75	68.35	27.13	22.13	45.51
P 7	51.83	50.51	32.31	25.46	53.73
P 8	53.40	47.34	33.92	25.53	56.52
P 9	49.16	48.15	40.58	25.07	43.77
P 10	44.77	52.43	29.61	33.79	53.63
S 1	53.19	48.93	38.51	19.75	43.58
S 2	46.82	42.30	25.93	22.11	40.68
S 3	51.72	41.37	0.00	21.40	47.96
S 4	49.05	49.68	24.61	21.98	58.08
S 5	45.13	43.40	31.59	26.33	42.49
S 6	60.14	39.30	32.29	25.99	49.00
S 7	52.47	58.71	46.98	31.17	59.01
S 8	58.66	45.58	31.00	28.64	47.39
S 9	57.74	56.16	29.00	27.30	56.17
S 10	51.95	59.21	28.68	27.54	53.31
PM 1	59.56	59.57	44.26	27.28	44.88
PM 2	53.48	53.19	32.48	23.79	51.78
PM 3	52.53	46.68	36.26	22.30	46.16
PM 4	47.13	51.86	40.55	22.45	49.28
PM 5	42.51	51.71	33.49	28.98	45.68
PM 6	58.55	47.42	27.51	25.35	59.00
PM 7	54.52	54.25	27.97	27.92	46.29
PM 8	53.49	53.90	27.62	23.19	45.52
PM 9	58.64	52.19	29.79	23.60	46.82
PM10	50.08	54.04	26.21	24.93	44.98
SM 1	51.30	52.20	31.45	24.34	61.86
SM 2	47.78	49.58	26.94	26.30	40.00
SM 3	44.95	44.72	30.32	20.50	51.16
SM 4	58.69	46.63	39.94	25.99	54.20
SM 5	52.78	54.92	41.08	20.43	59.10
SM 6	54.54	55.35	27.39	32.28	53.10
SM 7	58.70	52.91	36.75	30.22	51.95
SM 8	43.75	61.60	25.91	39.24	52.07
SM 9	58.49	49.32	29.47	22.27	49.91
SM10	49.01	57.90	29.88	21.57	36.70
I 1	48.96	61.45	26.30	25.56	48.86
I 2	51.94	00 00	27.67	26.27	52.82
I 3	54.91	48.86	37.05	24.62	49.60
I 4	55.47	47.64	43.26	28.58	51.74
I 5	57.08	51.18	27.84	21.31	56.19
I 6	46.47	51.58	28.91	23.08	51.66
I 7	62.24	54.05	28.44	20.23	47.86
I 8	53.04	59.66	34.23	24.78	49.39
I 9	53.86	51.08	30.58	30.33	55.88
I 10	45.30	52.82	26.58	29.76	49.76
A 1	69.26	74.53	70.56	43.55	60.55
A 2	59.52	67.20	62.86	41.89	67.14
A 3	65.12	61.05	51.80	49.25	49.12
A 4	74.15	56.99	37.16	42.53	48.57
A 5	57.97	67.32	49.97	48.03	62.62
A 6	66.76	62.76	60.13	46.67	66.57
A 7	54.16	63.02	48.00	40.40	61.32
A 8	69.39	60.36	48.49	33.91	61.74
A 9	54.32	56.16	41.95	38.65	53.97
A 10	68.64	73.87	33.71	45.62	66.74

4.3 % moisture content (continued)

	28/11/83	09/01/84	21/02/84	05/04/84	14/05/84
P 1	36.24	56.19	64.89	53.52	51.48
P 2	43.07	58.72	60.64	51.54	51.11
P 3	39.72	56.91	52.47	44.19	37.40
P 4	35.25	44.07	39.30	47.61	44.50
P 5	39.46	44.15	57.11	39.37	25.53
P 6	40.90	50.28	54.60	46.77	32.69
P 7	45.03	53.99	48.43	44.42	36.51
P 8	39.71	47.30	48.12	46.17	29.74
P 9	52.70	45.95	57.22	43.66	30.03
P 10	55.24	50.20	56.62	48.55	63.53
S 1	36.03	35.97	46.19	41.67	31.75
S 2	34.02	39.36	39.14	37.97	27.98
S 3	41.35	43.40	53.40	41.59	24.60
S 4	33.69	55.04	59.84	46.76	27.08
S 5	34.44	49.59	57.77	51.46	20.95
S 6	51.68	52.35	51.59	52.56	30.02
S 7	45.90	51.09	62.55	54.99	32.58
S 8	42.89	47.08	63.91	43.97	35.72
S 9	51.18	47.03	48.95	46.55	40.62
S 10	46.37	56.78	43.16	62.07	24.92
PM 1	47.22	50.06	54.27	49.32	
PM 2	51.47	48.21	53.31	43.50	
PM 3	42.56	54.90	67.33	56.40	
PM 4	46.03	51.66	47.25	49.39	
PM 5	46.75	51.78	55.11	49.66	
PM 6	44.74	48.66	56.97	54.93	
PM 7	45.91	53.06	49.03	51.10	
PM 8	45.24	53.63	51.03	42.26	
PM 9	53.67	49.09	46.35	48.75	
PM10	50.67	58.86	55.33	44.61	
SM 1	43.21	59.99	51.80	48.50	
SM 2	46.25	46.11	46.59	49.19	
SM 3	46.60	42.25	49.91	44.85	
SM 4	40.47	56.24	49.18	38.02	
SM 5	46.43	50.75	53.50	51.41	
SM 6	52.63	48.88	54.76	43.02	
SM 7	58.08	52.90	53.02	49.42	
SM 8	40.46	50.94	55.28	50.35	
SM 9	39.94	53.02	49.42	55.71	
SM10	49.76	38.91	60.82	57.00	
I 1	38.67	50.29	44.62	44.70	
I 2	44.39	45.20	49.63	56.16	
I 3	47.43	44.97	61.61	44.74	
I 4	44.24	52.27	47.02	44.44	
I 5	44.53	43.16	61.87	43.55	
I 6	47.41	48.51	45.07	54.97	
I 7	45.83	50.48	47.53	43.49	
I 8	44.74	48.63	48.33	48.92	
I 9	45.31	54.27	51.39	41.63	
I 10	51.74	49.06	54.72	53.04	
A 1	60.30	63.03	63.58	70.93	52.72
A 2	65.92	72.24	72.67	58.83	62.75
A 3	50.86	47.79	60.64	67.15	50.74
A 4	51.46	55.74	60.79	51.62	53.49
A 5	66.03	63.67	50.30	48.50	70.13
A 6	47.25	57.93	52.46	59.37	61.72
A 7	53.10		65.35	53.97	60.59
A 8	61.36	60.24	61.40	54.65	52.75
A 9	66.78	53.47	55.77	39.81	51.68
A 10	53.72	58.82	65.21	62.85	57.51

4.3 % moisture content (continued)

	26/06/84	07/08/84	18/09/84	30/10/84
P 1	54.19	26.78	43.59	48.67
P 2	47.48	43.32	44.22	46.45
P 3	36.23	24.55	46.29	47.91
P 4	45.48	28.20	47.28	35.41
P 5	48.35	41.22	51.54	49.00
P 6	39.63	30.66	49.18	42.90
P 7	32.50	42.14	39.94	44.28
P 8	32.34	30.88	39.05	45.48
P 9	38.67	41.23	32.20	53.30
P 10	44.53	45.20	38.54	40.88
S 1	26.49	36.62	31.76	38.78
S 2	29.27	31.87	57.25	39.29
S 3	38.11	36.96	45.99	38.77
S 4	43.53	39.89	39.32	40.75
S 5	34.38	31.05	44.71	41.60
S 6	46.33	28.97	37.81	57.00
S 7	46.17	47.40	49.85	52.16
S 8	36.79	38.95	38.68	50.97
S 9	55.11	51.85	56.58	62.86
S 10	45.89	44.48	45.06	47.38
A 1	47.45	45.28	65.62	65.41
A 2	48.81	64.57	59.31	68.19
A 3	57.72	47.29	49.19	63.25
A 4	52.45	58.70	46.38	65.87
A 5	60.93	61.23	69.00	51.46
A 6	56.11	60.26	69.29	47.62
A 7	67.27	51.24	62.28	59.22
A 8	67.28	53.90	50.71	58.49
A 9	67.31	57.54	42.96	56.90
A 10	54.39	67.11	52.61	41.63

4.4 Bulk Density (g cm^{-3}) of the 0-5cm soil samples collected from the pure stands of N. spruce, S. pine, alder and the N. spruce/S. pine mixture at six weekly time intervals.
(PM = S. pine half of mixture; SM = N. spruce half of mixture; I = the interface between the S. pine and N.spruce blocks within the mixture.)

	28/04/83	09/06/83	21/07/83	01/09/83	12/10/83	28/11/83	09/01/84	21/02/84	05/04/84
N. SPRUCE	.402	.523	.550	.473	.683	.600	.492	.418	.531
	.351	c	.496	.887	.778	.760	.449	.367	.649
	.432	.264	.739	.886	.510	.734	.564	.456	.706
	.517	.349	.809	.916	.636	.731	.794	.931	.650
	.343	.392	1.02	.747	.720	.806	.693	.470	.734
	.536	.392	.777	.707	.753	.586	.543	.381	.625
	.504	.652	.614	.647	.566	.610	.504	.580	.661
	.410	.714	.527	.679	.345	.740	.535	.622	.710
	.505	.609	.634	.735	.659	.509	.624	.477	.889
	.680	.615	.792	.548	.558	.425	.613	.623	.534
S. PINE	.389	.551	.432	.878	.553	.786	.599	.596	.558
	.462	c	.520	.650	.667	.839	.624	.579	.773
	.531	.824	c	.895	.518	.495	.651	.480	.674
	.636	.467	.700	.886	.330	.827	.387	.349	.663
	.610	.711	.610	.776	.427	.498	.657	.370	.631
	.463	.623	.544	.699	.506	.443	.469	.518	.552
	.601	.494	.409	.550	.437	.599	.505	.379	.425
	.474	.654	.521	.478	.655	.570	.443	.414	.674
	.418	.302	.592	.601	.388	.455	.660	.544	.615
	.505	.551	.695	.628	.573	.537	.449	.690	.330
SM	.510	.504	.594	.499	.646	.521	.671	.530	.650
	.574	.556	.634	.757	.618	.578	.599	.407	.723
	.538	.701	.628	.908	.588	.666	.471	.302	.530
	.593	.716	.409	.681	.660	.593	.563	.547	.621
	.917	.677	.643	.519	.546	.551	.532	.534	.651
	.428	.641	.618	.871	.447	.607	.595	.423	.385
	.565	.546	.705	.556	.664	.593	.599	.575	.552
	.573	.455	.599	.756	.578	.730	.568	.663	.946
	.565	.730	.807	.624	.677	.433	.614	.747	.616
	.676	.530	.625	.715	.596	.477	.488	.480	.739
PM	.705	.673	.574	.749	.408	.572	.495	.557	.651
	.698	.617	.628	.576	.930	.557	.747	.602	.493
	.774	.648	.631	.810	.599	.631	.750	.663	.756
	.402	.561	.510	.533	.581	.611	.515	.542	.848
	.690	.511	.585	.780	.445	.503	.458	.600	.536
	.523	.447	.695	.452	.585	.565	.663	.471	.678
	.449	.528	.569	.601	.603	.488	.584	.565	.646
	.575	.437	.596	.514	.578	.608	.559	.544	.620
	.511	.650	.661	.723	.623	.588	.512	.653	.487
	.672	.508	.575	.931	.745	.608	.860	.402	.523
INTERFACE	.689	.395	.769	.746	.568	.882	.613	.687	.666
	.533	c	.701	.567	.572	.586	.790	.574	.572
	.623	.564	.618	.663	.631	.568	.608	.430	.704
	.516	.628	.493	.594	.613	.710	.514	.584	.760
	.446	.620	.696	.743	.538	.520	.676	.430	.671
	.681	.636	.647	.729	.541	.728	.532	.722	.528
	.393	.554	.690	.881	.673	.719	.622	.760	.671
	.603	.405	.754	.786	.543	.551	.691	.591	.673
	.548	.677	.517	.686	.515	.605	.580	.542	.645
	.755	.603	.489	.505	.636	.433	.572	.534	.574
ALDER	.363	.286	.268	.430	.469	.362	.388	.480	.276
	.506	.418	.332	.379	.283	.366	.303	.324	.526
	.357	.464	.551	.353	.585	.558	.666	.532	.379
	.263	.562	.674	.514	.680	.601	.474	.412	.701
	.484	.350	.641	.588	.446	.351	.476	.655	.698
	.355	.420	.443	.522	.276	.476	.500	.595	.488
	.675	.370	.514	.681	.338	.499	.560	.438	.645
	.358	.471	.622	.722	.328	.404	.508	.472	.530
	.618	.553	.717	.711	.628	.323	.605	.597	.946
	.296	.211	.626	.475	.272	.624	.526	.354	.403

4.4 Bulk density (continued)

	14/05/86	26/06/84	07/08/84	18/09/84	30/10/84
	0.41	0.48	0.83	0.69	0.70
	0.49	0.63	0.53	0.81	0.60
	0.53	0.89	0.63	0.58	0.60
	0.66	0.51	0.69	0.48	1.1
	0.82	0.49	0.65	0.58	0.64
N. SPRUCE	0.80	0.58	0.7	0.61	0.60
	0.90	0.78	0.57	0.71	0.80
	0.78	0.56	0.62	0.79	0.67
	0.73	0.50	0.49	0.63	0.51
	0.26	0.54	0.52	0.61	0.70
	0.45	0.61	0.3	0.78	0.67
	0.87	0.47	0.4	0.31	0.61
	0.67	0.55	0.74	0.49	0.79
	0.78	0.55	0.46	0.61	0.68
	1.2	0.73	0.39	0.66	0.74
S. PINE	0.73	0.59	0.65	0.66	0.40
	0.65	0.67	0.36	0.54	0.47
	0.53	0.57	0.64	0.58	0.61
	0.48	0.33	0.46	0.55	0.36
	0.94	0.45	0.48	0.52	0.73
	0.58	0.69	0.68	0.36	0.38
	0.45	0.53	0.32	0.43	0.41
	0.68	0.49	0.74	0.69	0.46
	0.66	0.59	0.37	0.66	0.38
ALDER	0.29	0.44	0.43	0.25	0.64
	0.43	0.6	0.4	0.23	0.68
	0.44	0.36	0.57	0.39	0.54
	0.56	0.36	0.55	0.65	0.53
	0.58	0.38	0.45	0.84	0.52
	0.55	0.42	0.23	0.48	0.81

4.5 pH of air dried soil samples from the pure stands of N. spruce, S. pine, alder and the N. spruce/S. pine mixture at six weekly time intervals.
(PM = S. pine half of mixture; SM = N. spruce half of mixture; I = the interface between the S. pine and N. spruce blocks within the mixture.)

28/04/83	N. SPRUCE	3.1	3.3	3.2	3.5	3.2	3.4	3.3	3.2	3.2	3.2
	S. PINE	3.1	3.1	3.6	3.2	3.1	3.1	3.1	3.3	3.0	3.2
	ALDER	3.8	3.4	3.3	3.4	3.6	3.4	3.7	3.6	3.5	3.4
	SM	3.2	3.2	3.3	3.0	3.3	3.5	3.3	3.1	3.4	3.1
	PM	3.1	3.5	3.7	3.6	3.6	3.5	3.7	3.8	4.6	3.3
	I	3.3	3.1	3.3	3.2	3.0	3.4	3.2	3.4	3.3	3.4
09/06/83	N. SPRUCE	3.9	3.9	3.8	3.8	3.8	3.8	3.7	3.2	3.7	3.7
	S. PINE	3.3	3.1	3.2	3.0	3.1	3.3	3.3	3.4	3.2	
	ALDER	3.3	3.5	3.5	3.5	3.5	3.6	3.5	3.2	3.4	3.0
	SM	3.3	3.3	3.6	3.8	3.5	3.5	3.8	3.7	3.4	3.3
	PM	3.6	3.8	3.5	3.5	3.6	4.0	3.5	3.5	3.5	3.2
	I	3.0	3.6	3.2	3.3	3.7	3.3	3.1	3.4	3.1	
21/07/83	N. SPRUCE	3.4	3.4	3.5	3.5	3.2	3.1	3.0	3.1	3.1	3.3
	S. PINE	3.1	3.0	3.2	3.2	3.2	3.3	3.2	3.1	3.1	3.2
	ALDER	3.4	3.3	3.3	3.2	3.2	3.4	3.2	3.2	3.3	3.5
	SM	3.3	3.3	3.3	3.2	3.2	3.5	3.5	3.5	3.8	3.4
	PM	3.3	3.4	3.6	3.6	3.4	3.5	3.6	3.7	3.8	3.4
	I	3.4	3.4	3.4	3.3	3.5	3.5	3.6	3.5	3.4	3.4
01/09/83	N.SPRUCE	3.8	3.1	3.3	3.3	3.3	3.1	3.1	3.2	3.3	3.2
	S. PINE	3.2	3.2	3.2	3.2	3.0	3.0	3.0	3.0	3.0	3.0
	ALDER	3.2	3.1	3.3	3.2	3.1	3.1	3.1	3.3	3.2	3.2
	SM	3.2	3.1	3.2	3.1	3.2	3.2	3.4	3.3	3.4	3.5
	PM	3.2	3.4	3.4	3.3	3.2	3.4	3.2	3.3	3.6	3.2
	I	3.2	3.2	3.0	3.1	3.2	3.3	3.3	3.1	3.1	3.1
12/10/83	N. SPRUCE	3.7	3.9	3.4	3.4	3.4	3.4	3.4	3.5	3.6	3.8
	S. PINE	3.7	3.9	3.9	3.7	3.7	4.0	3.6	3.8	4.0	3.8
	ALDER	3.9	3.8	3.9	3.7	3.9	3.5	3.6	3.9	4.1	3.7
	SM	3.7	4.0	3.7	3.7	3.9	3.6	3.7	3.7	3.7	3.9
	PM	3.5	3.5	3.6	3.8	3.6	3.9	3.5	3.5	3.5	3.9
	I	3.6	3.5	4.1	3.8	4.0	3.8	3.7	3.6	3.4	3.6
28/11/83	N. SPRUCE	3.7	4.0	3.8	4.1	3.9	3.6	3.8	3.7	3.8	3.8
	S. PINE	3.5	3.7	3.9	3.9	3.7	3.8	3.8	3.7	3.8	3.5
	ALDER	4.0	4.1	4.1	3.9	3.8	3.8	3.8	3.6	3.7	3.8
	SM	3.4	3.7	3.6	3.6	3.8	3.7	3.4	3.7	3.6	3.7
	PM	3.9	4.2	4.1	3.9	4.2	3.9	3.9	4.3	4.2	3.9
	I	4.0	3.8	3.8	3.6	3.7	3.2	3.6	3.7	3.8	3.6

4.5 pH (continued)

09/01/84	N. SPRUCE	3.7	3.8	4.0	3.4	3.5	3.7	3.7	3.5	3.7	3.
	S. PINE	3.5	3.6	3.6	3.6	3.7	3.5	3.6	3.8	3.7	3.
	ALDER	4.0	3.5	3.6	3.7	3.6	3.4	3.9	3.8	3.9	3.
	SM	3.5	3.8	3.7	3.7	3.6	3.8	3.7	3.7	3.5	3.
	PM	3.1	3.3	3.4	3.7	3.3	3.7	3.8	3.7	3.8	3.
	I	3.9	3.7	3.6	3.6	3.9	3.6	3.8	3.5	3.9	3.
21/02/84	N. SPRUCE	3.2	3.2	3.8	3.2	3.7	3.3	3.5	3.3	3.2	3.
	S. PINE	3.2	3.4	3.2	3.9	3.6	3.3	3.2	3.4	3.6	3.
	ALDER	3.4	3.6	3.4	3.3	3.3	3.9	3.5	3.4	3.3	3.
	SM	3.6	3.5	3.3	3.6	3.7	3.8	3.2	3.6	3.5	3.
	PM	3.4	3.9	3.9	3.3	3.5	4.0	3.6	3.6	3.4	3.
	I	3.2	3.5	3.3	3.4	3.5	3.4	3.4	3.4	3.5	3.
05/04/84	N. SPRUCE	3.7	3.8	3.9	3.9	3.8	3.7	3.6	3.3	3.5	3.
	S. PINE	3.7	3.6	3.5	3.3	3.4	3.7	3.6	3.4	3.4	3.
	ALDER	3.4	4.1	3.8	3.8	3.8	3.4	3.7	3.8	3.8	3.
	SM	3.7	3.7	3.6	3.9	3.6	3.6	3.6	3.5	3.6	3.
	PM	3.7	3.5	3.7	3.3	3.8	3.8	3.6	3.9	3.7	3.
	I	3.6	3.7	3.7	3.9	3.8	3.7	3.7	3.6	3.2	3.
14/05/84	N. SPRUCE	3.8	4.2	3.9	3.8	3.9	3.7	3.7	3.7	3.6	3.
	S. PINE	3.6	3.7	3.6	3.6	3.7	3.5	3.7	3.7	3.6	3.
	ALDER	3.7	3.7	3.7	3.8	3.9	3.8	3.9	3.9	3.6	3.
26/06/84	N. SPRUCE	3.7	3.6	3.6	3.8	3.8	3.7	3.9	3.6	3.4	3.
	S. PINE	3.6	3.6	3.8	3.9	3.6	3.4	3.6	3.7	3.7	3.
	ALDER	3.5	3.6	3.5	3.9	3.3	3.7	3.8	3.8	3.9	3.

4.6 C/N ratios from the pure stands of N. spruce, S. pine, alder and the N. spruce half of the N. spruce/S. pine mixture at six weekly time intervals.
(SM = N. spruce half of the mixture)

	ALDER	SM	S. PINE	N. SPRUCE
	14.8145	10.7157	14.1302	18.4429
	11.5603	18.9636	15.9944	20.0745
	12.8145	17.4386	16.7442	15.875
28/04/83	11.5395	18.011	16.9747	15.0886
	11.2879	14.5366	14.8923	15.875
	13.4189	21.2857	17.086	16.3286
	12.5663	19.5119	16.3723	14.6705
	10.8976	10.2874	14.6705	14.9
	14.4086	14.5733	16.1333	17.9306
	13.1538	21.2857	7.32105	15.9821
	13.3529	14	21.5067	14.1964
09/06/83	12.5217	13.7012	21.925	17.4815
	15.4272	18.0568	18.7077	16.25
	13.2672	15.7041	32.4028	15.4667
	14.1176	13.1687	14.3816	18.37
	11.4248	21.725	15.2821	16.3556
	14.2188	17.25	21.3671	18.011
	15.5622	9.56881	17.1545	15.0886
	15.593	17.8594	16.5652	15.1463
21/07/83	15.1463	14.4211	19.1754	13.5606
	11.6075	16.8969	14.2041	17.7381
	13.812	15.2923	16.3606	16.5484
	13.5049	23.1207	14.9	16.0385
	14.5056	19.7069	17.0505	16.7887
	12.1138	15.2923	17.6	13.8837
	12.6536	16.1375	16.2759	14.0833
	28.8514	17.1636	15.9434	15.3636
01/09/83	15.8	14.7161	17.8113	18.0727
	11.3246	19.1282	16.0323	17.3492
	17.0137	14.9	16.5606	16.5606
	8.21805	14.8391	15.8933	12.42
	8.54967	16.7442	16.2969	14.9
	11.2177	15.7596	16.0735	15.9821
	16.4173	15.6286	17.9518	14.322
	14.3614	12.8588	20.2653	18.8182
12/10/83	5.62857	15.5542	16.5556	16.55
	14.1939	14.957	16.3288	15.89
	30.8659	17.9306	16.2951	15.8242
	13.3333	15.3944	14.8391	18.3951
	18.7449	14.1905	15.9571	13.4324
	12.6536	18.3385	14.7703	13.9844
	18.9381	16.3418	14.9	14.6721
	10.1533	14.5366	14.7161	18.1831
28/11/83	14.3402	15.5313	15.6481	9.80282
	21.587	17.7381	16.5556	14.9841
	8.54918	17.8333	16.9868	17.4021
	13.3933	15.1579	14.9639	16.5595
	19.486	18.4429	17.4386	14.5761
	15.9554	22.7639	19.0606	19.88
	14.4424	15.2258	15.8242	16
09/01/84	8.39437	13.2031	16.3814	18.5098
	14.3772	16.2143	18.2167	16.55
	15.7596	20.6308	14.8358	15.0886
	15.0674	11.6941	19.378	16.1744
	32.2281	13.9688	15.39	13.41
	19.5119	27.0909	15.6842	19.8588
	14.8505	23.84	17.1846	16.0323
	10.8245	12.6056	14.2688	17.9
21/02/84	12.6809	18.4355	16.2455	17.0597
	17.493	16.3288	15.5714	21.869
	10.4095	13.9688	18.9663	18.5556
	5.77907	16.5517	16.3636	11.92
	11.0719	20.8226	16.5606	16.2455
	9.49045	11.8286	13.1111	16.4231

4.6 C/N ratios (continued)

	ALDER	SM	S. PINE	N. SPRUCE
	18.119	14.4684	20.5957	16.5556
	13.1538	25.629	17.9574	20.119
05/04/84	15.488	17.7429	15.593	18.5254
	15.7765	6.6701	18.625	17.3182
	7.14379	18.2111	15.0893	17.3875
	19.3111	15.803	16.5517	16.0313
	9.3964	13.3293	18.1429	18.0545
	9.14111	16.3134	13.9844	20.6226

APPENDIX 5 D.B.H. and D.B.H/height relationships for the pure tree stands in Block II.

5.1 D.B.H. (cm) of all trees in the pure stands of N. spruce, S. pine, oak and alder in Block II. (assessed 15/11/82).

N. SPRUCE

13.7 7.9 7.4 14.9 9.6 8.4 7.2 5.5 16.1 12.6 21.7 6.7
11.5 7.5 5.8 9.7 4.9 11.7 4.9 5 19.5 17.1 11.7 10.1
12.7 9.9 9.9 16.3 14.9 6.1 4.6 13.8 13.7 13.3 7.3 15.5
7.3 12.1 7.6 6 13.3 10.6 8.3 16.1 5.7 8.8 11.3 10.4
10 13.1 8 13 10.8 17.3 7.8 9.3 17 6.8 12.5 18
14 6.4 7 12.4 9.5 10.7 6.9 14.4 13.6 13.5 7.7 10.1
11.7 11.5 13 11.2 5.7 17.7 9.4 13.7 12.2 17.5 18.1 11.3
14.1 7.7 4.1 9.4 14.2 15.5 11.9 15.3 18.5 14.7 7.2 16.2
15 7.4 6.5 8.8 5.3 5.5 5.8 8.4 7.2 11.3 14.7 8.7
10.5 16.3 17.1 19.3 5.3 11.5 12.7 9.6 9.2 4 13.9 7.5
14.8 6.5 7 12.9 12.2 9.5 7.7 9.7 9.4 6.4 11.9 7.2
19.7 5.2 15.3 8.7 9.3 5.7 13.7 6.3 14.1 6.6 11.9 19.4
16.5 12.7 8.4 21.1 16.8 6.4 13.8 11.8 9.1 8.3 7.8 12
10 16.2 13.3 9.2 8.2 14.5 10.6 14 8.1 8 16.4 7.3
9.9 10.1 16.5 10.9 5.1 13 13 8.9 12.4 10.6 10.7 7.5
9 9.5 19.2 12.7 16.8 5.6 8 9 11.9 4.9 12.2 14.9
8.8 11.4 11.3 11.7 4.5 4.7 13.6 16.7 9.7 19.1 5 14.2
10.9 15.4 7.8 14.5 14.5 5.9 16.7 8.8 21.6 9.7 12 5.2
13.9 11 8.1 17.5 8.3 5.6 8.9 9.3 4.2 8.2 14.1 8.2
16.5 8.3 19.4 4.9 5.1 15.6 9 11.1 8.2 14 10.5 11

S. PINE

15.2 19.5 13.4 8.7 15.7 16.6 11.6 17.5 9.3
12.4 12.4 19.5 20 17.7 22.2 7 7.5 12.6
11.7 11 18.5 18.8 8.9 14.2 12.6 18 7.4
15.4 14.2 14.1 13.3 8.3 11.9 18.2 5.7 19.7
8.4 15.8 10.6 10.9 7.9 9.1 10.7 16 12.2
15.2 15.6 9.8 12.4 16.5 8.1 13.6 12.5 12.8
14.5 18.5 13.5 11.2 16.5 15.2 15.1 15.3 10.8
18.2 12.2 11 12.7 11.6 10.8 18.8 12.1
16.3 7.4 9 8 16.5 9.2 8.2 8.7 24
17.1 8.2 14.6 15.4 11.4 16 12.7 14.2 14
18.7 20.4 8.7 22 8.6 14 15.1 14.7
12.7 10.5 10.4 17.7 12.3 7.9 20.7 16.4
16.7 19.3 17.7 11.4 12.3 19 11.1 15.2
9.8 9 10.5 7.1 13.9 8.5 9.5 11.5
12.6 11.1 12.1 16.3 13.7 10.1 17.5 7.7
15.1 7.5 15.9 14.6 16.3 10.4 11.2 20.7
11.1 15.6 17.3 17.1 14.4 14 7.8 13
16.5 17.2 8.3 13.7 17.2 16.1 18.4 21.9
19.6 9.4 19.1 20.1 20 12.7 13.7 10.9
7.7 20.3 8.2 11.4 15.5 13.5 18.3 13.9

5.1 (continued)

OAK

5.3 5.2 5.2 6.2 5.4 4 4.3 4.7 4.7 4.7 4.6
7.9 4.3 5.5 4.6 6.5 5.4 6.7 8.4 5.1 5.8 10.5
7 4 9.7 6.9 4.3 7.4 10.9 6.2 6.3 5.7 5.9
4.5 5.8 5.1 4.1 4.7 6 4.5 6 5.9 4 7.8
4.6 4.5 6.4 4.5 6.6 4.8 4.2 4.5 6.4 6.6 6.3
4.6 4.5 5.9 6.1 5 6.4 8.8 4.3 7.3 5.9 4.3
6.1 6 8.3 5.8 8.3 5.8 6.5 5.3 6.5 7.2 7.4
7.1 7.6 4.5 6.8 6.3 4.3 5.8 4.4 6.4 4.8 5.3
6.6 5.1 6 4 5.5 4.4 4.3 5.4 4.2 5.3 7.3
5.6 4.3 7.2 8.5 5.3 6 5.5 4.8 4.5 8.3 11.4
4.4 4.6 4.1 4.4 5.9 5.3 5 6.6 5 5.8 5
8 4.5 4.8 5.3 5.5 4.7 6 4 6.1 5.4 5.9
9.1 5.7 4.3 5.5 4.7 4.1 4 5.4 6.3 8.6 7
4.2 7 4.3 5.1 7.1 5.4 5.4 4 5.4 5.3 4.8
5.6 7.2 4.2 6.5 5.1 5.5 5.6 6.7 4.4 5.2 4.5
5.7 4.6 4.7 4.5 4.7 7 6.7 5.4 7.1 5.5 8
10.3 8.2 5.2 8.1 5 10.2 4.5 6.4 4.3 4.5 5.5
9.4 5.2 5 6.8 4.4 5.9 5.9 5.8 7.2 5.7 5.4
6.1 5 6.2 7.3 5.8 5.2 5.8 6.5 7.9 4.4 5.7
6.7 5.6 5.8 5.2 8 10 5.5 6.8 4.6 4.9 5.3
6.4 4.1 5 5.1 6.6 8.5 7.3 7.1 6.9 5.2
4.5 7.2 4.4 7.5 4.5 4 4.3 6.2 7.1 5.5
5 6.6 5.4 6.5 6 6.8 6.3 7.5 4.9 5.7
5.6 5.6 5.3 4.6 7.1 6.7 6.4 9.1 5.8 8.8
5.2 4.7 5.8 5 5.5 6 7.2 5.7 6.3 9.7 4.9 5.6 10.1 4.7 6.2
6.9 5.8 4.4 4 4.8 5 8.5 5.5 4.2 5.7 6.6 6.2
6.3 5.8 7.6 4.8 8.2 5.8 6.7 6.2 5.7 6 8.3 7.2
6.3 5.3 4.7 4.9 4.7 5.1 4 5.6 8.4 7.1 5.1 4.6

ALDER

8.7 10.2 10.7 10.8 5.3 6.9 7.8 6 8.8 7
5.3 6.8 6.9 13.8 11.2 6.1 11.5 10.9 13.8 8.6
11.7 6.6 5.4 6.6 6 12.3 6.4 6.1 10 4.8
9.7 6.8 11.9 7.6 7.6 4.9 7.4 8.2 7.5 3.7
4.9 6 8.9 6.5 8.1 7.5 6.1 9.6 7.4 9.5
12.6 6.6 4.3 6.5 6 4.6 9.1 5.6 8.5 10
7.6 8.5 7 7.4 11.4 8.8 5.9 7.9 7.5 10.2
7.2 6.7 9.5 5.9 10.8 6 6.2 6.2 5.2 10.4
7.1 11.9 5.6 4.6 5.6 8.1 8.8 8.8 10.3
14.3 11.7 8.4 4.3 4 6.4 7.6 7.9 10
9.5 11.5 7.5 9.3 5.8 8.4 5.4 8.3 9.3
5.2 6 8.9 11.2 4.9 4.3 9.9 5.2 12.2
6.9 7.1 10.3 8.2 4.7 9.5 6.1 11.2 11.2
4.4 5.2 4.3 9.4 6.8 7.9 6.3 10.3 8.2
15.1 4 4.9 5.2 12.4 11.4 8.8 10.8 4.4
12.5 9.5 10.6 8.7 5.7 13.4 7 13.3 7.9
13.2 4.7 7.8 4.3 8.9 11.8 8.1 7.9 6.3
9.9 6 5 10.1 11.8 5.1 7.3 7.5 9.5
6 5.2 10 10.5 9.2 8.3 4.1 8.1 7.6
10.7 6.3 7.3 9.9 5.7 5.2 13.1 7 14.1

5.2 D.B.H. (cm) and height (m) of a random sample of trees from the pure stands of N. spruce, S. pine, oak and alder in Block II.

N. spruce

D.B.H.(cm)	Height (m)
9	8.8
13	10
16	8.9
12	7.4
18	10.0
15	7.3
10	7.1
13	7.7
14	7.0
14	8.0
14	9.5
9	6.5
7	4.5
3	2.7
7	5.4
8	5.5
3	2.0
8	5.3
6	5.2
8	6.5

Oak

D.B.H.(cm)	Height (m)
12	6.6
5	3.6
6	5.7
2	2.0
9	6.7
13	7.2
4	3.2
3	3.0
11	6.3
2	2.4
6	5.5
7	6.2
10	5.5
7	5.3
5	4.8
4	2.9
11	6.8
2	2.4
5	4.6
10	5.5

Alder

D.B.H.(cm)	Height (m)
11	8.9
7	5.7
8	7.8
3	3.4
10	7.6
9	7.1
15	7.3
3	2.9
7	3.5
12	6.6
9	5.8
4	3.6
6	4.7
14	8.2
2	2.7
10	6.6
6	5.5
6	5.8
14	8.4

5.2 (continued)

S. pine

D.B.H. (cm)	Height (m)
22	8.5
19	13.7
18	11.9
10	6.8
13	11.5
14	11.1
8	8.9
12	10.5
20	10.8
9	8.6
19	12.5
14	10
10	8.6
20	13.1
19	12.2
8	8.5
15	12.8
16	10.3
9	7.9
25	15
12	7.6
10	8.7
8	10.2
17	12.7
18	10.9
12	12.5
20	13.2
22	10.7
20	12.2
16	11
23	11.2
12	10.5
17	13.5
9	9.1
15	10.1
16	11.4
10	8.0
25	11.5
12	10.3
15	11.2
27	11.5
10	10.5
15	11.2
16	11.6
10	11.0
14	11.4
16	10.5
12	9.5
9	8.7
27	13.5
18	12.9
15	10.3
17	12.6
9	9.4
18	12.9
21	14
20	13.3
23	12.7