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Studies on radiocaesium transfer in heather-dominant ecosystems

Final report to Scottish Development Department

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Experimental plot on podzolic soil at Loch Laggan field site.

Lysimeter cores from Loch Laggan field site , Banchory Research Station

EXECUTIVE SUMMARY

In 1986 areas of upland Britain received relatively large amounts (in excess of 20,000 Bq m^{2}) of radiocaesium from the Chernobyl accident. In Scotland parts of the Central Highlands and Galloway were amongst the most heavily contaminated in the United Kingdom. Heather (*Calluna vulgaris*) has an unusually high capacity to take up radiocaesium and herbivores which habitually eat heather can consequently have high levels (up to 3000 Bq kg^{-1} fresh weight) of radiocaesium in their tissues. Heather dominated systems are important to the Scottish rural economy as they are cropped for red grouse, red deer, hares and sheep.

Radiocaesium is retained and mobile in upland heather dominated ecosystems. The current study has investigated the deposition and movement of radiocaesium in heather dominated systems. Two soil types, a peaty podzol and a deep peat, with similar deposition levels, have been studied and the potential effects of an important management tool, burning, has been experimentally determined. The biological half-life of radiocaesium in red grouse, a bird feeding exclusively on heather, has been measured. The data has been synthesised into a user friendly model that can be used as an illustrative tool and which could be refined with further sampling.

Radiocaesium has moved down the soil profile of the pure peat more quickly than it has moved down the peaty podzol soil profile. Although only 37% of the total ^{137}Cs activity was in the 0-10 cm rooting zone at the peat site 30% was in above ground vegetation. In contrast, at the peaty podzol site, 71% was in the 0-10 cm layer and only 18% in the above ground vegetation. The difference in plant uptake for the two sites can probably be accounted for by differences in mineral content in the 0-10 cm soil layer at the two sites; 3% mineral matter for the peat site and c. 50% for the peaty podzol. A large proportion of ^{137}Cs activity in the peaty podzol may be adsorbed onto clay particles in the soil and unavailable for plant uptake.

The ground layer of mosses and lichens retained significant amounts of radiocaesium with 18% of the total on the peat and 9% on the peaty podzol. Within the heather plant the distribution of radiocaesium is similar in the two systems although the absolute amount in heather on the peat can be a factor of two greater than that for the peaty podzol. The quantity in the young heather shoots, an important food source for grouse and other animals, can be up to 40% of the total ^{137}Cs inventory in the plant. The origin of this ^{137}Cs activity may be recent uptake from the soils and/or translocation within the heather plant.

Heather burning can play an important part in the movement of radiocaesium. Between 10 and 40% of the radiocaesium in the plants can be removed in smoke. About 20% of the ^{137}Cs activity in the ash is immediately soluble in rainwater and will leach into the soil. Season of burning is potentially important; an autumn burn may allow leaching by winter precipitation to dominate whereas a spring burn may permit greater uptake by rapidly regenerating vegetation.

Red grouse, fed an experimental diet containing c.1400 Bq kg^{-1} ^{137}Cs activity, reached a steady state in tissues after 23 days with 23% of the radiocaesium in the diet being absorbed by the bird. Feeding an uncontaminated diet thereafter showed that the biological half-life of radiocaesium in the bird was about 10-11 days.

Using the data collected in the study a modelling exercise, carried out at the University of Nottingham, has produced an illustrative model in which a number of parameters such as: soil type, age of heather stand, type of burning and deposition rate can be varied by the user.

Data from this study indicates that Chernobyl radiocaesium will remain in the rooting zone of heather dominated ecosystems for many years. Some of the ^{137}Cs activity appears to be recycling into plants alongside nutrient elements. These cycling processes are more pronounced for heather growing on peat with a low clay content. Although some loss of radiocaesium will occur through leaching and burning it is probable that the major loss of ^{137}Cs activity will be through physical decay.

1 INTRODUCTION

1.1 GENERAL BACKGROUND

Surveys of Chernobyl-derived radioactivity in soils and vegetation have been carried out on behalf of the Department of the Environment (DoE) (Horrill *et al*, 1988) and the Scottish Development Department (SDD) (Miller *et al*, 1989). These surveys have shown that areas of upland Britain received relatively large inputs of radioactivity derived from the Chernobyl accident. In Scotland, parts of the Central Highlands and Galloway were amongst the most heavily contaminated in the United Kingdom (UK). Uptake of radiocaesium was shown to be greater from upland organic soils than it was from lowland mineral soils.

The DoE study indicated that heather *(Calluna vulgaris)* had a greater capacity to absorb radiocaesium than other plant species, and showed that the tissues of herbivores which habitually eat heather contained high concentrations of the radionuclide. These findings suggest that radiocaesium is especially concentrated, persistent and mobile in upland heather dominated ecosystems.

1.2 THE IMPORTANCE OF HEATHER DOMINATED SYSTEMS IN SCOTLAND

Heather-dominant ecosystems are important to the Scottish rural economy because they are cropped for red grouse (*Lagopus lagopus*), red deer (*Cervus elaphus*), mountain hares (*Lepus timidus*) and sheep. All form part of the human food chain, therefore it is essential to learn more about the cycling of radiocaesium in heather moorland and specifically to :-

a) identify pathways and quantify movements of radiocaesium between the various components of the ecosystem, and

b) investigate the effects of traditional management of the vegetation on these processes.

Some information already exists concerning the movement of radiocaesium through hill sheep (eg Howard 1987). However, little is known about the residence time and movement of radiocaesium in birds, including red grouse (*Lagopus lagopus*). Grouse are of interest because, for most of the year, they have a more restricted home range than deer or sheep and are likely to cycle the radiocaesium within their own relatively small territorial area. Captive stock at ITE Banchory have been used to investigate uptake, retention and loss of radiocaesium in red grouse.

1.3 POSSIBLE EFFECTS OF MANAGEMENT PRACTICES ON HEATHER DOMINATED SYSTEMS

Burning plays an important part in the management of many heather moorlands (Gimmingham 1972). Three direct effects on the availability of radiocaesium can be envisaged :-

a) Fire may transform radiocaesium, bound to various soil components, into more soluble inorganic forms. Ash, deposited on the soil surface, will be subject to leaching processes. In autumn, when plants are dormant, radiocaesium may be lost from the ecosystem by leaching and surface drainage. Conversely a spring fire may render caesium isotopes available for immediate uptake by vegetation at the beginning of a new season.

b) The heat generated by the fire will determine the amount of surface organic matter that is burnt. Hot fires will incinerate not only the standing vegetation but also any moss or litter at the soil surface; cool fires will remove only part of the heather canopy.

c) Very hot fires (>700°C) may lead to significant losses of radiocaesium, contained in the vegetation, in smoke particles.

Thus, depending on how, and at what time of year, the burning is applied, it might be used deliberately to decrease the amount of radiocaesium at a particular site; on the other hand it might actually enhance the cycling process.

1.4 EXPERIMENTAL OBJECTIVES

The overall objective is to predict changes with time in the availability of radiocaesium to herbivores grazing heather-dominated vegetation contaminated by Chernobyl fallout. Specific aims are to :-

a) Measure the amount, distribution and movement of radiocaesium within the soil and vegetation of heather moorland where post-Chernobyl contamination is known to have been high.

b) Determine the effects of heather-burning in autumn and spring on the availability of radiocaesium for plant uptake during post-fire conditions.

c) Investigate the ingestion of radiocaesium by red grouse, its retention within the bird's tissues, its rate of excretion and its biological half-life within the bird.

d) To produce a user friendly predictive model for use in the event of further incidents, based on data collected during this study.

2 STUDY AREAS

2.1 SELECTION OF STUDY AREAS

The 1987 survey of radiocaesium levels in Scottish soils showed that post-Chernobyl contamination had been relatively high in Glen Trool, Dumfries and Galloway region and in Glen Spean, Highland Region (Miller *et al.* 1989). The latter area was chosen for this project because heather-dominant vegetation occurred there on contrasting organic and mineral soils.

2.2 STUDY SITE DESCRIPTIONS

Two sites were chosen on the Ardverikie Estate. One site is covered by 15 - 20 year-old heather on a well-drained iron humus podzol with an A_o horizon some 10 cm deep; it is situated on a river terrace at an altitude of 305 m (National Grid Reference NN 528915). The second site, about 1.5 km distant, has heather, aged 25 - 30 years on a deep wet peat at an altitude of 320 m (National Grid Reference NN 533902). Each site occupies c.0.2 ha of fairly level ground. Initial surveys of the litter layer (taken as an indication of deposition of radiocaesium) showed that the deposition of ^{137}Cs was 4300 and 4900 Bq m^{-2} on the peaty podzol and peat respectively, confirming that these sites had received high levels of Chernobyl fallout.

The podzolic soil supports a dense stand of vigorous heather covering some 80% of the ground; the associated plant species include the grasses *Deschampsia flexuosa, Festuca ovina,* and *Agrostis vinealis* and the dicotyledenous herbs *Potentilla erecta and Galium saxatile*. The peat has a mixture of about 65% heather and 25% hare's-tail *(Eriophorum vaginatum)*, associated with cross-leaved heath *(Erica tetralix)*, common cotton-grass *(Eriophorum vaginatum)* and heath-rush *(Juncus squarrosus)*.

Red deer and sheep range freely over both sites and their droppings are found amongst the vegetation. However, plants do not appear to be heavily grazed indicating low stocking densities. Red grouse are scarce at the sites and mountain hares were not evident.

3 GENERAL METHODS

3.1 SAMPLE COLLECTION AND PREPARATION

3.1.1 Vegetation

All vegetation samples were cut either with shears or secateurs to ground level. Heather was parcelled separately from other vascular species which were bulked due to the small amounts present. After removing all the vascular plants, the moss layer was raked and collected as a separate sample. Care was taken at all stages to avoid contaminating vegetation with soil. All plant material was oven-dried at 80°C for 48 h and then weighed.

The main interest centred on the distribution of radiocaesium within the heather. It was therefore necessary to estimate the weight of the different components of the heather plants by using methods developed for studies of heather production (Miller 1979). A sub-sample of 5 - 10 heather plants, cut at ground level, was taken from each plot. These were separated by hand into the following components :-

a) current years's growth, ie long shoots, short shoots, increments on previous years' short shoots, and flowers (see Figure 1 in Chapman *et al.* 1975);

b) previous years' short shoots, ie all green material aged more than 1 year;

c) woody stems;

d) dead material, ie all dead long and short shoots, deadwood, and old flowers still attached to the plant.

After this material had been dried at 80°C and weighed the proportion of each component within the separated sub-sample was used to calculate the amount harvested from the whole plot.

All vegetation samples were ground to a particle size of 0.7 mm or less before gamma spectrometry (see 3.4).

3.1.2 Soils.

After removal of the vegetation the surface litter was raked up. This material comprised the undecomposed and partially decomposed organic remains that constitute the 'L' and 'F' surface layers of the soil; the top of the firm amorphous 'H' layer of wholly decomposed organic matter was then left exposed. Litter samples were treated as vegetation for the purposes of analysis.

Soil blocks were usually used for subsampling the soil and were taken from the centre of any sample plot. The block was removed in one piece and trimmed around the edges to minimise contamination of the lower parts of the block with surface soil. All dimensions were carefully recorded before taking horizontal sections, every 2.5 cm down the profile, from the surface of the 'H' layer usually to a depth of 15 cm, the final 15 - 20 cm was not sliced as it sometimes contained stones and would probably have disintegrated. Each section was bagged and labelled.

Soil sections were kept chilled at 3 - 5°C until they were processed. The soil was broken up by hand, dried at 60°C for 24-36 h, and rotary sieved. The <2 mm fraction was used for analysis. Any stones remaining in the sieve were weighed and then discarded. Organic material, particularly plant bases and roots in the upper soil layers, were separately weighed and analysed. The organic matter content of the sieved fraction was estimated by measuring the weight loss after ignition in a muffle furnace at 550°C for 2 h.

3.1.3 Water

Water samples from the field and lysimeter experiments were frequently of large volume and contained very low concentrations of radiocaesium. All samples were evaporated on a hot plate after the addition of 5 ml l^{-1} of nitric acid to destroy soluble organic matter. The final stage of the evaporation was carried out in a 5 cm diameter petri-dish under an infra-red heating lamp. The residue was then counted against an appropriate standard (see 3.4).

3.2 *RADIONUCLIDE ANALYSIS USING GAMMA SPECTROMETRY*

All samples were counted by high resolution gamma ray spectrometry using hyperpure or germanium-lithium detectors with relative efficiencies of 20 - 25%. Depending on the activity, counting times varied from 25 000 to 80 000 s. Calibration was by means of British Calibration Service certified mixed standards covering the energy range 60 - 1900 keV in a matrix appropriate to the sample being measured. The accuracy of the calibrations was checked against international standards and individual detectors were cross-checked to ensure that their results were comparable.

The spectral data were analysed using Canberra Apogee software. Counting errors at the 95% confidence level varied with sample activity and counting time but were within the range 3 - 8%. The minimum amount of radiocaesium that was detectable was generally around 4 - 5 Bq kg^{-1} dry weight (dw).

3.3 *ANALYSIS AND PRESENTATION OF RESULTS*

All measurements of activity in this report are expressed as Becquerels (Bq) - that is one atomic disintegration per second.

The activity of radiocaesium in soil, plant material and ash can be expressed in two ways. Organic material, such as vegetation or peat, contains much less mass per unit volume than does mineral soil so comparisons of concentrations (Bq kg^{-1}) can be misleading. Total amounts of activity per unit area (Bq m^{-2}) have therefore been used when considering the inventories of some soils. On the other hand, radiocaesium activity concentrations are entirely appropriate to comparisons of different plant tissues or losses from leached ash.

Data for ^{134}Cs activity reflect the distribution of radiocaesium originating from the Chernobyl accident - any ^{134}Cs derived from the testing of nuclear weapons will have decayed substantially before 1986. On the other hand measured ^{137}Cs activity includes depositions from above-ground bomb tests and the Chernobyl accident. A problem encountered in this work is that some of the recording has taken place over a time span comparable with the half-life of ^{134}Cs. In these instances only ^{137}Cs figures are reported.

The statistical significance of any comparisons of data sets is often apparent from an examination of the means and 95% confidence limits. However, where appropriate, standard 'F' and 't' tests have been applied to the data, using the 0.05 level of probability (P) as the criterion for statistical significance. In some cases, the 0.1 level of probability is quoted as being indicative of a possible effect or difference.

4 FIELD MEASUREMENTS

4.1 INTRODUCTION

Likely pathways of radiocaesium within the soil/plant system are illustrated in Figure 1.

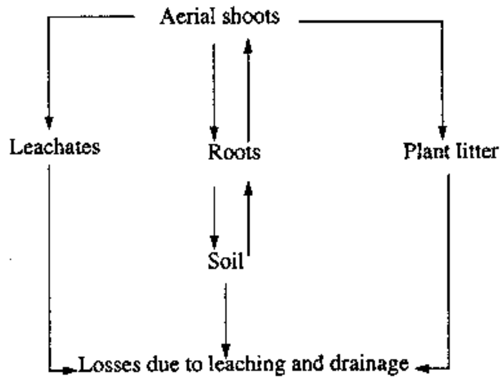


Figure 1. Possible pathways for the movement of radiocaesium within the plant/soil system

Transfers of radiocaesium and other nutrient ions from soil to roots to aerial parts occur mainly during the growing season, from May to September. At the end of the summer there may be some withdrawal from aerial parts to stems and roots. The shedding of plant litter containing radiocaesium will occur throughout the year, but more particularly during the autumn and winter period. Mineralization of the radionuclides in this organic litter and their transformation into a form suitable for plant uptake would predominately take place during the summer period when microbial activity is at its maximum. Breakdown by micro-organisms is slow in these upland systems and mineralization is also a slow process. Radiocaesium might therefore be expected to accumulate in the litter at the soils surface. Concurrent with any cycling of the radiocaesium or its accumulation in a particular component of the system there may be a gradual depletion by leaching and surface drainage.

4.1.1 Field sampling

Field samples for the determination of radiocaesium in soils, litter and vegetation were collected in June 1989, August 1989 and March 1990. On each occasion six replicate samples of each ecosystem component were taken from each of the the two study sites.

The purpose of this part of the investigation was to measure the distribution of the radiocaesium between different parts of the ecosystem and to try and estimate the magnitude of any movements that had taken place between components.

4.2 RADIOCAESIUM IN SOILS

The total soil inventory to a depth of 20 cm, excluding the litter layer amounts to c. 13 kBq m^{-2} on the peaty podzol site and 7 kBq m^{-2} on the peat site (Table 1).

At all three sampling occasions on the peaty podzol c.60% of the total system radiocaesium to 20 cm was contained in the 0-5 cm soil layer with c.8% and 3% in the 5-10 cm and 10-20 cm layers respectively (Figure 2).

The retention of such a high proportion of radiocaesium in the upper layer of the peaty podzol is probably due to the presence of c. 50% mineral matter in this layer (see Table 2). If this radiocaesium is bound to the mineral matter it may be unavailable for plant uptake.

In contrast, on the peat site, a much lower proportion of the total radiocaesium is contained in the upper soil layer. In June 1989 and March 1990 the 0-5 cm layer contained in the region of 30% of the total radiocaesium. The August values are reduced to half this amount. This reduction could represent movement into the plant component, as hypothesised in a previous report, but could also be attributed to sampling variation. The radiocaesium has moved much further down the profile on the peat site where about 8% was found in the 10-20 cm layer of the soil. In contrast to the 50% mineral matter found in the upper layer of the peaty podzol there was only c.3% mineral matter in the peat. It is also probable that measurable amounts of Chernobyl radiocaesium have passed below the 20 cm depth in this profile. This could account, to some extect, for the lower total values recorded for the peat site.

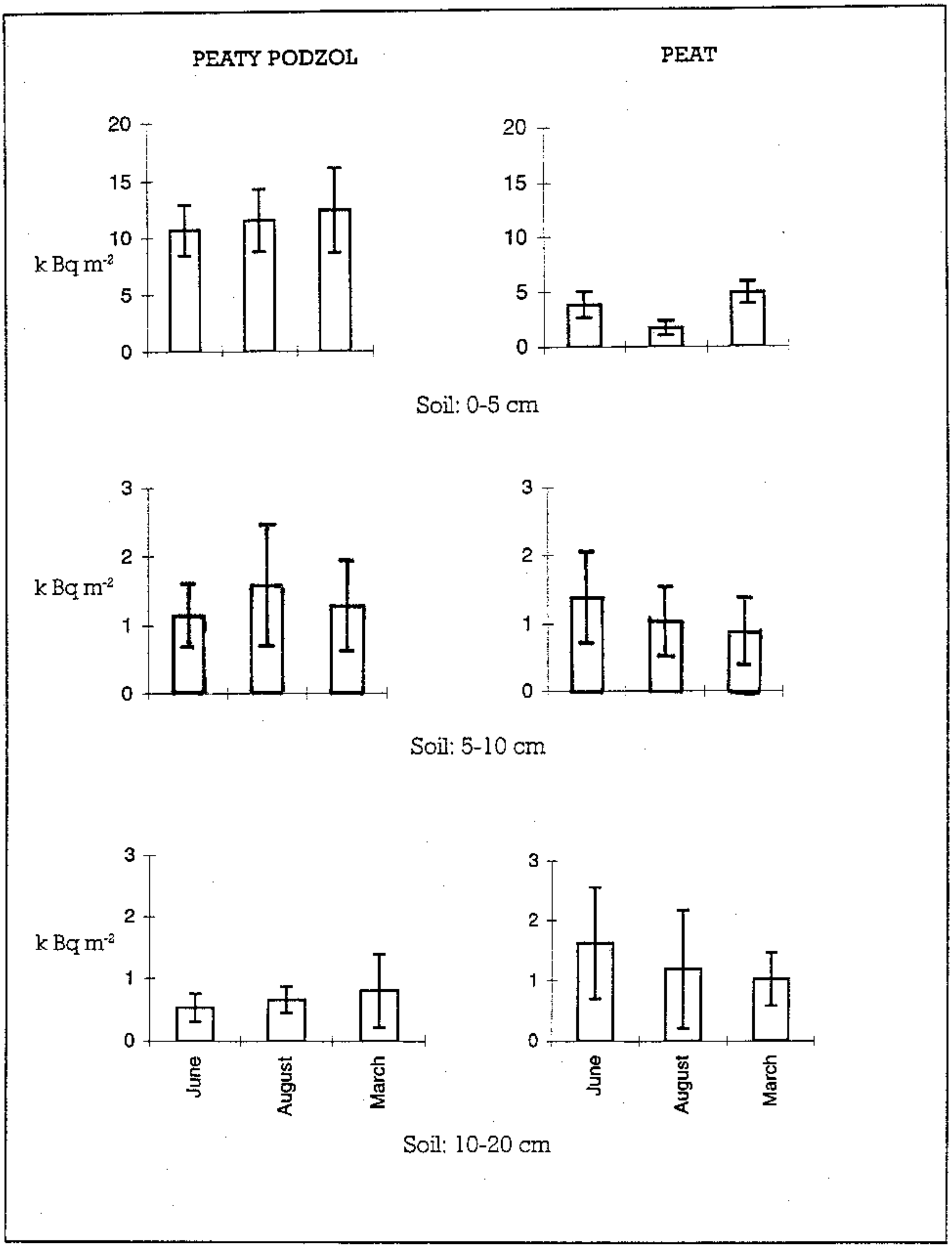


Figure 2. Amounts of ^{137}Cs measured in the soil at depths of 0-5, 5-10 and 10-20 cm at peaty podzol (left) and peat (right) sites in June, August and March 1989-90. Vertical lines show the 95% confidence limits of the mean.

Table 1 Content of ^{137}Cs (Bq kg^{-1} dw arithmetic means ± standard deviation) for six replicate samples, collected on three dates, from heather dominated peaty podzol and pure peat sites at Ardverikie

SOURCE	PEATY PODZOL			PEAT		
	JUNE 1989	AUGUST 1989	MARCH 1980	JUNE 1989	AUGUST 1989	MARCH 1980
Vascular plants (98% heather) n = 6	1473 ± 474	2249 ± 1080	849 ± 280	1671 ± 733	2367 ± 751	2245 ± 531
Bryophytes & Lichens n = 6	1472 ± 438	1687 ± 411	1168 ± 518	2601 ± 634	2474 ± 803	2699 ± 1530
Litter n = 6	1314 ± 330	1858 ± 243	2397 ± 383	3268 ± 793	3756 ± 1391	4717 ± 627
Soil 0-5 cm n = 6	10681 ± 2253	11510 ± 2739	12371 ± 3707	3876 ± 1207	1737 ± 670	4978 ± 1012
Soil 5-10 cm n = 6	1163 ± 451	1590 ± 886	1293 ± 653	1397 ± 660	1036 ± 504	895 ± 483
Soil 10-20 cm n = 6	538 ± 223	659 ± 208	808 ± 586	1621 ± 930	1190 ± 986	1015 ±440

4.3 *RADIOCAESIUM IN THE LITTER LAYER*

The litter layer on upland heather moors is variable and difficult to sample accurately because there is an ill defined boundary at the litter/peat interface. The litter layer contains residual material from past years, new litter fall from heather, other species, mosses and lichens, surface peat particles and wind blown debris. Because of the difficulty of sampling the litter layer accurately interpretation of the analytical data for the litter is also difficult.

On first examination the data obtained from the litter layer (Table 1 & Figure 3) seem to show a steady increase in total radiocaesium at the peaty podzol site and a similar trend at the peat site. However, on closer examination of the data we found that on the peaty podzol the

Table 2 Organic matter content as indicated by loss on ignition (%) in soils collected from peaty podzol and peat sites in June 1989

Site		Loss on ignition (%)						
		Soil depth (cm)						
	Plot no	**0-2.5**	**2.5-5**	**5-7.5**	**7.5-10**	**10-12.5**	**12.5-15**	**15-20**
(a) Peaty podzol	A1	98	42	24	9	15	16	16
	A2	57	25	23	17	12	5	7
	A3	67	28	16	15	13	10	7
	A4	41	25	23	20	18	13	10
	A5	69	16	11	11	9	8	11
	A6	84	60	32	23	19	17	9
(b) Peat	B1	98	97	97	97	97	97	97
	B2	98	97	97	97	97	97	97
	B3	97	98	98	97	97	97	96
	B4	98	98	97	97	95	96	96
	B5	97	98	97	95	93	97	96
	B6	98	97	98	97	96	96	95

Table 3 Weights and ^{137}Cs activity concentrations of the litter layers from the peaty/podzol and peat sites

Sampling Date	Peaty podzol Dry weight g m^{-2} mean ±SD	^{137}Cs Bq kg^{-1} mean ±SD	Peat Dry weight g m^{-2} mean ±SD	^{137}Cs Bq kg^{-1} mean ±SD
6-7 June 1989	308±85	4295±336	678±173	4847±458
8 August 1989	440±83	4265±424	1141±331	3402±1106
10 March 1990	711±147	4265±474	1517±232	3191±312

increase in total radiocaesium is entirely due to the increase in dry weight of the litter. The radiocaesium activity concentration (Bq kg^{-1} dw) remains constant within experimental error (Table 3). At the peat site radiocaesium activity concentrations decreased with time during the field experiment although an increase in litter weight for successive samplings meant that an overall increase in total radiocaesium per unit area has occurred.

A number of factors affect the litter layer mass to a greater or lesser extent during the season. These include fresh litter fall, decomposition and surface movement of material by agencies such as wind. An explanation of the increase in litter weight at both sites is difficult to make in terms of litter fall alone as the standing crop is insufficient to provide such a large mass of material over the experimental period. There are two possibilities which may explain these anomalies, (a) Sampling technique - with a component as difficult to define as the litter layer, which merges gradually with the soil, slightly different sample selection may be made depending on soil moisture content, for example more peat may be included in dry conditions. (b) Condition of plants - during the course of the experiment we noticed that due to hard frosts in winter and recent dry summers a severe browning of the heather had taken place compared with the healthy green state at the commencement of the work. This may have caused excessive litter fall.

4.4 RADIOCAESIUM IN THE GROUND LAYER

The ground layer is dominated by hypnaceous mosses and some lichens. Radiocaesium activity concentrations at both sites are of the same order of magnitude as those found in litter and vascular plant components of the system (see Table 1). The amounts of radiocaesium contained in the ground layer were greater on the peat than on the peaty podzol site ($P < 0.001$) but there was no significant variation between months.

Bryophytes are thought to be important sinks for radiocaesium in ecosystems (Sawdis, 1988). For this reason a study of the radiocaesium concentrations between and within moss species was undertaken in 1990 by Joep Frissel, a visiting Dutch student. As has been found for higher plants not all moss species from the same habitat contain similar concentrations of radiocaesium. *Pleurozium schreberi*, one of the most abundant mosses at the peat site, contained significantly greater activity concentrations of both radiocaesium isotopes than did other mosses common in this habitat.

Unlike vascular plants, however, mosses contained more radiocaesium in their older tissues than in recent growth. This is probably due to the lack of translocation in the plant (Callaghan 1976). They can thus be used to indicate the availability of radiocaesium in an ecosystem with time. *Hylocomium splendens* is easily partitioned into successive years of growth. Analysis of this material (Figure 4) showed a progressive decline in the ^{137}Cs content from 1986, the year of the Chernobyl accident, to 1989.

The supply of radiocaesium to the moss will either be from groundwater, aerial deposition or throughfall from the overhead plant canopy. Measured values reflect a slow decrease in available radiocaesium for uptake by mosses and lichens at the Ardverikie sites.

4.5 RADIOCAESIUM IN HEATHER PLANTS

For the purposes of this report the heather has been partitioned into four components: actively growing green shoots of the current

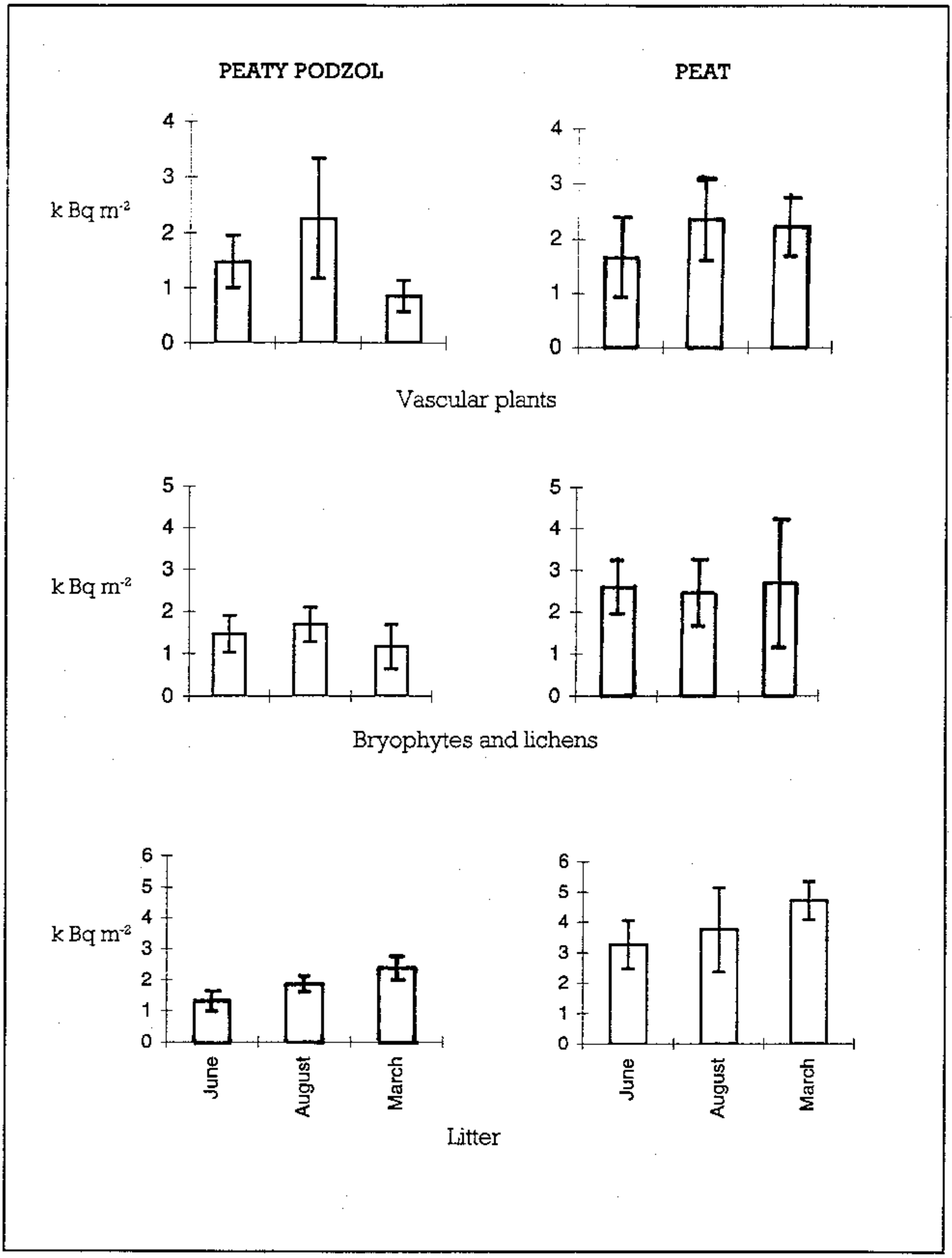


Figure 3. Amounts of ^{137}Cs measured in vascular plants, bryophytes and lichens and litter at peaty podzol (left) and peat (right) sites in June, August and March 1989-90. Vertical lines show the 95% confidence limits of a mean.

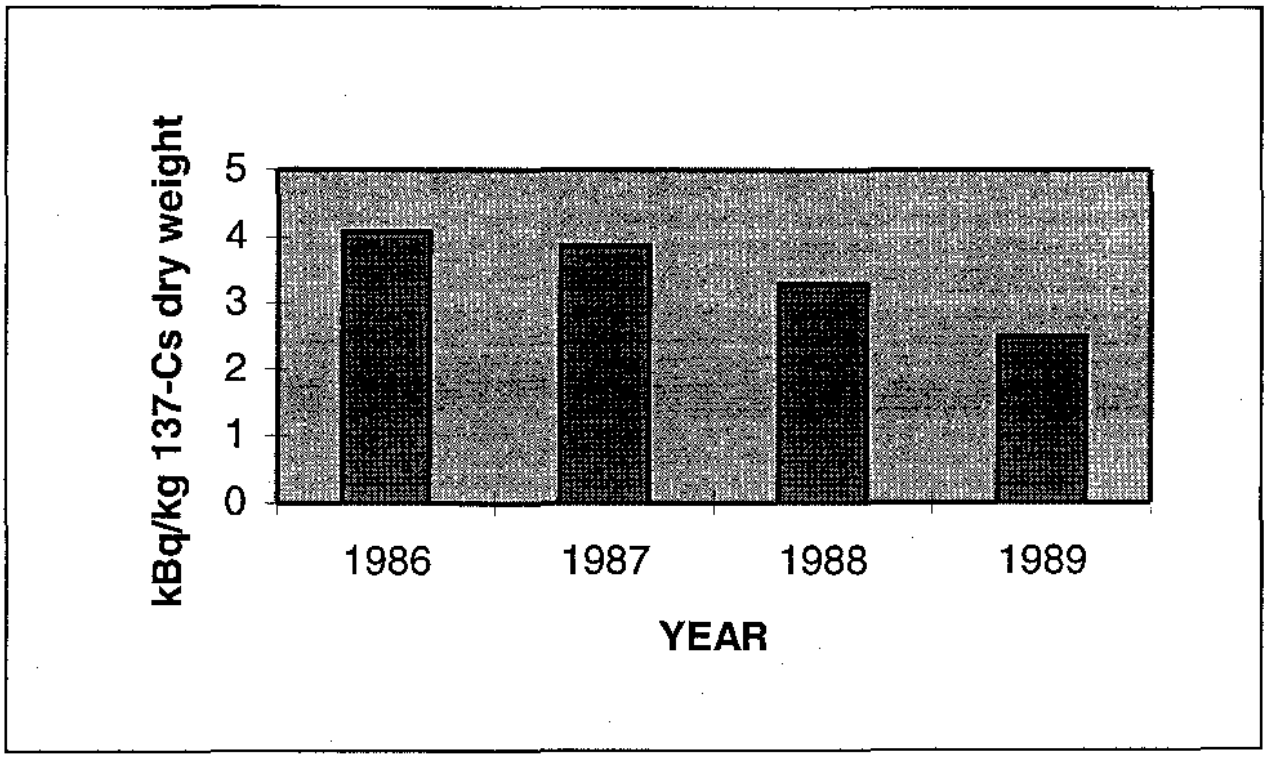


Figure 4. Concentrations of ^{137}Cs in individual years' growth of the moss *Hylocomium splendens*.

year (CYG), green shoots of past year's growth (PYG), woody tissue and dead material.

Although CYG represents only 6-18% of the total standing vegetation (dry weight), it was found to contain between 20-45% of the radiocaesium inventory (depending on site and season). This is important because grouse, deer and sheep are all known to graze selectively on CYG, therefore young heather shoots are a potential source of enhanced radiocaesium activity concentrations entering the human food chain.

Mechanisms governing the movement of radiocaesium in vascular plants are poorly understood. Radiocaesium measured in CYG may have originated from internal plant translocation processes or by root uptake of available radiocaesium from the soil.

Considerable amounts of radiocaesium were also measured in the past year's growth (PYG), particularly for the peat soil (Table 4). In June 1989 the total amounts of radiocaesium were comparable at c.20%, but by August measured radiocaesium in CYG was more than double that found in the older tissues. Care must be taken when assessing the March 1990 values. Shoot growth for 1990 would not yet have started so that the shoots identified as CYG will actually have grown during 1989. It is therefore not surprising to find that radiocaesium concentrations for March 1990 CYG are very similar to those for the summer of 1989, for both the peat and the peaty podzol (Table 4).

Woody tissue and dead shoots contained much lower radiocaesium concentrations, with no significant difference between soil types. Although heather woody tissue contained 30-50% of the radiocaesium in standing vegetation its potential effect on human foodchains is reduced because it also represents 60-70% of the plant biomass and is generally unpalatable to grouse, sheep and deer.

Dead heather tissue contained about 10% of the overall radiocaesium inventory of the standing vegetation. A proportion of this material will be shed into the litter layer each year and become available for recycling.

The percentage radiocaesium distribution between components of the heather plant is very similar at both sites for all three sampling

Table 4 Percentage contribution of heather components on peat and peaty podzol sites for three sampling dates at Ardverikie

	Peat			Peaty Podzol		
JUNE 1989	**g m⁻²**	**k Bq¹³⁷Cs**	**% ¹³⁷Cs**	**g m⁻²**	**k Bq ¹³⁷Cs**	**% ¹³⁷Cs**
CYG n = 6	46	0.33	21	70	0.27	21
PYG n = 6	53	0.32	20	71	0.25	20
Wood n = 6	401	0.52	33	488	0.68	54
Dead n = 6	228	0.39	26	55	0.06	5
AUGUST 1989						
CYG n = 6	140	1.05	45	128	0.52	34
PYG n = 6	71	0.34	15	84	0.27	17
Wood n = 6	519	0.78	34	423	0.63	41
Dead n = 6	65	0.15	6	65	0.12	8
MARCH 1990						
CYG n = 6	214	0.86	36	183	0.27	33
PYG n = 6	23	0.12	5	36	0.10	12
Wood n = 6	790	1.25	53	580	0.38	47
Dead n = 6	88	0.15	6	62	0.06	8

CYG = current year's growth
PYG = past year's growth

periods. However, when total amounts are calculated the measured radiocaesium in heather from the peat site is always greater than that from the peaty podzol site, sometimes by a factor of two (see Table 1 where vascular plants, other than heather, comprise less than 3% of the total biomass).

4.6 RADIOCAESIUM IN OTHER VASCULAR PLANTS

The radiocaesium content of the other vascular plants growing at the two sites was similar to that of the whole heather plants, but much less than the concentrations found in the green heather shoots (CYG). Although these plants are of low biomass they may be grazed selectively by animals and their importance in the food chain to man may be more than their apparent contribution to the ecosystem.

4.7 TOTAL RADIOCAESIUM ACTIVITY IN ARDVERIKIE PEAT AND PEATY PODZOL HEATHER DOMINATED ECOSYSTEMS

Total radiocaesium activity of ^{137}Cs in soil and vegetation (Table 1) of the peaty podzol, averaged over three samplings in June and August 1989 and March 1990, was 18 (17-19) kBq m^{-2}, significantly ($P < 0.001$) greater than the 14 (12-16) kBq m^{-2} measured on the peat site. This supports the original hypothesis that a more rapid leaching of the radiocaesium would take place at the peat site. Examination of the soil profile data and results from lysimeter studies presented later in this report support the idea that the differences in total activity at each site is due to a faster leaching rate at the peat site.

The total radiocaesium activity at the two sites is distributed very differently. This is illustrated in Figure 5 where the mean percentage distribution is shown for June 1989. A similar distribution pattern was found for the other sampling periods (see Table 1). No seasonal trends could be identified when sampling variability was taken into account. The absolute amounts of radiocaesium contained in the 0-5 cm of the peat and peaty podzol are significantly different (Table 1). As illustrated in Figure 5 about 60% of the total ^{137}Cs inventory occurs in the upper horizon of the peaty podzol whereas only 30% is present in this layer of the peat. Despite this the proportion of radiocaesium in vegetation growing on the peat (30%) is far greater than that found on the peaty podzol site (18%), although absolute amounts are of similar magnitude. The mobility of radiocaesium down the soil profile and its availability for plant uptake is different for the two sites. On peat soils, despite the smaller total activity to 20 cm, a greater proportion of radiocaesium is

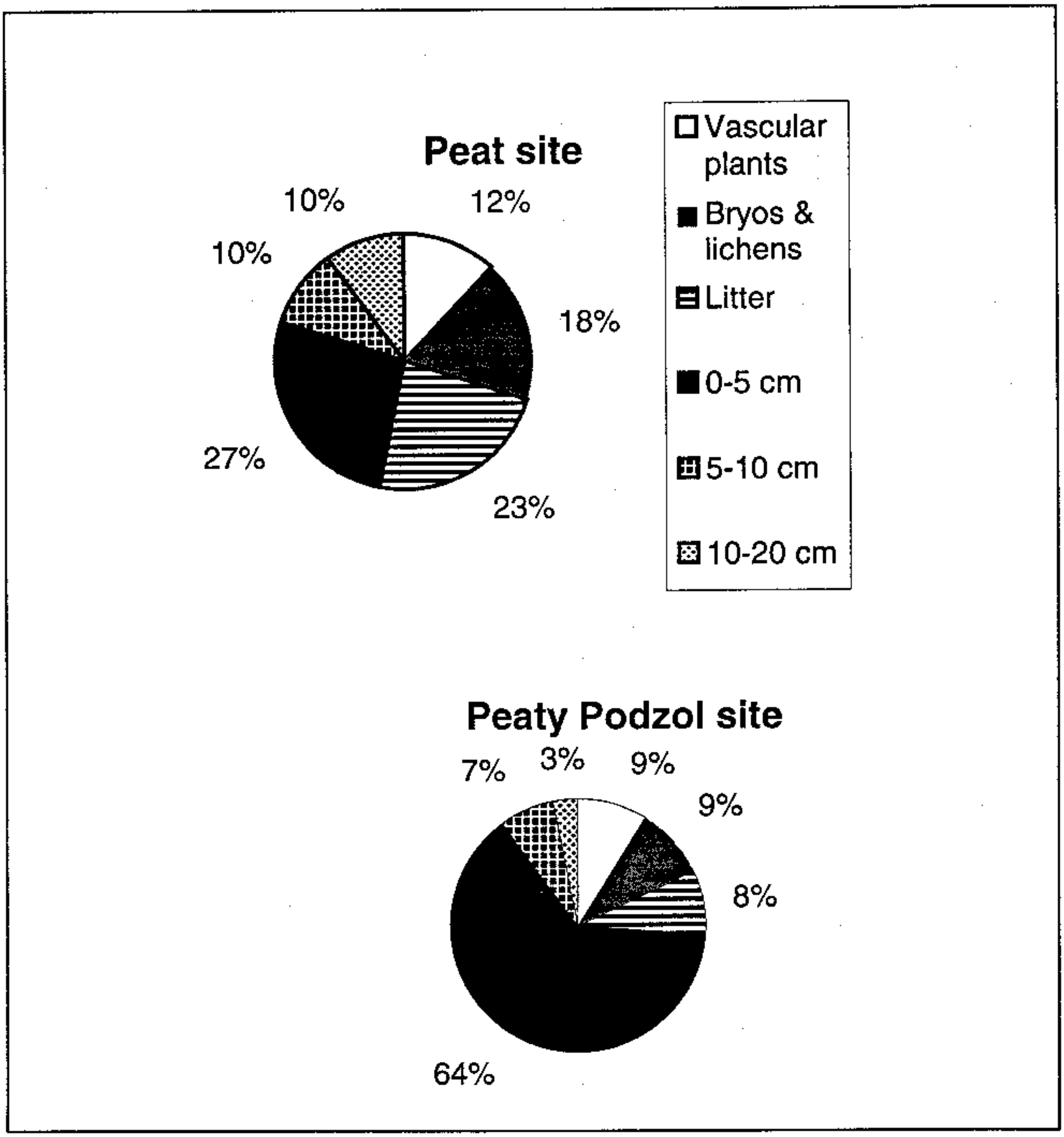


Figure 5. Mean percentage distribution expressed as ^{137}Cs Bq m^{-2} in different components of heather dominated ecosystems at Ardverikie

transferred to plants and is potentially available to herbivores.

4.8 *ROLE OF ANIMAL FAECES IN RADIONUCLIDE RECYCLING*

4.8.1 Background

The faecal material of grazing animals will decompose so that nutrients and pollutants associated with it will be leached into the under-lying soils and may become available for plant uptake. Published data has shown that a large proportion of the radiocaesium ingested by herbivores is excreted in the faeces (Howard *et al.* 1987, Howard & Beresford 1989, Beresford & Howard 1991). In view of the potential importance of this pathway for radiocaesium cycling an estimate of the breakdown rate of sheep and deer faeces was made at both experimental sites. This work has allowed an assessment of the release rates into the litter and soil layers.

4.8.2 Experimental method

Approximately 5.5 kg of fresh deer faeces was collected from the Ardverikie estate at the end of April 1990. On 30 April 1990 24 marked 100g portions were placed randomly along a transect within each fenced experimental area on the peat and peaty podzol sites. Sheep faeces were more difficult to collect in the region due to the low stocking density and the need for a large quantity of fresh material. Fresh sheep faeces were therefore collected from Corney Fell in Cumbria at the end of May 1990. This material was then divided into 48x100g portions and placed in the fenced experimental areas on 31 May 1990.

Six random, replicate deer faecal samples were harvested from each experimental site at monthly intervals for the first three months, starting on 31 May 1990. The final sample was taken three months later on 25 October 1990. A similar programme was maintained for the sheep faeces, but, as these were not placed in the field until the end of May, only two months elapsed between the third monthly sampling and the final sampling on 25 October 1990.

4.8.3 Results from faecal decomposition experiment

It was expected that almost complete disintegration of faecal material would occur within the six month duration of this experiment. As can be seen from the results this was not the case (Tables 5 and 6). After 6 months 47-73% of the deer faeces (dw) and 52-63% of the sheep faeces (dw) still remained. This result was probably due to an unusually dry period early in the experiment. It would have been interesting to re-run the trial for a longer period in a wetter year but this was precluded by the problem of obtaining sufficient fresh faeces from the field.

The fresh weights of sheep and deer faeces were very different from one another probably due to differences in the diet of the two species. Measured values are presented in Tables 5 and 6. Analysis of variance of the dry weight data shows that there is a significant difference between the rate of decomposition of sheep and deer faeces ($P<0.001$). By the end of the experimental period the sheep faeces had largely lost their physical structure whereas the deer faeces remained as well formed, distinct pellets. Therefore it is not surprising that sheep faeces were found to decompose faster than deer. Thirty two % of the dry weight of the sheep material and 47% of the deer faeces (Table 6) remained on the peaty podzol site. In contrast the figures for the peat were 47% and 73% respectively. Thus decomposition of both faecal types was faster on the surface of the peaty podzol soil. This was interesting as, if moisture was the overriding factor in determining the decomposition rate, it would be expected that the rate would have been greater on the damper peat site.

Initial decomposition of the sheep faeces was relatively fast. By week 12 the dry weight had reduced by 50-70% (Table 6). Decomposition rates between weeks 12 and 21 were much slower with little reduction in overall dry weight. In contrast significant decomposition of the deer faeces did not begin to take place until week 12 with 77-85% remaining at that time. There was then a steady reduction in dry weight to 47% of the original at the peaty podzol site. Similar changes, but of lower magnitude occurred at the peat site for deer faeces. Seventy three % of the dry weight still remained at week 25. Differences between sites were shown to be significant ($P<0.05$).

Although the dry weight of the sheep faeces had fallen to 32-47% of the original by the end of the experiment 52-63% of the radiocaesium in the material still remained. If the release of radiocaesium from the faeces is a slow process it is more probable that it will be available for plant uptake and not flushed rapidly through the soil by rainfall.

A different pattern was observed for deer faeces on both sites. During the first four weeks an initial flush of 23-24% of the radiocaesium associated with the faecal material was released to the soils at both sites. It is highly probable that this radiocaesium loss was due to leaching, rather than physical processes, as the faeces retained their original physical structure almost to the end of the experiment. During the next 20 weeks loss of radiocaesium was much slower with only 8% more of the original material being lost from the faeces. Differences between the deer and sheep may, in part, have been due to the fact that the deer experiment was started 4 weeks prior to the sheep. There was, however, a

Table 5 ^{137}Cs activity concentrations and dry weight values for deer faeces from the peaty podzol and peat experimental plots at Ardverikie

Sampling date		DEER FAECES	CONTROL SAMPLES
		^{137}Cs Bq kg^{-1}	Dry weight g
31 May 90	1	4224	40.6
	2	4041	45.3
	3	3759	49.8
	Mean	4008 (100%)	45.2 (100%)
	Std dev	192 (5%)	4.6 (10%)

		DEER FAECES FROM PEATY/PODZOL		DEER FAECES FROM PEAT	
		^{137}Cs Bq kg^{-1}	Dry weight g	^{137}Cs Bq kg^{-1}	Dry weight g
31 May 90 (Week 4)	1	3047	39.0	2921	40.0
	2	2964	39.2	3237	40.7
	3	3051	40.4	3053	40.7
	4	3343	37.5	3040	39.7
	5	3099	40.6	3017	40.1
	6	3006	40.3	2985	33.7
Mean		3085 (77%)	39.5 (87%)	3042 (76%)	39.2 (87%)
Std dev		134 (3%)	1.2 (3%)	106 (3%)	2.7 (6%)
26 June 90 (Week 8)	1	2764	34.6	3137	38.3
	2	3136	41.3	2803	36.9
	3	3081	38.3	2990	36.7
	4	3063	39.5	2190	37.2
	5	2967	37.9	2865	42.4
	6	2831	38.6	3021	38.8
Mean		2974 (74%)	38.4 (85%)	2834 (74%)	38.4 (85%)
Std dev		148 (4%)	2.2 (5%)	120 (3%)	2.2 (5%)
25 Jul 90 (Week 12)	1	2941	36.9	3043	38.3
	2	2500	26.4	3934	41.3
	3	2803	30.2	2429	37.8
	4	2426	36.9	2792	35.9
	5	2596	36.7	2705	39.1
	6	3069	41.0	2879	37.2
Mean		2722 (68%)	34.7 (77%)	2964 (70%)	38.3 (85%)
Std dev		255 (6%)	5.3 (12%)	214 (5%)	1.9 (4%)
25 Oct 90 (Week 25)	1	2703	12.2	3128	31.9
	2	2797	23.5	2797	32.9
	3	2803	8.7	2453	35.0
	4	2779	18.8	2578	38.3
	5	2400	35.2	2786	30.8
	6	2786	29.9	2554	29.0
Mean		2711 (68%)	21.4 (47%)	2716 (68%)	33.0 (73%)
Std dev		156 (4%)	10.2 (22%)	243 (6%)	3.3 (7%)

sharp initial drop in radiocaesium content for both types of faeces indicating immediate removal of leachable material. The ensuing losses were probably due to weathering and decomposition of the faecal material.

It has been observed, in the field, that both deer and sheep graze relatively small areas intensively. Therefore these areas could also receive a high faecal input. Thus, although radiocaesium originating in faeces, probably makes only a small contribution to the inventory of a large area it could be locally significant.

Table 6 ^{137}Cs activity concentrations and dry weight values for sheep faeces from the peaty podzol and peat experimental plots at Ardverikie

Sampling date		SHEEP FAECES	CONTROL SAMPLES
		^{137}Cs Bq kg^{-1}	Dry weight g
31 MAY 90	1	1338	29.6
	2	1539	27.7
	3	1728	31.5
Mean		1535 (100%)	29.6 (100%)
Std dev		195 (13%)	1.9 (6%)

		SHEEP FAECES FROM PEATY/PODZOL		SHEEP FAECES FROM PEAT	
		^{137}Cs Bq kg^{-1}	Dry weight g	^{137}Cs Bq kg^{-1}	Dry weight g
26 June 90 (Week 4)	1	1444	17.5	1305	12.2
	2	1350	17.4	1279	13.9
	3	1479	18.2	1475	19.0
	4	1448	22.1	1518	20.3
	5	1534	22.6	1730	12.5
	6	1195	20.3	1363	16.2
Mean		1408 (92%)	19.7 (67%)	1445 (94%)	15.7 (53%)
Std dev		120 (8%)	2.3 (8%)	168 (11%)	3.4 (11%)
25 Jul 90 (Week 8)	1	1253	19.9	970	8.2
	2	987	18.9	1226	13.7
	3	1297	18.5	1286	13.0
	4	1042	17.0	1246	14.2
	5	991	17.5	1619	14.9
	6	1077	17.3	1214	15.5
Mean		1108 (72%)	18.2 (61%)	1260 (82%)	13.3 (45%)
Std dev		134 (9%)	1.1 (4%)	208 (14%)	2.6 (9%)
24 Aug 90 (Week 12)	1	860	9.0	1009	14.3
	2	1086	7.1	1129	22.7
	3	924	7.7	995	16.4
	4	1020	16.2	1641	6.0
	5	1709	7.4	1369	14.7
	6	1079	6.9	1032	16.8
Mean		1113 (73%)	9.0 (31%)	1196 (80%)	15.2 (51%)
Std dev		305 (20%)	3.3 (11%)	259 (17%)	5.4 (18%)
25 Oct 90 (Week 21)	1	980	2.3	1137	25.6
	2	671	8.7	962	9.3
	3	741	7.1	839	11.4
	4	910	12.3	1042	9.9
	5	810	11.6	745	10.8
	6	716	15.4	1058	15.8
Mean		805 (52%)	9.6 (32%)	964 (63%)	13.8 (47%)
Std dev		120 (8%)	4.6 (16%)	147 (10%)	6.2 (21%)

5 EFFECTS OF HEATHER BURNING ON RADIOCAESIUM MOBILITY

5.1 ASH PRODUCTION FOR HEATHER BURNING EXPERIMENTS

It was not possible to burn the experimental plots because:

(a) it would not have been possible to control the temperature of the heather burn, the type of ash produced or to measure the radiocaesium content of the ash on each of the small experimental plots and

(b) heather burning is not used as a management tool by the Ardverikie estate.

A considerable amount of heather was machine cut at Ardverikie, air dried and transported to Merlewood Research Station where it was burnt to provide ash for the field experiments.

5.2 FIELD EXPERIMENTS ON HEATHER BURNING

Two experiments were laid out amongst heather dominated vegetation at the study sites on the Ardverikie Estate, one on the podzolic soil and the other on the peat. The aim was to investigate burning effects on radiocaesium mobility in a mineral soil with a shallow peaty surface horizon and in a purely organic soil. Each experiment comprised 24 plots measuring 2.5 x 1.5 m. these were arranged in the form of 6 randomised blocks containing factorial combinations of the following treatments :-

a) Two seasons of burning - this was achieved by spreading known weights of ash in autumn (October/November 1989), and then spring (March/April 1990) - to study the effects of radiocaesium mobilisation at different phases of the annual cycle of plant growth and uptake.

b) Two intensities of burning - this was achieved by removal of heather only to simulate a light fire, and removal of heather, moss and litter to leave the top of the'H' layer exposed to simulate a severe fire.

Each site was fenced against sheep and deer in spring 1990.

Activity in the ash used was measured as 72,000 Bq kg^{-1} dw of ^{137}Cs and 12,800 Bq kg^{-1} dw of ^{134}Cs. The ash was spread over the plots on 22-23 November at the following rates :-

a) Podzol: 45 g m^{-2}, equivalent to 3850 Bq of radiocaesium.

b) Peat: 90 g m^{-2}, equivalent to 7700 Bq of radiocaesium.

The larger amount of ash applied to the peat reflected the greater biomass of vegetation and litter there and its larger radiocaesium content. However, to expedite the subsequent measurements, both soils in fact received twice the amount of radiocaesium that was contained in the fuel (standing vegetation) on the site. Similar amounts of ash were applied to the spring-burnt plots in April 1990.

A lysimeter was installed near the surface at each plot to enable measurements of radiocaesium in the drainage water. Each consisted of 3 lengths of plastic trunking, 25cm long and 1cm wide buried at a depth of 5 cm and connected to a 10 litre collecting bottle. Collecting bottles were emptied at approximately monthly intervals.

5.2.1 Heather burning experiment - results

The anticipated heather regrowth on both sites A & B has currently failed to take place and consequently it has not been possible to carry out the planned sampling programme. However, extensive regeneration of 'other species' has taken place and sampling of these has been carried out.

Table 7 Dry matter yield and ^{137}Cs concentrations in 'other species' from peat and peaty podzol sites at Ardverikie. All values are means (± SD) for six replicate samples after simulated burning treatments

	DRY MATTER YIELD g m^{-2}	
TREATMENT	Peaty podzol (Site A)	Peat (Site B)
Autumn light	19.0±7.7	62.6±28.3
Autumn severe	9.2±4.7	28.5±19.5
Spring light	17.9±2.2	57.6±16.6
Spring severe	9.2±3.6	45.5±20.3
	CONCENTRATIONS OF ^{137}Cs Bq kg^{-1}	
TREATMENT	Podzol (Site A)	PEAT (Site B)
Autumn light	856.6±329	908.2±284
Autumn severe	712.4±556	659.8±97
Spring light	920.2±253	844.1±200
Spring severe	583.7±265	763.1±196

The reasons for the lack of heather regrowth are probably the lack of vigour of the old rooting systems and the unusually dry summers in the two years following the cutting of the heather. On both sites numerous heather seedlings have developed but these either succumbed to frost or drought. It is hoped that once the 'other species'(which at the moment are dominated by *Deschampsia flexuosa*) have established a permanent cover heather regeneration will take place. To this end it is planned that the two fenced plots will be kept on a 'care and maintenance' basis and examined again in a few years time.

Data for the combined 'other species' has been obtained for both the dry weight yield and radiocaesium activity concentrations (Table 7). Despite the large degree of variability in the data there are significant (P<.002) differences between the dry weights for the severe and light treatments on the peaty podzol site (Table 7). This probably reflects the effects of drought on regeneration on the severely denuded plots combined with the damage done by the removal of the moss and litter layers. Indications are that a similar effect took place on the peat site but the wetter nature of the area meant that the effects did not reach such a high level of significance (P<0.05).

Radiocaesium activity concentrations from both sites show a high degree of variability, possibly reflecting the mixture of species which make up this category. Due to the high variability significant statistical differences were not found between either between treatments or times of year. It can, however, be seen that the means for the light treatments tend to be greater than those for the severe treatments at both sites. This could indicate that radiocaesium is more likely to be retained and recycled in the surface soil layers when the moss and litter layer is not completely destroyed during heather burning.

Field lysimeters at this site have not proved to be a success. Instead of drawing water from the plot where they were installed it was found that they were acting as a drain for a much larger area. Puddles outside the plots disappeared as the lysimeter collection bottles were pumped dry so it is probable that water was being drawn from outside the plot. This meant that samples of drainage water collected could not be directly related to individual plots. However, bulk samples of soil water collected both from control areas and experimental plots over a period of ten months have been analysed. These values give an idea of the soluble radiocaesium concentrations available to plant roots in the surface soil layers.

Samples were collected approximately monthly between January and October 1990 with the exception of one date in February when it was not possible to reach site A due to snow (Table 8a & 8b).

Caesium-137 was measurable in all samples but ^{134}Cs was often below the levels of detection (<0.1 Bq l^{-1}). In control areas on the peaty podzol ^{137}Cs activity concentrations

Table 8(a) ^{137}Cs activity concentrations (Bq l^{-1}) from control plots on peaty/podzol and peat sites

Date	Peaty podzol (Site A)	Peat (Site B)
10.01.90	0.64	0.54
02.02.90	Bad weather; no samples	0.52
13.02.90	0.26	0.24
12.03.90	0.65	0.56
03.04.90	0.59	0.54
31.05.90	No rain; no sample	0.56
26.06.90	0.28	0.59
25.07.90	0.29	0.60
24.08.90	0.13	0.34
25.10.90	0.25	0.64

Table 8(b) Measured concentrations of ^{137}Cs ($Bq\ l^{-1}$) in field lysimeter waters (bulked) from areas treated with heather ash

Date	Peaty podzol (Site A)	Peat (Site B)
	Ash added October 1989 - autumn burn	
10.01.90	0.59	2.39
02.02.90	Bad weather; no sample	0.48
13.02.90	0.30	2.22
12.03.90	0.27	2.60
03.04.90	0.50	0.70
	Ash added end of April 1990 - spring burn	
31.05.90	2.56	3.50
26.06.90	0.73	2.16
25.07.90	0.39	1.50
24.08.90	0.18	1.40
25.10.90	0.18	1.23

ranged from 0.13 - 0.65 $Bq\ l^{-1}$, those on the peat site were more consistent with a range of 0.24 - 0.64 $Bq\ l^{-1}$ with most values in the region of 0.5 $Bq\ l^{-1}$. These figures should be representative of the soil solution concentrations available to the feeding plant roots in the upper soil layers.

Concentrations for water samples collected under the treated plots which have been bulked and analysed are presented in Table 8b. Whilst this data is of limited use it can be noted that in nearly all cases the activity concentrations exceed those of the control areas. There has therefore been an effect of adding the ash to the experimental plots. It will be seen from Table 8b that the greatest concentrations were measured on the peat site where over 3 $Bq\ l^{-1}$ has been measured in the spring samples of 1990.

5.3 OUTDOOR HEATHER BURNING LYSIMETER EXPERIMENT

A simulated burning experiment has also been carried out at the Banchory Research Station using small lysimeters set up in an outside enclosure. The design is basically similar to that adopted in the field - a peaty podzolic soil and a peat were used. Removal of the heather or the heather, moss and litter simulated burning at different intensities and ash was added either in the autumn or spring.

The experimental lysimeters consisted of plastic drain pipes 15cm in diameter and 20 cm long. These were used to extract soil monoliths from randomly chosen locations at the two Ardverikie sites on November 22-23 1990. At each location a pipe was centred over a heather plant, and fully driven into the soil. The monolith was then excavated and transported to Banchory where the vegetation was cut and ash added to simulate burning at different intensities as in the field experiment (see 5.2 (b)). Each treatment consisted of 6 replicates; 48 monoliths were collected (2 types x 2 intensities x 6 replicates x 2 seasons).

Ash containing 88,900 $Bq\ kg^{-1}$ dw of ^{137}Cs and 15,950 $Bq\ kg^{-1}$ dw of ^{134}Cs was spread on monoliths from both sites in December and April for the autumn and spring treatments at the rate of 20 g per 15 cm diameter plot. This is equivalent to a radiocaesium deposition of 118,700 $Bq\ m^{-2}$ a much greater load than was applied to the field plots. Drainage water percolating down through each 20 cm soil monolith was led through silicon tubing to a collecting bottle which was emptied monthly and sent to Merlewood for radiochemical analysis.

In this experiment the rainfall collected had passed through the whole 20 cm soil column, including the mineral horizons of the peaty podzol. During dry spells some additional rainfall was provided using a garden sprinkler, this was to avoid the cores in the lysimeters drying out, shrinking and allowing water to run directly down the outside edge of the monoliths.

The experiment at Brathens was terminated in April 1992 when the vegetation was harvested, the soil monoliths extruded from the lysimeters and sliced at 2.5 cm intervals. In all nearly 400 samples were taken to Merlewood where after drying, weighing and grinding radiocaesium determinations were made.

5.3.1 Results

Clay minerals are known to bind radiocaesium (Eisenbud 1987) and this experiment assessed the extent to which this might occur in the 'A_1' and 'B' horizons of the peaty podzol. From the experiment it was also possible to determine the rate of movement of radiocaesium through contrasting soil types and to estimate the residence time of radiocaesium in the soil profiles.

The results presented, (Figures 6 and 7), are for ^{137}Cs only as, although ^{134}Cs was determined in all samples, the short physical half-life of this isotope compared with the length of the experiment makes interpretation difficult.

The soil monoliths, as collected from Ardverikie already contained radiocaesium both from Chernobyl and above-ground weapons test fallout. An estimate of this pre-experimental radiocaesium was obtained by calculating a mean radiocaesium activity concentration for each horizon. These values have been used as a correction factor when the content of the soil monoliths has been calculated.

The results from the soil leachates are included with profile data as total values although breakdown into monthly figures is available and will be presented in a scientific paper. All soil and vegetation results are the means of six replicates and are presented as percentages of the total radiocaesium added to the monolith.

It is evident that there is a significant difference between the amount of radiocaesium leached from the peaty podzol (Figure 6) and peat (Figure 7) lysimeters. In all treatments the leachate from the peaty podzol represents less than 1% of the material applied to the surface; mean values for the peat soils were 6 - 8% of the total. In many of the monthly samples the ^{137}Cs was not detectable in the leachate from the podzols and in most cases the total leachate for the year contained less than 10 Bq. This contrasts with the peat lysimeters where total amounts leached were between 100 and 200 Bq. The total amount of water passing through the lysimeters over the experimental period was variable but for the autumn treatments generally amounted to between 15 and 20 litres and for the spring treatments c.10 litres.

The contribution to the total inventory from the vegetation grown on the monoliths was very small on both soil types due to the low biomass (often <1 g) of the vegetation harvested. The heather roots failed to regenerate, as in the field experiment, and the vegetation which developed consisted mainly of grasses, sedges and rushes. Nevertheless concentrations in the small amounts of material produced often reached between 2000 - 3000 Bq kg^{-1} dw or greater. This illustrates that plant uptake had taken place from the added material and shows the intake that could be possible for animals selectively grazing the graminoid component of the vegetation.

Penetration of the added radionuclide is, as would be expected from the leachate results, more extensive on the peat soils. Even the lowest horizons, 15-20 cm, of the peat profiles contain over 3% of the total radiocaesium whilst peaty podzol profiles never exceed 2% and in some cases were less than 1%. Examination of the histograms shows a more consistent penetration of the ^{137}Cs activity from the surface ash in all the peat profiles. In the majority of cases penetration in the peaty podzols is minor below the 5.0-7.5 cm region, ie movement takes place mainly in the horizons dominated by organic material. There is little evidence of radiocaesium moving down the profile and attaching to the top of the mineral layers, indeed very accurate depth sampling would be needed to show this and it is doubtful if this could be achieved in a real situation. Examination of the loss on ignition data (Table 2) shows that the organic layer of the peaty podzol contained a significant amount of mineral material (c.50%). The presence of this mineral matter has probably enhanced the retention characteristics of the organic layers overall in the peaty podzol, slowing radiocaesium movement down the soil profile.

Results from the pot experiment show that 55-77% of the added radiocaesium remained in the top 2.5 cm of the soil, a year after application, for both soil types, regardless of the severity of the simulated burn or the season when the ash was applied. For the treatments where both the litter and moss layers were removed (severe burn conditions) this radiocaesium is present in the top organic layer of the soil only. For the pots where the litter and moss layers were largely undisturbed (light burn conditions) the greater proportion remained in the litter layer. This implies that atmospheric fallout radiocaesium deposited onto soils is likely to remain in the upper organic soil layers for long periods of

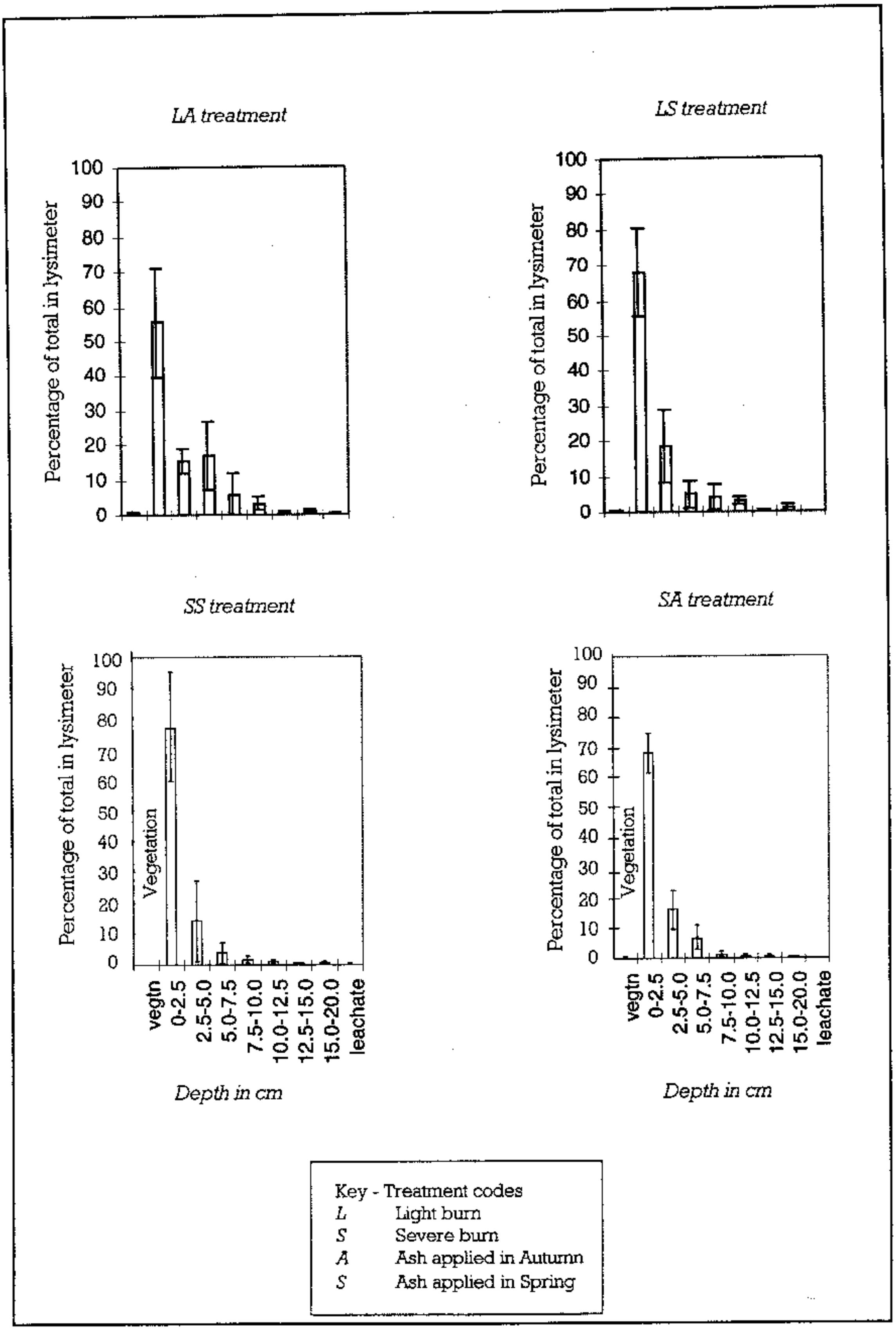


Figure 6 Mean percentage [137]Cs measured in components of six replicate peaty podzol lysimeters. There were four treatments.

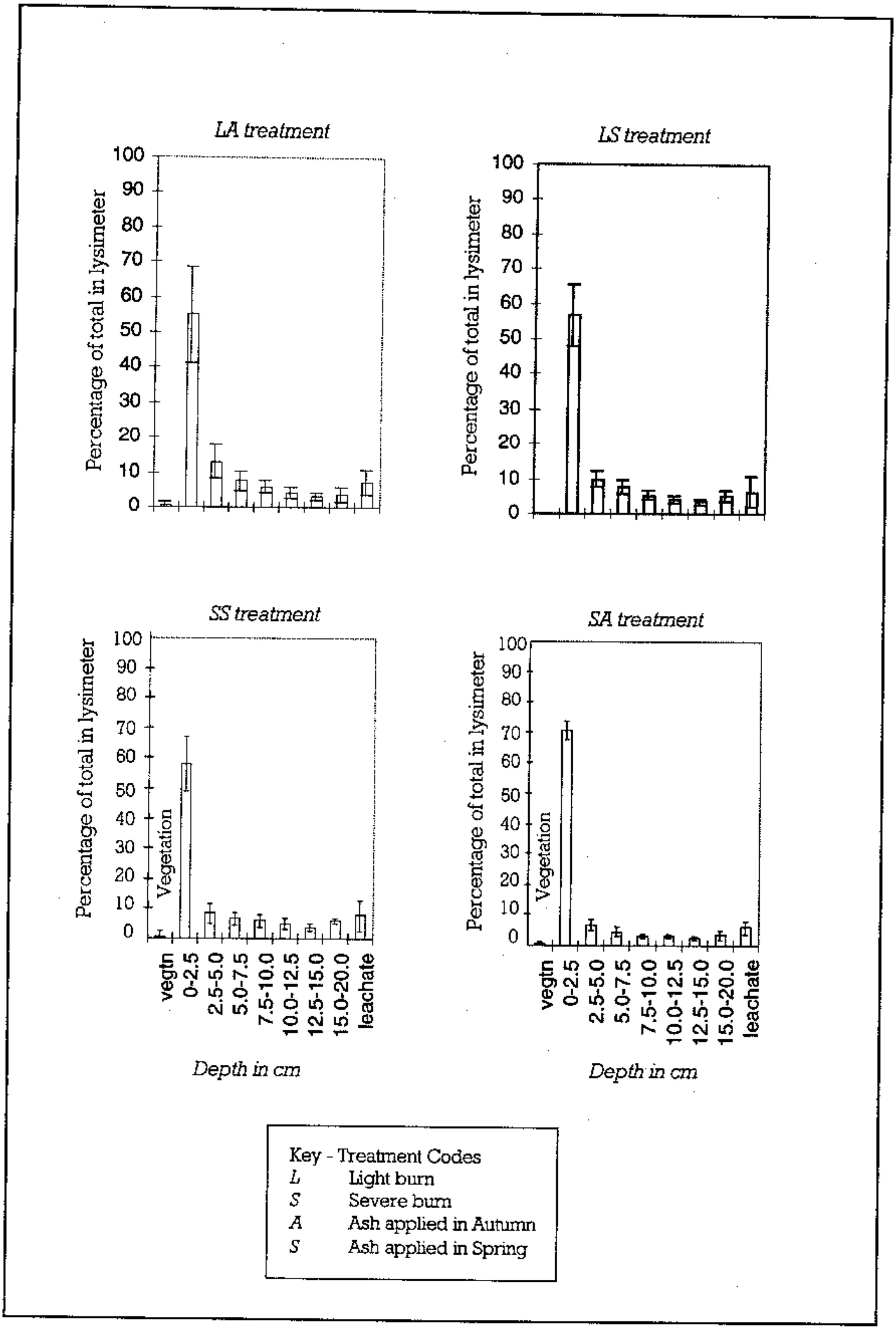


Figure 7 Mean percentage ^{137}Cs measured in components of six replicate peat lysimeters. There were four treatments.

time. It is possible that this radiocaesium will then be gradually released in a form that is available for uptake by roots in the surface soil layers and could become locked into plant/soil recycling processes for many years.

As an estimate of the possible residence time of the radiocaesium in the soil one has to assume that the more easily leachable fraction has come through first. Even in the peat soils, therefore, it is likely to be tens of years before the material migrates below the rooting zone of the plants and this could possibly be an order of magnitude greater on the peaty podzol sites where the rate of radioactive decay of ^{137}Cs could be as important as physical losses.

5.4 LABORATORY HEATHER ASH LEACHING EXPERIMENTS

5.4.1 Introduction

Laboratory experiments have been carried out to investigate the mobilisation of radiocaesium from heather ash. Whilst the temperature in a fire will be variable depending on the amount of fuel, moisture content and wind so might the subsequent release of the radionuclide from the residue ash. Release may depend on the frequency, amount and pH of the incoming rainfall and other environmental variables.

5.4.2 Ash preparation and loss of radiocaesium in smoke

Harvested heather was burned under two regimes which simulate conditions typical of:

i) An autumn burn - a hot fire under dry conditions with a following wind (severe burn) and

ii) A spring burn - a cool fire where air flow was restricted (light burn).

Under conditions of the hot fire the temperature reached 650-700°C, as measured by thermocouple. About 40% of the radiocaesium was lost in the smoke (Table 9) and the resulting ash was fluffy and light. Under cooler conditions the temperature reached 550-600°C and the loss of radiocaesium was of the order of 10% (Table 9). The resulting ash was black and

Table 9 Loss of ^{134}Cs and ^{137}Cs in smoke when heather is burnt under two fire regimes

'SEVERE BURN' - MEAN TEMPERATURE 660°C			
48 kg of air dry heather yielded 0.95 kg of ash (2.05%)			
	Total Bq before burning	Total Bq after burning	Loss in Smoke %
^{137}Cs	152220	92723	39
^{134}Cs	22355	14509	35
'LIGHT BURN' - MEAN TEMPERATURE 550°C			
50.1 kg of air dry heather yielded 2.2 kg of ash (4.4%)			
	Total Bq before burning	Total Bq after burning	Loss in Smoke %
^{137}Cs	120340	105996	11.9
^{134}Cs	23447	20884	11

contained much carbonaceous material.

5.4.3 Experimental methods

The experimental work involved leaching radiocaesium from the two types of ash using artificial rainwater of different pH values. Each individual treatment used 22 g of ash which corresponded to the amount of ash produced by burning 2 m² of heather dominated vegetation. This ash was then leached with successive 140 ml aliquots of artificial rainwater.

Leaching treatments were applied to the two types of ash in order to simulate continuous or intermittent rainfall (Table 10). This was done to test the hypothesis that soaking between leachings might have an effect on the amount removed. 'severe burn' and 'light burn' ash were both subjected to a leaching regime which consisted initially of 8 leachings at 2 h intervals followed by 4 leachings at 2 d intervals. In a further treatment 'light burn' ash was leached at 2 d intervals, during the intervening periods between leaching the ash was kept moist by covering with cling film.

A final effect investigated was that of subjecting the ash to a freeze/thaw cycle. Under the conditions of an autumn burn in the field it is highly probable that the ground surface will freeze sometime during the winter. Freezing might lead to more rapid weathering of the ash and an enhanced release of radionuclides. Therefore an experiment was carried out using 'severe burn' ash which was frozen between each leaching to investigate this possibility.

Table 10 Summary of ash leaching regime for ^{137}Cs ash leaching experiments.

Experiment	Ash type used	Leaching regimes	Number of leaches
T1 n=6	'light burn' ash	140 mls /2 h for 16 h 140 mls /2 d for 8 d	8 4
T2 n=6	'light burn' ash	140 mls /2 d for 24 d	12
T3 n=3 n=3	'severe burn' ash freeze/thaw ash control ash	140 mls /2 d for 12 d	6
T4	'severe burn' ash	140 mls /2 h for 16 h 140 mls /2 d for 8 d	8 4

Four types of water were used for the leaching - distilled and three types of artificial rainwater buffered to pH 3.5, 4.5 and 5.5. Rainwater collected in gauges at Ardverikie usually had a pH of c.4.5. All three experiments comprised 6 replicates with factorial combinations of 2 leaching intervals and 4 water acidities.

5.4.4 Results of Leaching Experiments

The series of experiments resulted in a large number of samples (in excess of 400) for radiocaesium determinations. It was decided, therefore, to test the effects of the different rainwaters on two complete sets of replicates taken early and late in the leaching sequence. In neither case did analysis of variance show any significant differences in the amounts of radiocaesium leached from the ash by water of differing pH. Measurements of pH taken after leaching showed that in all cases the leach water was quite alkaline with a pH value ranging from 9.5 to 10.1. It is suggested that the small amount of buffering capacity in the artificial rainwater was completely swamped by the solutes in the ash. In view of this result, and the need to reduce the counting load, the radionuclide determinations were only carried out on the ash leached by artificial rainwater water of pH 4.5. This pH was representative of that measured in the rainwater at the experimental sites.

The results of three of the leaching experiments are shown graphically in Figure 8.

Although absolute quantities leached are different a similar pattern of release occurs irrespective of the interval between leachings. The amount released is greater at the second leaching for the 'light burn ash' in both experiments (Figure 8) and is probably due to the dry ash absorbing a large proportion of the water at the first application. This initial lower value was not found for the 'severe burn' ash. The difference was probably attributable to differences in initial ^{137}Cs activity concentrations and the physical characteristics of the two ash types. In all cases at the end of the first day, (8 x 2 h leaches), the amount of radiocaesium in the leachate had fallen to below 5 Bq per leach. There was a slight rise of about 4 Bq in the amount leached when the interval was extended to 2 d (leaches 9-12) indicating that some longer term weathering of the ash had taken place, this was not the case where a 2 d leach interval was used throughout the experiment. Towards the end of the experiment all treatments rose slightly probably due to warmer conditions in the greenhouse used for the experiment.

There is no significant difference between the amounts of radiocaesium released from the 'light burn' ash despite the two different leaching regimes (Table 11). The removal of radiocaesium resulting from 12 successive leachings is of the order of 21-24% of the total contained in the original heather ash. The bulk of the soluble ^{137}Cs activity is removed in the first few leachings; thereafter a small but steady amount is extracted by each subsequent leach.

When the 'severe burn ash' is considered the results are again consistent over the 6 replicates with a mean value of c.17% of the total soluble ^{137}Cs activity being removed during the 12 leaching treatments (Table 11). Although this value is somewhat lower than for the 'light burn ash' the absolute amounts released are much greater being three to four times as much for this type of ash.

A smaller experiment investigated the effects of freezing the ash between leachings using a 2 day interval between successive leachings (Table 12). In this case 'severe burn' ash was used and the percentage release agrees well with the previous experiments on this ash type. There appears to be no significant difference between the frozen and unfrozen treatments the amount released being 16-17% of the total in all cases.

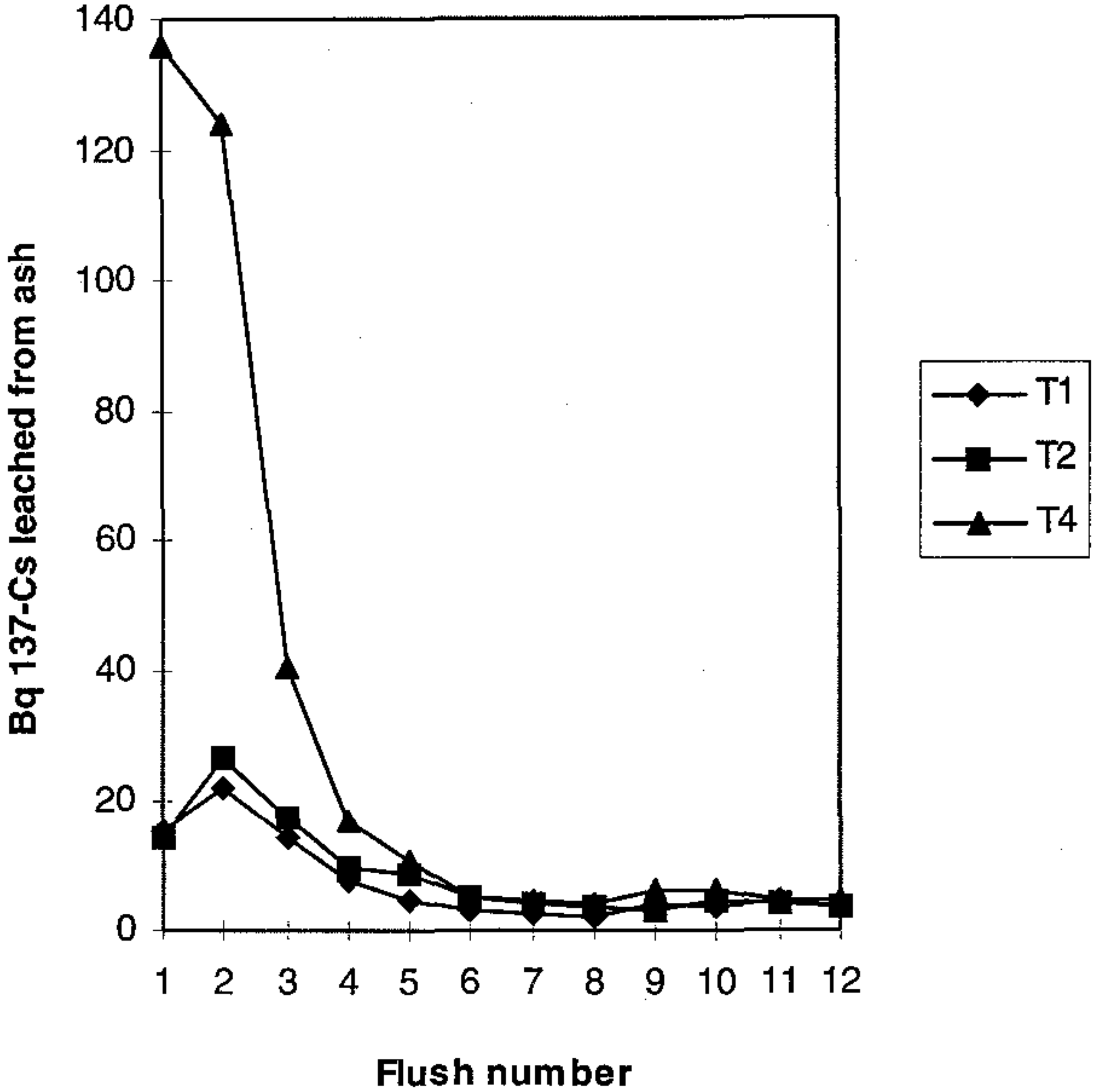


Figure 8. Rate of leaching of ^{137}Cs from heather ash (for treatment details see Table 10).

5.4.5 Conclusions

The experiments on heather burning and the subsequent leaching of the resultant ash have demonstrated that these are important mechanisms for the remobilisation of radiocaesium. Depending on the temperature of the fire between 10 and 40% of the radiocaesium in the standing crop of heather will be removed from the site and presumably redeposited elsewhere depending on weather conditions. The ash contains soluble material and within a relatively short period this will be removed by rainfall.

The timing of the heather burning as a management tool will have an important effect upon the fate of the leached radiocaesium. Under autumn conditions plant growth is at a minimum and rainfall high. There will be a greater chance that the radiocaesium will pass down the soil profile beyond the rooting zone. In the case of a spring burn there is more chance that the material might be taken up during regrowth and recycled into the vegetation. There will, of course, be a marked effect of soil type on this movement as has been illustrated by the lysimeter experiment at Banchory. Movement in the peaty profiles can be expected to be greater than on soils with an inorganic matrix of mineral particles. The severity of the fire is also important. Light burns, which leave the moss and litter layers intact, should be avoided as these layers can act as a 'sink' for radiocaesium leached from the ash.

Table 11 ^{137}Cs activity concentrations leached from light and severe burn ash under different watering regimes using artificial rainwater buffered to pH 4.5.

Experiment	^{137}Cs in ash Bq l^{-1}	^{137}Cs leached from ash Bq l^{-1}	^{137}Cs leached from ash %	Total ^{137}Cs in system Bq l^{-1}
T1 - light burn' ash, 140 mls every 2 hours for 16 hours (8 leaches) then 140 mls every 2 days for 8 days (4 leaches)				
R1	262	81	24	344
R2	285	80	22	365
R3	301	93	24	393
R4	227	87	28	314
R5	285	92	24	377
R6	306	95	24	401
Mean	278	88	24	366
Std dev	29	6	2	33
T2 - 'light burn' ash, 140 mls every 2 days for 24 days (12 leaches)				
R1	280	94	25	374
R2	432	98	19	530
R3	388	104	21	492
R4	298	95	24	392
R5	410	93	19	504
R6	405	101	20	506
Mean	369	98	21	466
Std dev	64	4	3	66
T4 - 'severe burn' ash, 140 mls every 2 hours for 16 hours (8 leaches) then 140 mls every 2 days for 8 days (4 leaches)				
R1	1944	371	16	2315
R2	1333	327	20	1660
R3	2112	442	17	2554
R4	2131	350	14	2481
R5	1493	375	20	1868
R6	1852	318	15	2168
Mean	1811	364	17	2174
Std dev	329	45	3	351

Table 12 ^{137}Cs activity leached successively (every 2 d) from freeze/thaw and control 'severe burn' samples (22 g) using artificial rainwater buffered to pH 4.5

	Freeze/thaw			Control		
Leach N°	**Ash 1**	**Ash 2**	**Ash 3**	**Ash 4**	**Ash 5**	**Ash 6**
L1	138	109	167	96	148	111
L2	199	278	179	143	208	161
L3	97	69	80	53	111	99
L4	35	36	34	22	60	45
L5	20	23	19	51	30	27
L6	12	19	16	27	14	18
Total ^{137}Cs leached	501	534	495	421	572	460
^{137}Cs in ash residue	3295	2703	2705	2195	2697	2039
% leached	13.2	19.5	15.5	16.1	17.4	18.4
Mean % leached	-	16.1	-	-	17.3	-

6 RADIOCAESIUM METABOLISM IN RED GROUSE

6.1 INTRODUCTION

Heather dominated systems in Scotland, and also some parts of northern England, provide direct radionuclide pathways to man via animal tissues. From an agricultural viewpoint sheep meat is the main product but two other natural sources are particularly important. These are red deer and grouse. All three graze heather but red grouse, feeding almost exclusively on the young heather shoots, will probably have the highest radiocaesium intake. A survey carried out shortly after Chernobyl showed that concentrations of nearly 3000 Bq kg^{-1} fw of ^{137}Cs could be found in the fresh breast muscle of the birds.

Advantage was taken of the presence of captive birds at the Banchory Research Station to investigate the role the grouse could play in heather dominated systems. At the same time the biological half-life of radiocaesium in the bird was determined under experimental conditions.

6.2 EXPERIMENTAL DESIGN

The birds were fed an experimental diet containing contaminated heather (Table 13), until their ^{137}Cs content had reached equilibrium. This was taken to be when whole-body counts had reached a maximum and had remained the same for three bi-weekly counting sessions. The assumption of equilibrium was later checked by ^{137}Cs balance calculations comparing differences between food intake and faecal output. At equilibrium some birds were killed so that the ^{137}Cs activity concentrations and content of tissues could be determined and transfer coefficients calculated. The remaining birds were transferred to an uncontaminated oat based diet with a negligible radiocaesium activity (<1 Bq kg^{-1} dw). The rates at which they excreted radiocaesium was used to estimate i) the biological half-life of radiocaesium in the birds ii) the turnover rates of radiocaesium in the bird's tissues at equilibrium and iii) the true absorption at equilibrium.

Table 13 Composition of Diets

Experimental Diet	%	Standard Diet	%
Dried heather	60	Oats	60
Wheat	12	Wheat	12
Grass meal	12	Grass meal	12
Fish meal	6	Fish meal	6
High protein Soya	6	High protein Soya	6
Soya oil	1.6	Soya oil	1.6
Lime	1.2	Lime	1.2
Dicalcium phosphate	0.5	Dicalcium Phosphate	0.5
Vitamin & Minerals	0.5	Vitamin & Minerals	0.5
Salt	0.2	Salt	0.2

6.3 MATERIALS AND METHODS

Heather was cut by hand in winter (January-March) 1991 from a site near Loch Laggan, (National Grid reference NN 528915), known to be contaminated by Chernobyl fallout (see 2.2). Only the tips of the plants, 5-10cm in length were fed to the grouse. After drying, in a forced-draught oven at 40°C for three days, the heather was milled to pass a 1.5mm mesh and incorporated into pelleted diets containing 60% heather.

Twelve captive-reared adult red grouse, six males and six females, were housed in individual cages within an aviary. The cages had a welded mesh floor (area 0.4 m^2) which allowed faeces to be collected from a tray situated under the cage. Food intake and faecal output were measured twice weekly throughout the experiment. Samples of food and the entire output of faeces were collected and stored for analysis. All material was dried and weighed prior to analysis and with the exception of bird tissues, which were analysed fresh, all results are expressed on a dry weight basis.

Radiocaesium levels in live birds were measured by whole body counting. For each measurement the bird was put into a darkened plywood box, to reduce stress, of dimensions 30cm x 15cm x 15cm whish was positioned directly over a 3" sodium iodide crystal. Counts in the ^{137}Cs channels were recorded on a Canberra series 20 multi-channel analyser for a period of 1000 s.

The birds were fed the experimental diets for 35 d. Whole body counts had stabilized at their maximum level after 21 d and radiocaesium balances were not significantly different from zero after 23 d. At 35 d two cocks and hens were killed to measure equilibrium of ^{137}Cs in their whole carcases. The remaining eight birds were then fed the oat-based diet for 35 d by which time the radiocaesium in the faeces had fallen to 5% of the amount at equilibrium on the experimental diet. All radionuclide analyses were carried out as outlined in section 3.4. Transfer coefficients (F_f) were calculated as the activity concentration of the tissue (Bq kg^{-1} fw) at equilibrium divided by the daily intake of radiocaesium (Bq d^{-1}) as defined by Ward & Johnson (1986).

6.4 RESULTS

6.4.1 Carcase burdens and transfer coefficients

The heather-based diet contained 120±3 and 1370±25 Bq kg^{-1} dw of ^{134}Cs and ^{137}Cs respectively, whereas the uncontaminated oat-based diet contained < 1 Bq kg^{-1} dw of each isotope. The carcasses of the four sacrificed birds contained 200±14 (SEM) Bq ^{137}Cs. The pectoral muscles from the four birds, at equilibrium, contained an average of 435±71 Bq kg^{-1} fw ^{137}Cs and 36±6 Bq kg^{-1} fw ^{134}Cs and the transfer coefficients were therefore 9.2±1.6 and 9.4±1.7 d kg^{-1} respectively.

6.4.2 Radiocaesium excretion by experimental red grouse

Faeces from birds on the experimental diet would have contained radiocaesium from two separate sources i) that from the diet which had not been absorbed by the gut and was excreted directly into the faeces and ii) that excreted from the tissues and endogenously excreted into the gut and subsequently lost in the faeces. The first faeces collected after the change in diet contained some ^{13}Cs activity from the contaminated diet. Subsequent collections were used to calculate ii), ignoring the negligible amount in the oat-based diet. Values of ii) were extrapolated back to the beginning of the decontamination period, thereby giving estimates of that passing through the tissues of the bird at equilibrium. The latter must have been equal to the net amount of radiocaesium absorbed by the bird's tissues from the contaminated diet at equilibrium. Hence, expressed as a proportion of the total amount of radiocaesium excreted at equilibrium from both sources, it provided an estimate of the proportion of ingested radiocaesium absorbed by the bird (the true absorption). From the rate at which this value decreased the turnover rate and biological half-life of radiocaesium was also calculated. Regressions of $\log_e$(Bq $bird^{-1}$ d^{-1}) excreted on the oat-based diet were respectively :-

a) $\log^{137}Cs=2.403(\pm0.073)0.0682T$ (±0.0032) $(R^2=0.87)$

b) $\log^{137}Cs=-0.106(\pm0.081)0.0649T$ (±0.0038) $(R^2=0.83)$

The intercept for the ^{137}Cs equation was greater than that for the ^{134}Cs because the birds had eaten more ^{137}Cs and secreted more from their tissues (11±0.8 Bq day^{-1} vs 0.9±0.08 Bq day^{-1} at day 0 on the oat based diet). The slopes were almost identical, as can be seen from a) and b) (Figure 9) because the rate of excretion of both isotopes was the same. Residuals from neither equation showed any clear pattern, and in particular there was no indication of a slow release component due to longer retention in other tissue compartments.

Analysis of covariance with individual bird as the class variable showed significant bird effects ($F_{1,60}=4.37, P=0.0006$:$F_{1,55}=3.96$, $P=0.0015$ respectively): this meant that different birds excreted different amounts of radiocaesium (intercepts differed between birds). There was however, no significant bird x time interaction: hence the rate at which the excretion rate declined did not differ detectably between birds (slopes did not differ between birds). This analysis increased R^2 values only marginally relative to the simple regression equations in a) and b) above (0.91 and 0.89) respectively) and gave very similar estimates for slopes (-0.0679±0.0028, P= 0.0001 and 0.0649±0.0038,P 0.0001.)
From these slopes it was calculated that the amount of radiocaesium excreted fell by 6.6±0.4% a day, giving a biological half-life of 10-11 days.

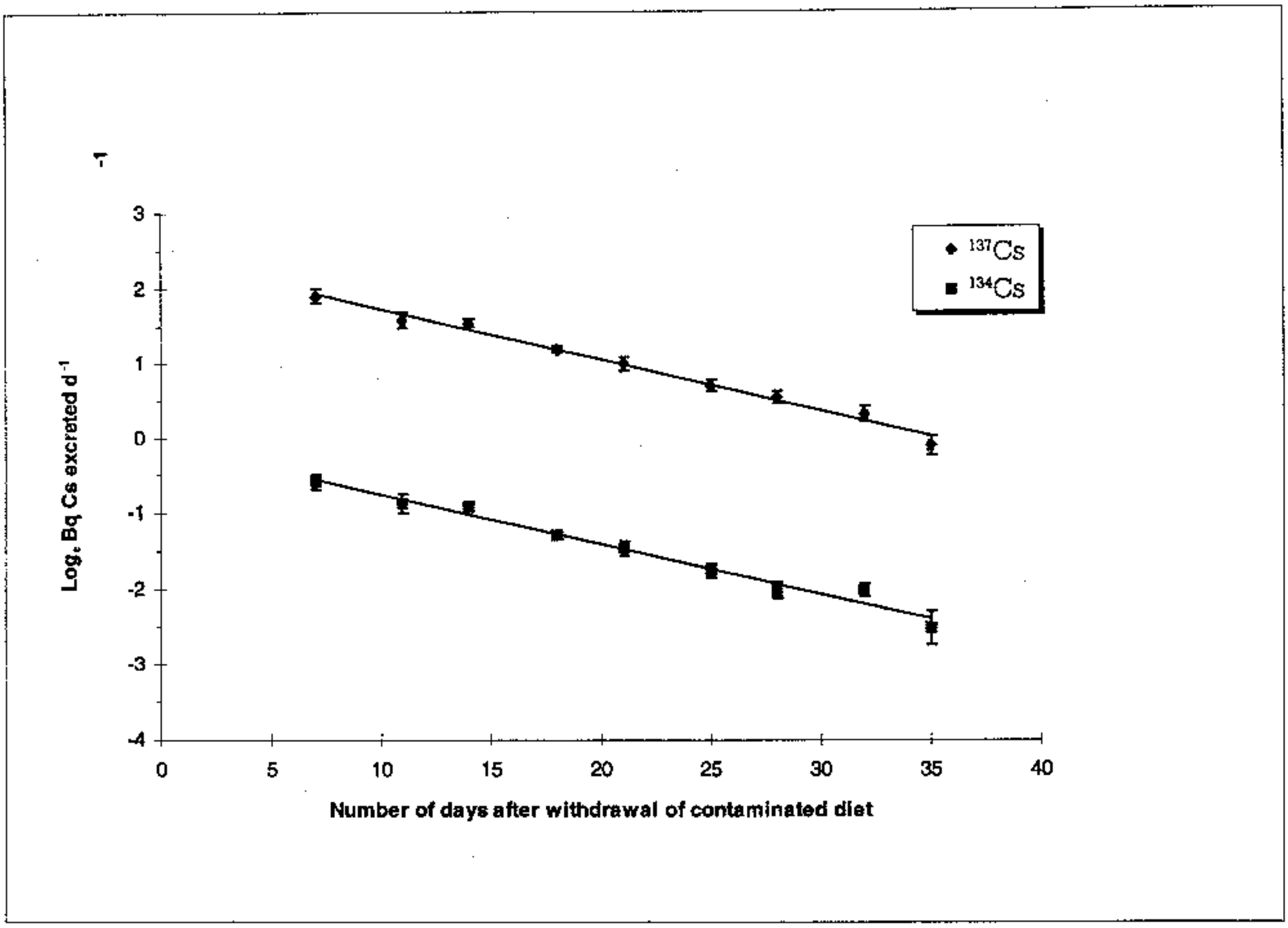


Figure 9. ^{137}Cs and ^{134}Cs activity concentrations in grouse faeces after withdrawal of contaminated diet

Comparisons of the calculated output from the birds' tissues at day 0 (ie the intercepts in the above regression equations) with the amounts of radiocaesium actually present in the faeces (ie unabsorbed radiocaesium and that excreted from the tissues into the gut) indicated that at equilibrium 23% of the ^{137}Cs in the faeces was endogenously secreted by the birds and 77% derived directly from the diet. Since at equilibrium absorbtion and secretion must have been the same, the true absorption of radiocaesium at equilibrium was also 23%.

6.4.3 Comparison with wild red grouse

Radiocaesium content of the food (largely heather) in the crops of shot wild birds was compared with that of their pectoral muscles (Figure 10). Using data from 11 birds the regression equation for ^{137}Cs was:-

$$\text{Flesh} = 0.503(\pm 0.117)\text{food} + 221(\pm 200) \quad (R^2=0.67)$$

When the values from the experimental birds' food (1370 Bq ^{137}Cs kg^{-1}) was inserted in the above equation the mean predicted concentrations in pectoral muscle (911±96 Bq) was greater than the observed value (436±71 Bq) for the experimental birds. This could have been partly because wild birds eat more each day (55±2 g), calculated from Savory 1978) than the experimental birds (35±2 g) by a factor of 1.58±0.11.

Transfer coefficients (F_f) can be calculated for wild birds by assuming i) that the birds last meal was a representative sample of their previous diet and ii) that the birds were at equilibrium for radiocaesium. The F_f value for wild birds was 13.2±2.1 d kg^{-1} for ^{137}Cs which is not significantly different from the transfer coefficient for the experimental birds.

6.4.4 Discussion

Estimates for the biological half-life of radiocaesium during this study are broadly comparable with the previous reports available for undomesticated birds. In bobwhite quail (*Colinus virginianus*) Anderson, Dodson & Van Hook (1976) found that the

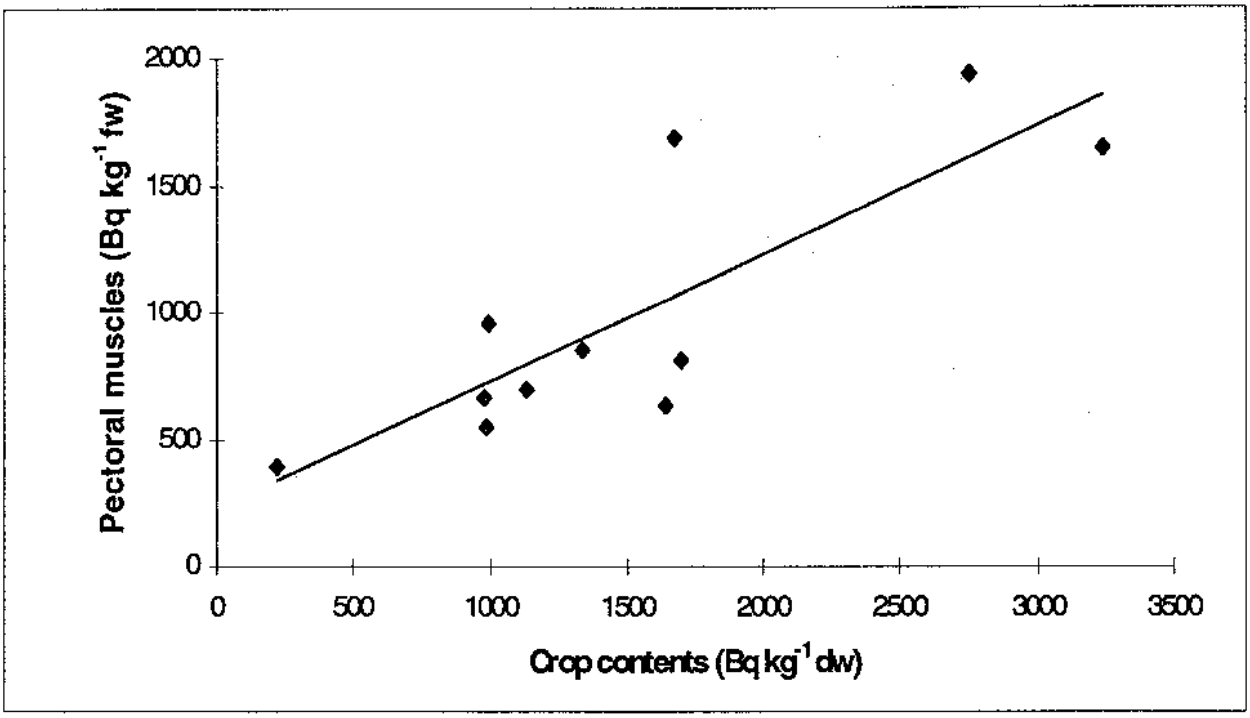


Figure 10 Comparison of ^{137}Cs activity concentrations in pectoral muscles and crop contents of wild grouse

body burdens of ^{137}Cs began to approach equilibrium after 21 days of feeding, which is similar to the present results. The same authors also found that the biological half-life of ^{137}Cs was 10-11 days, again very similar to the present result. Fendley, Manlove and Brisbin (1977) worked with wood ducks (*Aix sponsa*) and found a biological half-life for radiocaesium of about 6 days. This might indicate a difference in metabolism between avian orders since quail and grouse are both galliforms while wood ducks are anseriforms. More data would be required to confirm this suggestion.

About 77% of the radiocaesium ingested by the experimental birds was excreted directly without passing through the tissues. so the true absorbtion was about 23%. This value only applied to this experiment and could vary with different diets, with different foodstuffs and with different species. This represents a very low absorption rate for radiocaesium, compared with mammals where absorption for plant incorporated radiocaesium is generally over 75% (Beresford *et al.* 1992).
Heather is an unusual food for birds, being low in protein and phosphorus, fibrous, indigestible and rich in tannins (Moss & Hanssen, 1980). It might therefore be expected that transfer rates from red grouse would differ from other birds. Previous reports for domestic hens give values ranging between 1.4 and 9.5 d kg^{-1}, (Voigt *et al.* 1993) hence the value reported here, of 9.2 d kg^{-1} are at the higher end of the reported range. Recent data for Chernobyl fallout for other birds are sparse, but for domestic hens Ff values of 1.2 d kg^{-1} for leg muscle and 1.6 d kg^{-1} for breast muscle when the hens were fed on contaminated grass pellets, and higher values of 2.8 d kg^{-1} for leg muscle and 3.2 d kg^{-1} for breast muscle when the hens were fed on contaminated wheat have been reported by Voigt *et al.* (1993).

The data provided no indication of compartments with longer retention times ie the kinetics of radiocaesium excreted by red grouse appeared to be first order. If so, then (Ward & Johnson, 1986) at equilibrium

$$al=kq$$

where a is the assimilation fraction, l intake in Bq d^{-1}, k the effective biological rate constant and q Bq the total activity of the radionuclide in the compartment of interest. Here the compartment is the entire body and kq was empirically determined from the intercept of the regression of ^{137}Cs output upon time) to be 11 ± 0.8 Bq d^{-1}. The amount of ^{137}Cs in the carcases of the 4 birds sacrificed at equilibrium was 201 ± 14 Bq and the proportion excreted (from the slope of the regression of ^{137}Cs output upon time) 0.066 ± 0.004 d^{-1}. A separate estimate of kq, assuming first order kinetics, was therefore

$$201\pm14 \text{x} 0.066\pm0.004=13\pm1.$$

These values are not significantly different, confirming that the observed rate of excretion did not differ detectably from first-order kinetics.

Red grouse are likely to be good indicators of radiocaesium contamination in British upland ecosystems. Concentrations in pectoral muscle from wild grouse reflect concentrations in their heather diet, and heather accumulates high concentrations of radiocaesium relative to other plants. Grouse shot as game are readily available from sporting estates and could form the basis of a sensitive and inexpensive monitoring network.

7 MODELLING THE RADIOCAESIUM DYNAMICS OF HEATHER DOMINATED ECOSYSTEMS

7.1 INTRODUCTION

Previous collaborative work between ITE and the University of Nottingham has led to the development of two models with relevance to radioecology which continue to be the focus of considerable research effort.

- RUINS: A soil-sward-grazing model for radiocaesium transfer.
- The Galer model for the radiocaesium metabolism of sheep (Galer *et al.* 1993)

In this project the techniques and approaches used to develop RUINS have been applied to the case of heather dominated ecosystems, rather than the grassy vegetation (ie mixed swards) to which it was previously applied.

As shown in Figure 11 RUINS considers the soil as a series of layers, each sub-divided into three compartments representing three soil phases, solution, labile and non-labile. Only radiocaesium in the solution phase is available for plant uptake, although the solution is in an effectively instantaneous dynamic equilibrium with the labile compartment. Rate coefficients describe transfer between the labile and non-labile compartments, simulating a time dependent fixation process. Downward flow of radiocaesium occurs between solution compartments on the basis of water flow.

Plant uptake is controlled by plant growth which is calculated by a simple sward growth model, driven by light and temperature. Radiocaesium is lost from the sward, either by senescence and litterfall, or by grazing. Translocation of radiocaesium during senescence is simplistically considered and gives rise to interactions between sward radiocaesium concentration and grazing intensity.

Radiocaesium deposited externally on plant surfaces is distinguished from that absorbed via the root system. This enables differential bioavailability of fallout to be considered if necessary. External radiocaesium is removed via a process of weathering and leaf turnover.

A simplified version of Galer's sheep radiocaesium model is included in RUINS to predict sheep muscle radiocaesium concentration.

Elements of the RUINS model are currently the subject of further study and experimental work.

- The soil kinetics in the model have been intensively studied by Absalom *et al.* (in press) for a range of upland organic soils. This has led to modification of the model and experimental determination of the kinetic parameters (see below 7.4).

- The grazing interaction with radiocaesium concentration is being investigated at Stirling University (Salt, pers comm) and GSF (Voigt, pers comm).

- The transport of radiocaesium downwards through the soil profile is poorly modelled at present. It is hoped to incorporate improved methods for water transport and hydrodynamic dispersion into the model. This work is at a very early stage.

7.2 OBJECTIVES OF THE MODELLING WORK

The modelling work described here has had the following objectives.

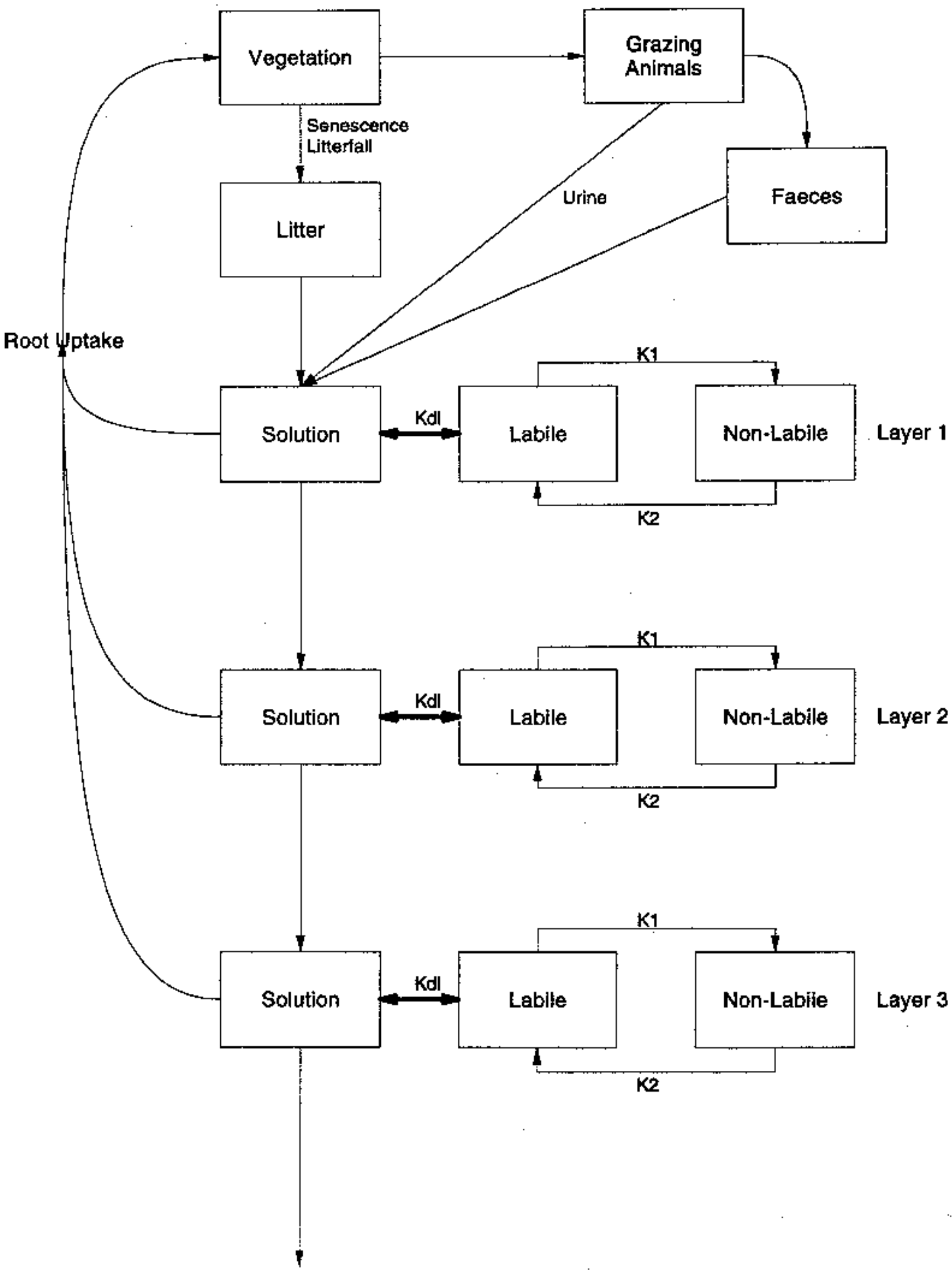
- To use the data collected by Horrill *et al.* (Sections 1 - 6) to develop a simulation model which describes the dynamics of radiocaesium in heather dominated ecosystems.

- To ensure that the model is sufficiently self-contained and simple that it can be usefully applied.

- To include in the model consideration of important heather management systems (ie burning).

- Discuss the limitation and reliability of the model and indicate what further work would be required to improve its use.

Figure 11 Schematic representation of the RUINS model



- Provide a standalone model implementation for PC-Windows 3.1 with outline documentation.

7.3 MODELLING APPROACH

Careful consideration has been given to the approach used to achieve the above objectives making best use of the available data. The nature of the project is such that it has not been possible to follow an ideal model development approach such as that shown schematically in Figure 12.

In this case the modelling work has been undertaken after the completion of the field work. There was no possibility for the requirements of model development to influence the experimental programme. Whilst the data set is comprehensive it is quite limited in terms of replication and time span. Obviously this is due to the restrictions of time and resources, but given the variability inherent in semi-natural systems it limits the detail possible in the modelling work.

There are also some limitations of the previous RUINS work (indicated above) which mean that it cannot be widely applied without considerable effort in terms of parameterisation. This is particularly the case with the leaching of radiocaesium from the soil profile and characterisation of the soil kinetics.

It was therefore decided that a highly pragmatic approach to the heather model would be required. A simple scheme would be devised which could describe the data reasonably well with the minimum of detail, in particular the soil description would be simplified from that used in the full RUINS model.

The greatest limitation of this work is that the data sets available do not allow for effective 'validation' of the model without further study. As shown in Figure 12 this is an important step in developing a reliable simulation model. Therefore extra effort has been devoted to determining the reliability of the model (see 7.), and we urge caution in the use of the model. It should be regarded as illustrative rather than predictive.

7.4 MODEL DESCRIPTION

To develop the model the heather moorland ecosystem has been broken down into a number of sub-components. Each of these has been modelled separately with linkages where appropriate. The key features are:-

- A heather biomass model which simulates the distribution of biomass within the heather canopy as a function of time. The biomass categories considered correspond to those defined by in the field studies.
- A radiocaesium uptake and distribution sub-model whose principal assumption is that radiocaesium flux within the heather canopy follows dry weight fluxes calculated by the biomass model.
- An initial deposition sub-model which deals with the situation immediately following a fallout event when a proportion of the radiocaesium will be intercepted by the heather canopy before being washed to the soil surface.
- A soil kinetics sub-model which simulates the dynamics of radiocaesium bioavailability within the soil and leaching from the soil profile.
- A grazing sub-model which considers the transfer of radiocaesium from the heather canopy to grazing animals (lambs) and birds.

Each of these is described below together with their assumptions in relation to the field data presented above.

Throughout the models have been developed using the ModelMaker simulation system and in addition to the standalone software the original ModelMaker files are also provided. These provide complete access to the model's relationships and parameters.

7.4.1 Heather Biomass Sub-Model

It is not the objective of this work to predict the biomass fluctuations of heather canopies, the biomass model is required only to provide inputs to the radiocaesium transfer sub-model.

Figure 12 Idealised Development Process for a Simulation Model

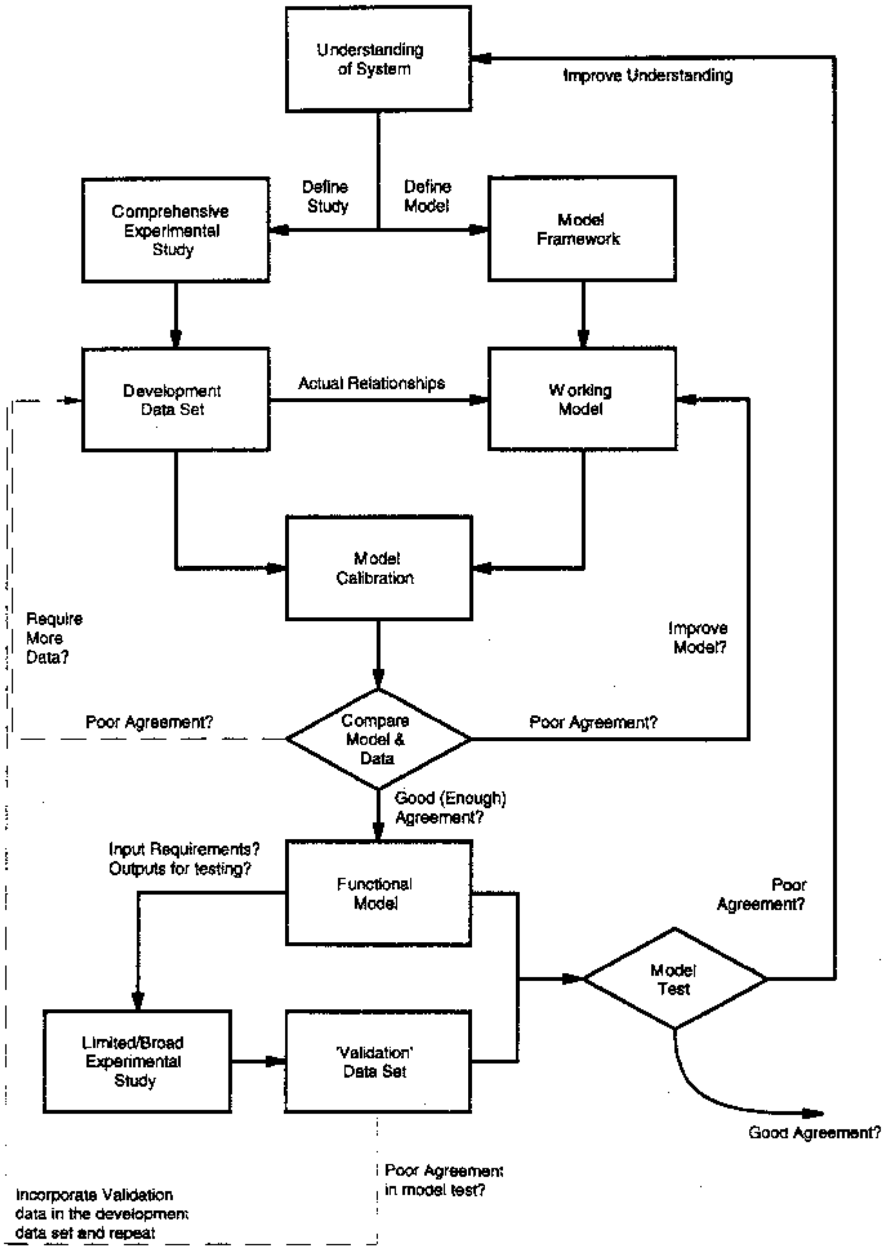
This schematic shows experimental and modelling work as part of the same process, not as separate activities.

The existing understanding of a system defines a model framework and an experimental programme to measure its behaviour. Defining the model and experimental work would ideally be done in parallel.

The experimental study results in a data set which can be used for model building. The model framework leads to a working model whose relationships are derived from the development data set.

Model development (or 'calibration') proceeds by making comparisons between model predictions and the data, adjusting both the model's parameters and equations. This process is quite likely to require additional data from the experimental programme.

When the model simulates the experimental data accurately (or more commonly, the agreement is 'good enough') then the functional model exists and this can be tested or 'validated'.



This functional model will have input requirements and will calculate one or more key outputs. These can be used to define an experimental programme for model testing. These experiments need only satisfy the input requirements of the model and measure the key outputs the model calculates. The experiments can therefore be more limited than those used to generate the development data set. However the validation experiments should be broad, covering a wide range of circumstances and situations.

The validation data set is compared to the corresponding model predictions. If the agreement is good (enough) then a reliable and robust model has been developed. If the agreement is poor, then it is back to the drawing board. The understanding of the system may need to be revised, the development data is expanded to include the validation data and the cycle is repeated. In this case the validation exercise will need to be repeated with new data. A model should not be 'tested' against its 'development' data.

Table 14 Observed biomass data for heather canopy components ($g\ m^{-2}$ dw); SEs calculated from SD between the two sites

	CYG	PYG	Dead	Wood
June 1989	58±12	62±9.0	141±43.0	440±43.0
August 1989	134±6.0	77.5±5.0	65±6.0	471±8.0
March 1990	198±15	29±6.5	75±13	685±105

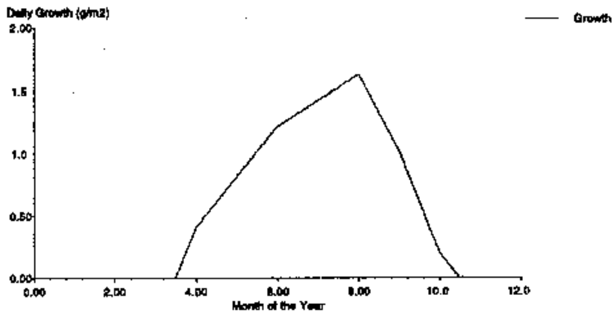


Figure 14 Annual variation of daily biomass production

A very simple approach has been taken, justified by the limited data which is available. This is similar to work by Armstrong & MacDonald 1992; Grant & Armstrong 1993 in the MLURI hill vegetation growth model.

From the field data it was noted that the heather biomass was similar between the 2 sites (Table 4), the only major differences being the 'wood' observation in March 1990 and the 'dead' observation in June 1989. Of particular note is that at both sites an annual biomass production of about 200 $g\ m^{-2}$ occurred. Because of these similarities it was decided to pool the data and develop a biomass model which adequately describes growth at both sites. The pooled data, derived from Table 4 is shown in Table 14.

The biomass model is shown schematically in Figure 13, it consists of a series of compartments representing the categories measured in the field. New growth is added to the CYG compartment and transfers of dry matter occur as shown. The relationships used for the various processes are described below.

Following the approach of Armstrong & MacDonald 1992 new growth is assumed to be distributed throughout the year according to temperature, such that growth is proportional to temperature above 4°C. Below this temperature no growth occurs. Using typical meteorological data it is then possible to calculate the proportion of the annual growth that will occur for each day of the growing season, as shown in Figure 14.

This new growth is added to CYG ($g\ m^{-2}$) whose value is given by

$$\frac{dCYG}{dt} = f_g G - r_{cyg} CYG$$

where

f_g is the proportion of annual growth per unit time, as shown in Figure 14

G, is the annual biomass production, 200 $g\ m^{-2}$

r_{cyg} is a rate coefficient (d^{-1}) describing the transfer of heather biomass from the CYG to PYG category.

The value of r_{cyg} varies as shown in Figure 15. This has the effect of moving the contents of

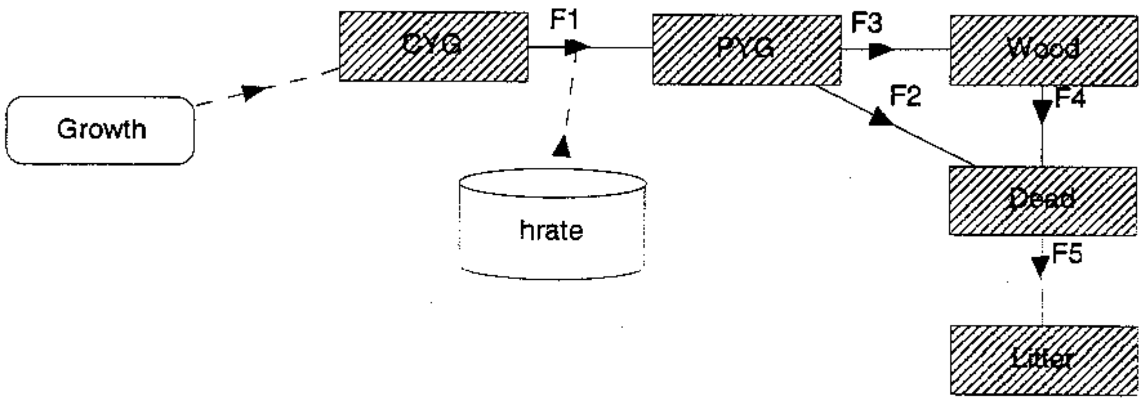


Figure 13 Schematic Layout of the Heather Biomass Sub-model

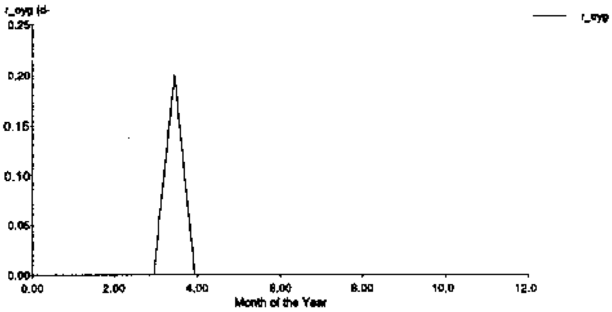


Figure 15 Variation of r_{cyg} during the year

CYG into PYG during the early spring, which is the basis on which the field classification has been carried out.

The previous years growth, PYG (g m^{-2}), is given by

$$\frac{dPYG}{dt} = r_{cyg}CYG - r_{pyg}CYG^2$$

where

r_{pyg} is a rate coefficient (d^{-1}) controlling the removal of material from PYG.

The power term is used because the PYG component appears to decline rapidly during the early part of the season, but more slowly later in the season. Some of the lost PYG is added to the dead compartment, the remainder becomes wood. The basis of this is outlined below.

The wood compartment is modelled by

$$\frac{dwood}{dt} = r_{pyg} f_{wood} PYG - r_w wood$$

where

r_w is a rate coefficient (d^{-1}) controlling the death of woody material.

f_{wood} is the fraction of PYG which becomes woody (see below)

The dead compartment is modelled by

$$\frac{ddead}{dt} = r_{pyg} 1 - f_{wood} PYG + r_w wood - r_d wood$$

where

r_d is a rate coefficient describing the transfer of dead material to the litter layer (d^{-1}).

A reasonable value for f_{wood} can be estimated on the basis of the relative radiocaesium concentration observed in Wood, PYG and Dead. Assuming that there is no translocation of radiocaesium from dying PYG and wood and that the residence time of dead material is quite short, the dead concentration [dead] will be

$$[dead] = 1 - f_{wood}[PYG] + f_{wood}[wood]$$

therefore

$$f_{wood} = \frac{[dead]-[PYG]}{[wood]-[PYG]}$$

where

[PYG] and [Wood] are the radiocaesium activity concentrations in the PYG and Wood compartments respectively.

This can be calculated for the 6 observations that have been made in the field, giving values around 0.8-0.9. A value for f_{wood} of 0.85 was therefore chosen for use in the model.

Values for r_{pyg}, r_w, and r_d were chosen on the basis of a model calibration which adjusted the coefficients to give reasonable agreement between the observed and modelled biomasses. Final values were r_{pyg}=7.5×10^{-6}, r_w=0.001 d^{-1}, and r_d=0.01 d^{-1}.

When this model is run from initial conditions of CYG=PYG=wood=dead=0.0 (ie a new canopy) a process of heather 'building' is observed. The wood biomass in particular takes some 10-15 years to reach an equilibrium value.

Both heather stands studied here are sufficiently old to have reached this 'equilibrium', although in the field annual variation in climate etc. will give season to season variability not apparent in the simulations. Figure 16 shows the wood biomass, predicted and observed, over a 13 year period clearly demonstrating heather 'building'.

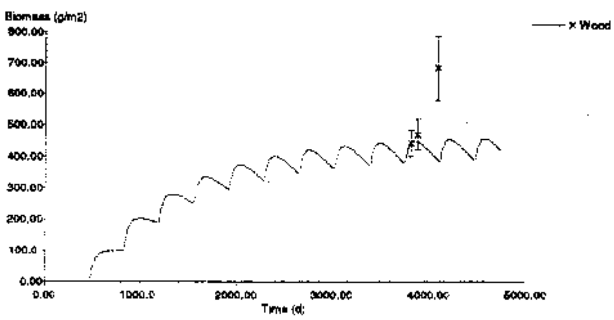


Figure 16 Build up of wood biomass over a 13 year period

Figures 17(a)-(d) shows the equivalent results for each compartment on an expanded time scale. The result for CYG is satisfactory, for dead performance is adequate given the variability in the data. The first two observations for wood are well modelled but the large increase in wood biomass between August 1989 and March 1990 is not reproduced. In the case of PYG the model diverges from observations early in the season but is satisfactory later.

Clearly a much wider range and detail of data would be required to further develop the model and it has evident limitations. Nevertheless it gives reasonable relative estimates of biomass of the various compartments. The crucial compartment in terms of radiocaesium transfers to the food chain is CYG and this is well simulated. The biomass model was therefore deemed to be satisfactory for the purposes of this project.

7.4.2 Radiocaesium Uptake and Distribution Sub-Model

This sub-model considers the uptake of radiocaesium by the heather canopy and its subsequent transfer within the plant. The transfers of dry matter calculated by the biomass sub-model are used to calculate the transfer of radiocaesium. A principal assumption of the model is therefore that radiocaesium 'follows' dry weight. For example the flow of radiocaesium from the CYG compartment to the PYG compartment, $Cs_{cyg-pyg}$, (Bq m^{-2} d^{-1}) is given by

$$Cs_{cyg-pyg} = \frac{dw_{cyg-dyg}}{dw_{cyg}} Cs_{cyg}$$

where

$dw_{cyg-pyg}$ is the flow of dry matter from cyg to pyg (g m^{-2} d^{-1})
dw_{cyg} is the dry weight of the cyg compartment (g m^{-2})
Cs_{cyg} is the radiocaesium content of the cyg compartment (Bq m^{-2}).

Equivalent equations are used for transfers from PYG to dead, PYG to wood, and wood to dead. The arrangement is shown schematically in Figure 18.

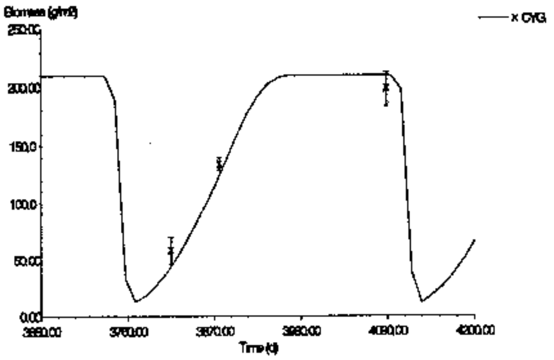


Figure 17a Biomass predictions and observations for the 'CYG' compartments

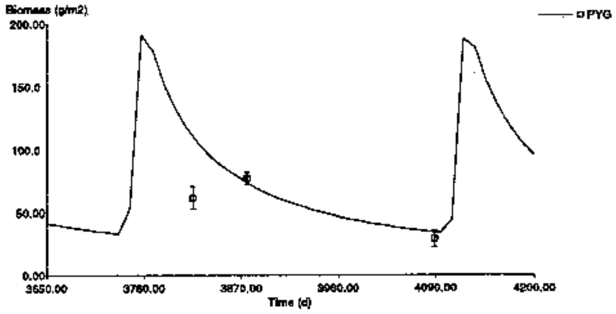


Figure 17b Biomass predictions and observations for the 'PYG' compartments

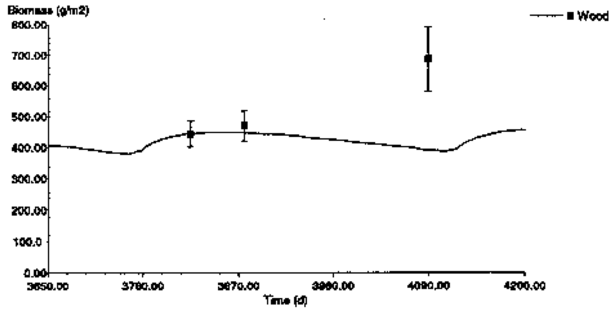


Figure 17c Biomass predictions and observations for the 'Wood' compartments

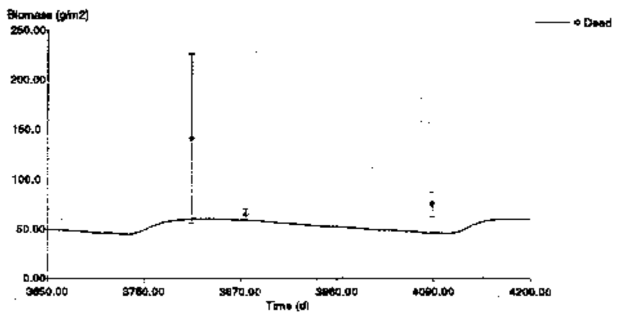


Figure 17d Biomass predictions and observations for the 'Dead' compartments

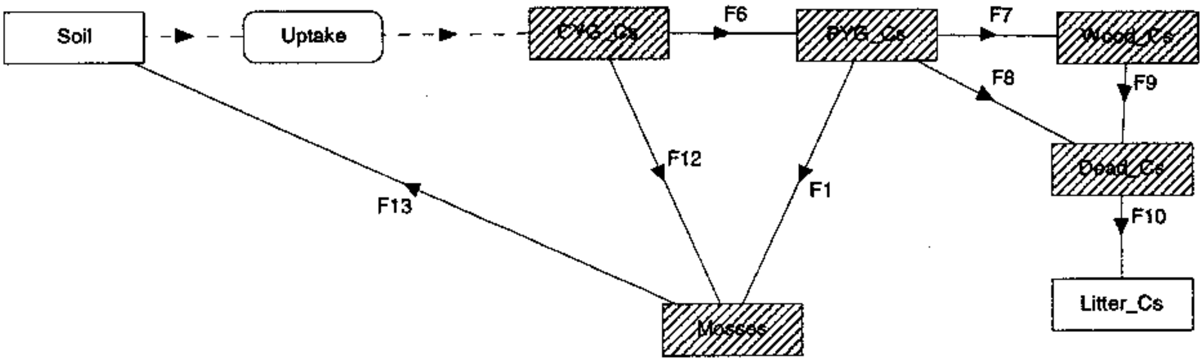


Figure 18 Schematic layout of the radiocaesium distribution model

Uptake, U (Bq m^{-2} d^{-1}), of radiocaesium from the soil by the roots is modelled by the same approach used in RUINS, it is proportional to radiocaesium present in the soil solution (Cs_{sol}) and the rate of plant growth, so

$$U = \alpha x Cs_{sol} x Growth$$

where α is a rate coefficient discussed below. This radiocaesium is added to the Cs_{cyg} compartment.

It is apparent in the field data that the activity concentration of radiocaesium in both PYG and CYG falls between August and March by about a factor of two (Table 4). There is expected to be very little uptake of radiocaesium in this period and it is a reasonable assumption therefore that Cs is being lost from the canopy via throughfall of rain water. This is further supported by the relatively high amounts of radiocaesium present in the bryophyte layer under the heather canopy. This is simulated by a compartment, *Mosses,* which is assumed to intercept throughfall and absorb it through external surfaces, such that

$$\frac{dMosses}{dt} = Throughfall - r_m Mosses$$

where
r_m is a rate coefficient (d^{-1}) whose value is discussed below.

Throughfall is the transfer of radiocaesium between CYG and PYG, given by

$$Throughfall = r_t(CYG + PYG)$$

where
r_t is a rate coefficient whose value, 0.0025 d^{-1}, is set to give the observed fall for the CYG and PYG compartments between August and March.

Summarising the differential equations for the Cs compartments

$$\frac{dCs_{cyg}}{dt} = U - Cs_{cyg-pyg} - r_t Cs_{cyg}$$
$$\frac{dCs_{pyg}}{dt} = Cs_{cyg-pyg} - Cs_{pyg-wood} - Cs_{pyg-dead} - r_t Cs_{pyg}$$
$$\frac{dCs_{wood}}{dt} = Cs_{pyg-wood} - Cs_{wood-dead}$$
$$\frac{dCs_{dead}}{dt} = Cs_{pyg-dead} - r_d Cs_{dead}$$

This model required calibration for the value of r_m. This was done by firstly assuming that the dynamics of radiocaesium in the soil have reached an effective equilibrium by the time of the field study, some three years after Chernobyl deposition (see 4.4). Secondly the model was calibrated in terms of the *distribution* of radiocaesium within the heather canopy, rather than its absolute values. This has the considerable advantage of separating the dynamics within the heather from the problem of uptake from soils with differing bioavailabilities, enabling the distribution data from the two sites (Table 4) to be pooled.

It is then possible to use a constant and arbitrary value of Cs_{sol} and take as 1.0 for the purposes of model calibration. The value of r_m was then adjusted to obtain the comparisons show in Figure19 (a)-(e).

Given the limited model calibration required for these comparisons, they depend largely on the biomass sub-model, the level of agreement is very encouraging. CYG is well modelled. Wood and dead show the correct

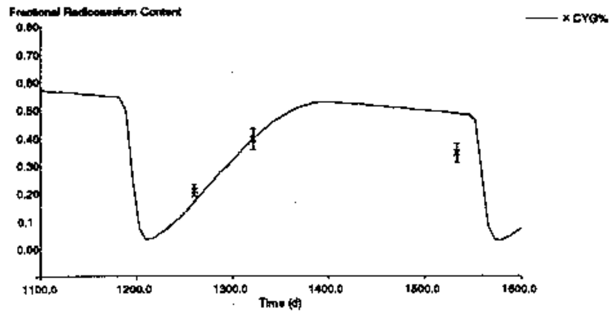


Figure 19a Modelled and observed distribution of radiocaesium in the CYG component of the heather system

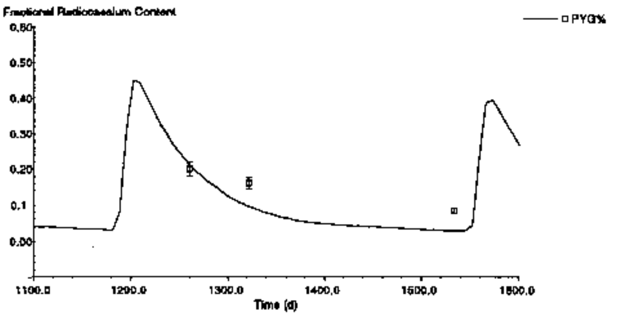


Figure 19b Modelled and observed distribution of radiocaesium in the PYG component of the heather system

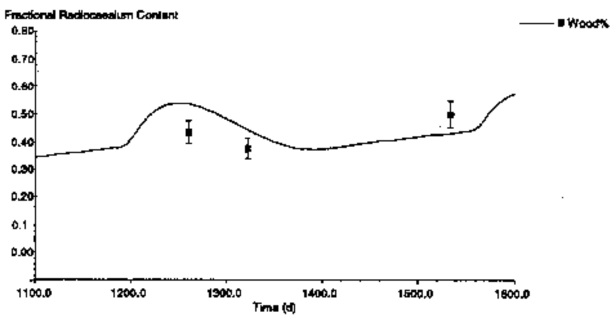


Figure 19c Modelled and observed distribution of radiocaesium in the wood component of the heather system

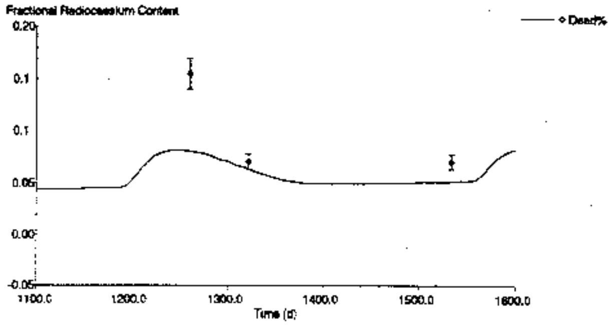


Figure 19d Modelled and observed distribution of radiocaesium in the dead component of the heather system

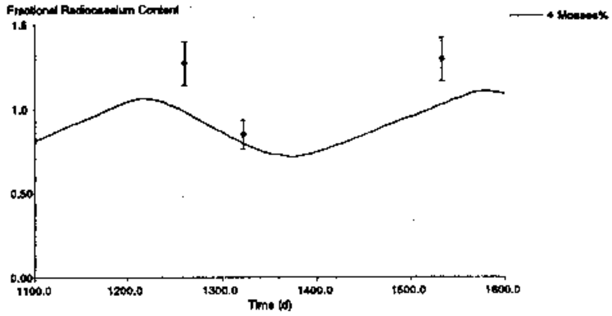


Figure 19e Modelled and observed distribution of radiocaesium in the moss component of the heather system

trends although the actual values are not reproduced, especially for the June 1989 measurement of dead. Similarly PYG shows and reasonable trend although the model under predicts later in the simulation. Most remarkably the comparison for the bryophyte layer shows good agreement in terms of trends.

Above we have described the simulation of radiocaesium distribution within the heather canopy. The magnitude of uptake is controlled by the uptake parameter. The value of this has been set to 0.02 by comparing modelled and observed uptake using the soil kinetic sub-model described below for the peat site. The same value was applied at the peaty podzol site. The factors which would affect this are not clear, certainly the nutritional status of the heather and its root length distribution are likely to be important.

7.4.3 Initial Deposit Sub-Model

When a deposition event occurs material may be deposited onto the soil, or directly on the external surfaces of plants. Many factors affect the relative distribution between plants and soil, including rainfall intensity and plant canopy density. These factors are not well understood although Chamberlain (1970) presents a relationship for plant fractional interception, f_i, in terms of canopy density

$$f_i = 1 - \exp(-\mu w)$$

where w is the herbage density (kg m^{-2}) and μ is a parameter whose value lies in the range 2.3 to 3.3 kg m^{2} . This relationship was developed for 'grassy' canopies and may not be appropriate for heather stands. Nevertheless we have applied it as there is little other information available. We have further assumed that all radiocaesium intercepted by a heather stand is attached to the shoots, ie either CYG or PYG. This is simply on the basis of heather morphology and is not supported by any observation data. The distribution between CYG and PYG is given by their relative biomass at the time of deposition, ie

$$f_i^{cyg} = \frac{CYG}{CYG + PYG} f_i$$

$$f_i^{pyg} = \frac{PYG}{CYG + PYG} f_i$$

where f_i^{cyg} and f_i^{pyg} are the fractional interception values for the CYG and PYG compartments respectively.

Once material has been deposited on the canopy it is removed by a process of weathering. This is modelled as a first order loss with a rate coefficient of 0.05 d^{-1}. This value is based upon observation by Ertel *et al.* (1989). Again it is based upon observation with 'grassy' canopies rather than heather stands and therefore may not be appropriate for heather but is the only information available.

Interception of initial deposit by the bryophyte layer has not been considered. We assume that everything not intercepted by the heather stand is deposited to the litter layer. Clearly this is arguable but there is no data available and any effect included would be pure speculation.

7.4.4 Soil Kinetics Sub-Model

The kinetics of radiocaesium in the soil needs to be considered as it has an important effect on the availability of radiocaesium in the soil for uptake by heather (and indeed, other vegetation).

The approach used draws heavily on work by Absalom *et al.* (in press) in which a number of possible models of radiocaesium behaviour in soils are proposed. These are shown schematically in Figure 20 and their essential features are outlined below

Model 1 - RUINS approach, Labile Non-Labile. The soil is divided into three pools, solution, labile and non-labile. Only radiocaesium in the non-labile pool is available for plant uptake or transport down the soil profile. Radiocaesium in the solution pool is assumed to be in a rapid and dynamic equilibrium with radiocaesium in the labile pool. This equilibrium is characterised by a distribution coefficient, k_{dl}. Radiocaesium transfers can occur between labile and non-labile pools controlled by first order kinetics with rate coefficients k_1 and k_2, respectively controlling the transfer from labile to non-labile and vice versa.

Model 2 - Fast-Slow Non-labile. This is an extension of model 1 and considers two stages of non-labile absorption. There is an additional non-labile compartment with first order transfers from the first non-labile compartment.

Model 3 - Labile, Non-Labile Diffusion. In this case rather than including an additional compartment to represent the observed dynamics of absorption in a purely empirical fashion a mechanistic diffusive transport is incorporated. This can be envisaged as planar solid phase diffusion into the clay mineral.

In Absalom *et al's.* study these models were applied to data obtained for 5 soils collected from sites in Cumbria. It was found that whilst Model 1 approximated the behaviour of these

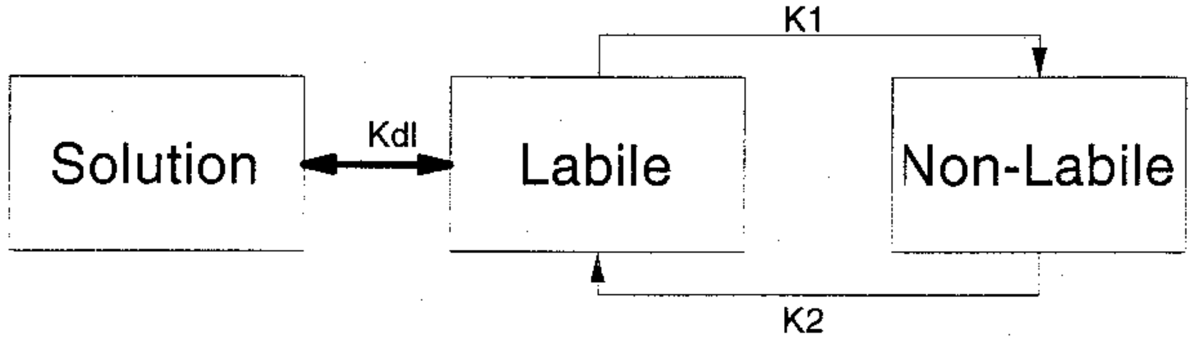


Figure 20 Schematic of Absaloms Model 1

soils both Model 2 and 3 gave good agreement with observation. Absalom *et al.* prefer the use of Model 3 as it is more mechanistically based, however in this work we shall utilise Model 2 because it is less numerically demanding to solve within a simple model.

The model is formally expressed as

$$S = \frac{L}{k_{dl}}$$

$$\frac{dL}{dt} = -k_1 L + k_2 N_1$$

$$\frac{dN_1}{dt} = -k_2 N_1 + k_1 L - k_3 N_1 + k_4 N_2$$

$$\frac{dN_2}{dt} = -k_4 N_2 + k_3 N_1$$

where

S, L, N_1, and N_2 are the radiocaesium amounts in the solution, labile, first and second non-labile compartments respectively (Bq).

k_{dl} is the distribution coefficient between solution and labile compartments

k_1, k_2, k_3 and k_4 are rate coefficients (d^{-1})

The values for the kinetic parameters derived by Absalom for 5 soils are given in Table 15.

Table 15 Soil kinetic parameters measured by Absalom (pers comm) for 5 Cumbrian Soils

Site	Soil Type	k_{dl}	k_1	k_2	k_3	k_4
Wastwater	Brown Podzol	32.8	0.045	0.029	0.0079	0.00046
Ennerdale	Brown Podzol	50.1	0.210	0.013	0.00022	0.00590
Corney 2	Raw Oligofibrous Peat	3.60	0.010	0.019	0.0025	0.0
Woodend	Humic Ranker	4.00	0.200	0.160	0.0290	0.00064
Sellafield	Brown earth	270	0.016	0.00058	0.0	0.0

An important feature of the parameters shown in Table 15 is the variation between soils of the same type (Brown Podzol, as defined by the soil map of Cumbria). It is hypothesised that this is because the radiocaesium kinetics of the soils is dominated by a small amount of illitic clay mineral whose composition can vary widely within a given soil type. Table 16 shows mean values for the brown podzol and uncertainties based on the range of the values measured. The peaty podzol values also shown in Table 16 are based on the observed peat values and the mean brown podzol values.

In order to give an estimate of the uncertainty in the soil solution activity due to the soil kinetic parameters 68% confidence intervals have been calculated for the predictions shown in Figure 21 for the brown podzol. This shows predicted soil solution activity over a period of 1 year for the case of deposition=1 Bq m^{-2} at t=0, no leaching or uptake considered. Clearly the variation is considerable.

In the RUINS model outlined earlier this type of soil kinetic model is used for each layer of the soil profile and leaching occurs by a transfer between adjacent solution compartments. This obviously increases the complexity of the model and has been found to give a poor description of the vertical flux of radiocaesium. In this work a more pragmatic approach has therefore been taken. The soil is considered as a single layer which encompasses the rooting zone of the

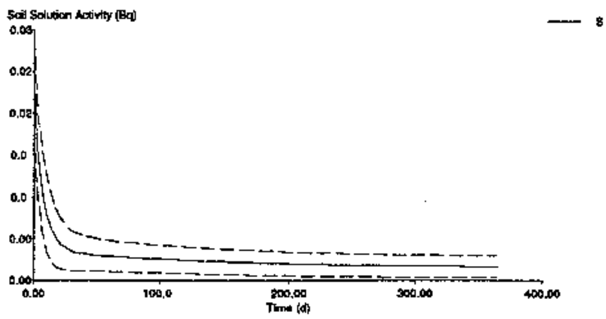


Figure 21 Predicted soil solution radiocaesium activity over a 1 year period for a Brown Podzol, shown with a 68% confidence interval

Table 16 Soil kinetic parameters used for the soil types Brown Podzol and Peaty Podzol

Soil type	k_{dl}	k_1	k_2	k_3	k_4
Brown Podzol	41±6	0.12±0.06	0.021±0.008	0.005±0.003	0.0032±0.0027
Peaty Podzol	20	0.05	0.021	0.005	0.0032

heather. To simulate the leaching of radiocaesium from this zone a simple first order rate coefficient has been estimated from the observed data, k_{leach} (d^{-1}). The rate of leaching (Bq d^{-1}) is then given by

$$Leaching\ Rate = Sk_{leach}$$

In reality leaching rate will depend upon rainfall and would be better expressed in terms of water passing through the soil profile. The advantage taken here has the advantage of minimising the input data requirements for the model. Whilst it will not give accurate values on a daily basis it is expected to provide a reasonable simulation over a period of time. Given the low relative rates of leaching, even from the peat soil, for example compared to nitrate, the approximation should be satisfactory. However caution should be exercised if the model is to be applied in an environment with significantly different rainfall. The value of k_{leach} used for the two sites studies is 0.005 d^{-1}, based on comparisons with the observed data. The models sensitivity to this parameter is discussed below (section 7).

7.4.5 Grazing Sub-Model

Two grazers have been considered, lambs and grouse. Each is modelled in a similar fashion although as would be expected the parameters used differ. It has been assumed that only the current years growth of heather shoots is grazed (ie CYG) and therefore the radiocaesium concentration in the grazers is controlled by the radiocaesium concentration of the CYG compartment only. We have also assumed that the consumption of heather by grazers is a negligible pathway in terms of the overall dynamics of radiocaesium distribution in the ecosystem as a whole. On the basis of data from this study this is a reasonable assumption.

Radiocaesium concentration in the grazers is calculated from the concentration of radiocaesium in the CYG, $[Cs_{cyg}]$, using

$$\frac{d[s]}{dt} = F_m^g \lambda_s [Cs_{cyg}] H_s - \lambda_s [s]$$

$$\frac{d[g]}{dt} = F_m^g \lambda_g [Cs_{cyg}] H_g - \lambda_g [g]$$

where

[s] and [g] are the radiocaesium activity concentrations in the meat of lamb and grouse respectively (Bq kg^{-1})

F^g and F^y are the transfer coefficients for lamb and grouse meat respectively (d kg^{-1})

λ_s and λ_g are rate coefficients for the removal of radiocaesium from the meat of lamb and grouse respectively. These are derived from the observed biological half-life of radiocaesium in the animals

H_s and H_g are the herbage intake of lamb and grouse respectively (kg d^{-1})

This approach is more complex than simply using an equilibrium transfer factor method but still avoids the problem of requiring a detailed animal description in the model. It has the advantage that the dynamics of radiocaesium transfer are considered so that the effect of a changing concentration of radiocaesium in the heather is simulated.

In the model we have used transfer coefficients of 0.6 and 9.2 d kg^{-1} for lamb and grouse respectively. Biological half-lives have been taken as 14 and 9 days for lamb and grouse respectively. Figures for lamb are based on established values (Galer *et al.*, 1993), grouse values are based on data from this study. Herbage intake is taken as 1.5 kg d^{-1} for lamb and 0.07 kg d^{-1} for grouse.

The method above assumes that all the radiocaesium consumed is incorporated into the heather, rather than adhered to the external surfaces. This will apply in the longer term but shortly after a deposition event external contamination by initial deposit is likely to be important. An important characteristic of the deposit from Chernobyl was that it had a lower bioavailability than plant incorporated radiocaesium. To simulate these factors the equations above are modified as to give

$$\frac{d[s]}{dt} = F_m^g \lambda_s \left[Cs_{cyg}\right] + A\left[Cs_{cyg}^{ext}\right] H_s - \lambda_s [s]$$

$$\frac{d[g]}{dt} = F_m^g \left[Cs_{cyg}\right] + A\left[Cs_{cyg}^{ext}\right] H_g - \lambda_g [g]$$

where

$[Cs^{ext}_{sig}]$ is the concentration of external radiocaesium on the heather shoots (Bq kg^{-1}), described earlier.

A is a factor representing the availability for gut absorption of initially deposited radiocaesium relative to plant incorporated radiocaesium. A value for A of 0.3 is used in the model (although it can be adjusted by the user), being representative of that observed for the Chernobyl fallout.

7.5 *PREDICTING THE RADIOCAESIUM BEHAVIOUR FOR THE TWO STUDY SITES*

The model predictions are compared to observation in Figures 22-23 for the CYG and total soil activity (0-20cm) respectively. CYG is shown as this is the key compartment in terms of transfers to the foodchain. Soil is also shown as this a reasonable indicator of the persistence of radiocaesium contamination. In each case we have assumed a deposition of 18000 Bq m^{-2} on Julian day 120.

As the heather uptake parameters were obtained from the data collected at the peat site the agreement there is reasonable. The result for the peaty podzol is less satisfactory. In each case there is considerable disagreement between the model and observation. Model parameters could be adjusted to improve this agreement, yielding a more acceptable visual result, but this would overstate the model's performance. Given the uncertainty associated with the soil kinetic parameters accurate simulation of heather uptake is very difficult. The results reflect this.

Simulation of the radiocaesium remaining in the soil is more acceptable. The observations on the peaty podzol are reproduced, although the model underpredicts for the peat site.

7.6 *THE EFFECT OF HEATHER BURNING*

As described earlier two types of heather burning were investigated experimentally, a 'cool' and a 'hot' burn. These have rather different results in terms of radiocaesium behaviour and are therefore considered separately in the model, although a similar approach is adopted for both.

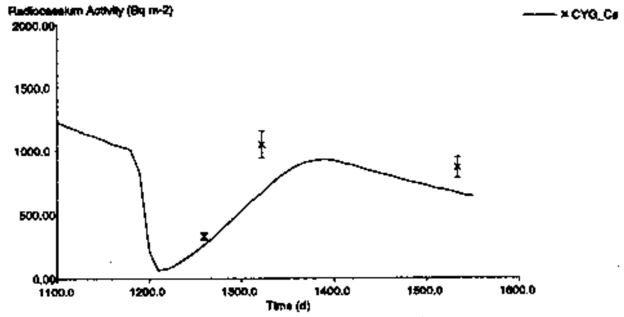


Figure 22a Predicted and Observed Radiocaesium Activity in CYG for the Peat Site

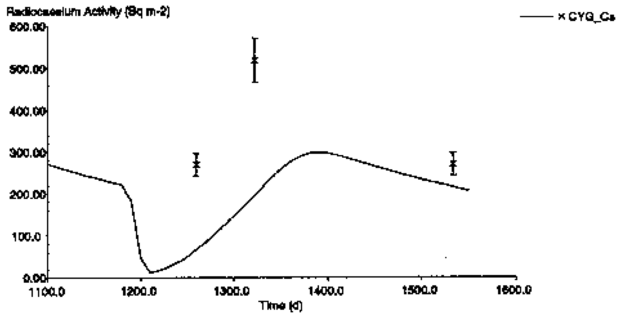


Figure 22a Predicted and Observed Radiocaesium Activity in CYG for the Peaty Podzol Site

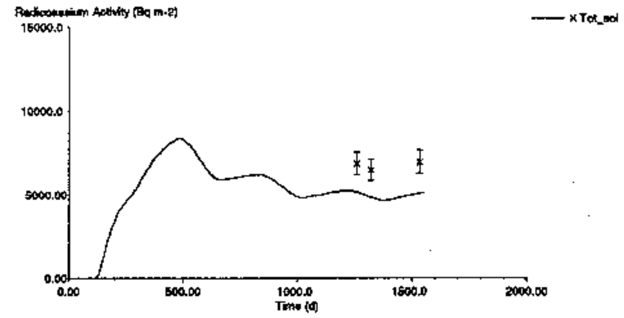


Figure 23a Predicted and Observed Radiocaesium Activity in the soil for the Peat Site

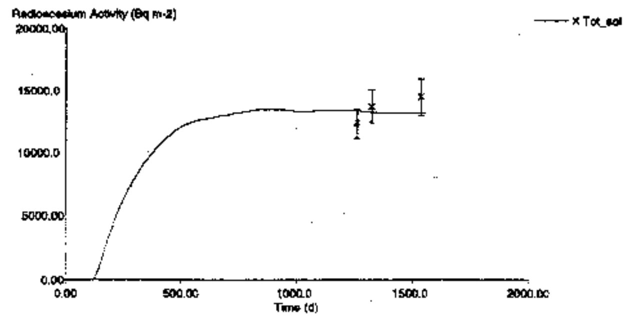


Figure 23b Predicted and Observed Radiocaesium Activity in the soil for the Peaty Podzol Site

When a burning event occurs the biomass of the heather canopy is reduced to zero. A fraction of the radiocaesium in the canopy is released from the system as smoke. Obviously this material will be deposited somewhere although this is not considered in the model. Of the remaining radiocaesium a fraction is rapidly leached from the ash, this is added directly to the solution compartment of the soil. Radiocaesium not leached immediately from the ash is assumed to be lost by a first order process controlled by an ash weathering rate. The value of the weathering rate is not easily determined from the experimental data as the model requires a value per unit time whereas the experiments were done on a per leaching basis. Clearly rainfall data would be required to provide a reliable conversion. We have chosen a value for the weathering rate of 0.01 d^{-1} as this appears to give reasonable results. The sensitivity of the model to this parameter is considered below.

Values used for the fractions lost to smoke and immediately leached for the two types of burn are shown in table 17.

Table 17 Model parameters for the 'Hot' and 'Cool' Heather burning

Burn	F_{smoke}	$F_{leached}$
'Cool'	0.15	0.24
'Hot '	0.37	0.24

We have assumed that during a 'hot' burn all above ground biomass is destroyed, including the bryophyte layer. In the case of a 'cool' burn only the heather itself is destroyed.

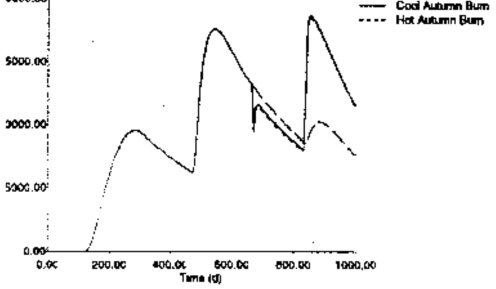


Figure 24 Effect of an autumn burn on subsequent radiocaesium activity of CYG

Predicted responses to heather burning are shown in Figures 24 and 25 for autumn and spring burns respectively. In each case 'hot' and 'cool' burns are compared. These results suggest that autumn burns have the effect of reducing radiocaesium concentration for a short time but greatly increasing radiocaesium uptake in the following spring. Spring burns on the other hand are neutral in effect, the reduction due to the hot burn is simply attributable to the higher fraction of radiocaesium removed in the smoke. In the model this is because after an autumn burn radiocaesium removed from the ash and recycled to the soil is not taken up by the heather because there is no growth. Although there are some losses by leaching this nonetheless results in a higher soil solution activity in the spring and a 'flush' of uptake. In the case of the spring burn this effect is spread over the growing season and there is no significant increase in solution activity. Clearly these results could have practical importance, however they should be treated cautiously, the model should be tested against further data before its predictions can be applied.

We have not attempted to consider the fate of radiocaesium in the smoke from heather burning. As modelled this is always a beneficial loss from the system. It may deposited locally, possibly on another area of heather, which may in turn be burned.

7.7 DISCUSSION OF MODEL

The model presented here can be used as an illustrative tool. The level of agreement shown in Figures 19 and 22 with the field data is such that it should not be used to make unsupported predictions.

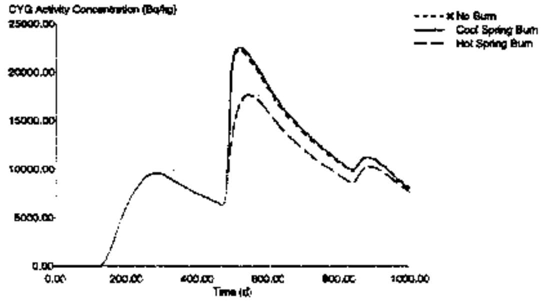


Figure 25 Effect of a spring burn on subsequent radiocaesium activity of CYG

In order to develop confidence in the model more field data would be required. This could be used to both develop and test the model. Some time has elapsed since these studies were undertaken, a repeat sampling of heather at the two sites would be a very useful check of the predictions.

Readers wishing to obtain a copy of the model for research purposes should contact Dr A D Horrill at Merlewood Research Station.

8 CONCLUSIONS

The study has attempted to investigate the deposition and movement of radiocaesium in a heather dominated system. Two soil types, a peaty podzol and a deep peat, have been considered and the potential effect of an important management tool, burning, has been investigated experimentally. The biological half-life of radiocaesium in red grouse, a bird feeding almost exclusively on heather has been determined experimentally.

Deposition was assumed to be similar on both soil types but there is evidence that it has moved faster through the deep peat. This is suggested by the total ^{137}Cs activity inventories for both sites and the ^{137}Cs activity distribution within the soil profiles. The upper layers of the soil, in both systems, still retain considerable amounts of radiocaesium. The litter layer has also been shown to be an important repository. The ground layer of mosses and lichens contained significant amounts of radiocaesium with greater quantities being present at the peat site. The distribution of ^{137}Cs activity between species of moss is not even. Some species can be used as indicators of past radiocaesium availability, due to the lack of translocation between yearly growth increments.

Within the heather plant itself radiocaesium distribution is very similar on both sites although the absolute amount on peat can be a factor of two greater than that for a peaty podzol. ^{137}Cs activity in the young shoots, an important food source for grouse and other animals, can be up to 40% of the total inventory. The origin of this ^{137}Cs activity may be root uptake from the soils and/or translocation within the heather plant.

Other plant species were present but only represented a small proportion of the whole. They can also contain high concentrations of radiocaesium. These may be selectively grazed and hence play a greater part in radiocaesium transfer than their abundance would indicate.

It has been shown that heather burning can influence the movement of radiocaesium in these ecosystems. Depending on fire temperature between 10-40% of the radiocaesium can be removed in smoke although, of course, it will be deposited elsewhere. Some of the ^{137}Cs activity associated with heather ash is immediately soluble in rainwater and will be leached into the soil. Season of burning is important; an autumn burn may allow allow leaching by the winter precipitation to dominate, whereas a spring burn may permit enhanced uptake by growing vegetation.

Experimental work using lysimeters both in the field and under more controlled conditions has shown that low, but measurable amounts of radiocaesium are present in the soil waters of both sites. Soluble ^{137}Cs activity associated with ash from heather contaminated by the Chernobyl reactor accident has consistently leached further down the peat soil profile than down the peaty podzol soil profile. However, most of the Chernobyl radiocaesium still resides in the top 0-10 cm layers of the soil; the main plant rooting zone.

Movement of Chernobyl radiocaesium down the soil profiles for both sites is relatively slow. Data from this study indicates that ^{137}Cs activity is likely to remain in the rooting zone for many years. Some of this ^{137}Cs activity is recycling into plants, particularly those growing on the peat soil with very low concentrations of clay minerals. It is likely that ^{137}Cs physical decay processes will be the dominant mechanism for the reduction of radioactivity in these soils although there will be some losses due to leaching by soil water.

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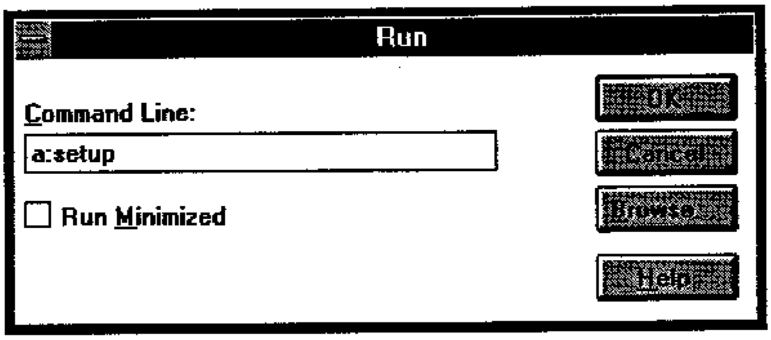
APPENDIX

Heather Model - User Notes

Installation

To install the software:-

- Run Microsoft Windows 3.1
- From the program manager file menu select Run
- Place the diskette in the drive
- Enter a:setup as shown below.

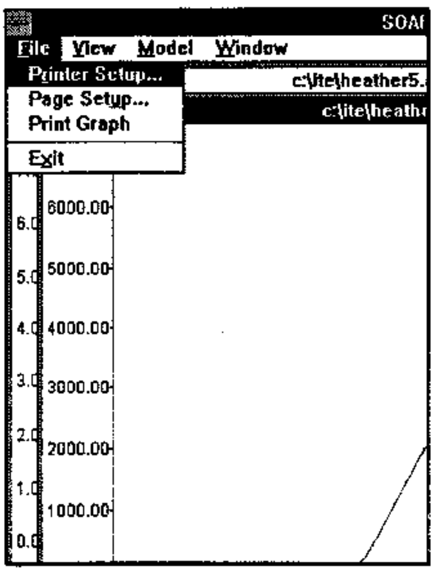


The setup program will create a directory, copy the require files and setup an icon and group within the windows file manager. The icon can be moved to any group window that you wish to use.

Model Menus

The Heather Model has a number of menu options to allow easy configuratio and use of the program. These are itemised below.

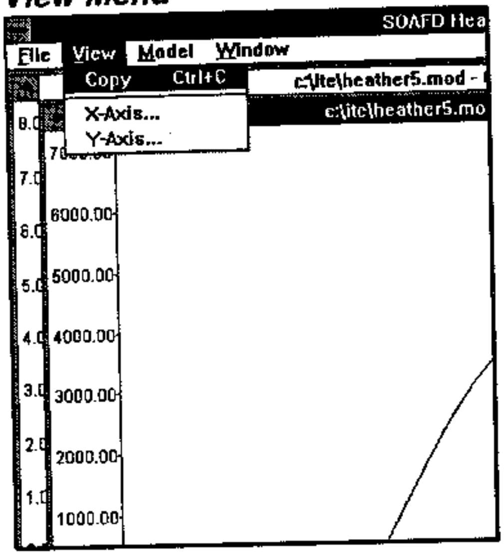
File Menu



This has the following options

- Printer Setup. Allows you to select which printer you want to use.
- Page Setup. Allows you to adjust the margins on your printer.
- Print Graph. Prints the current window using the currently selected printer and page setup.
- Exit. Leaves the Heather Model and returns to the program manager. If you have changed any options in the program you will be given the chance to save them.

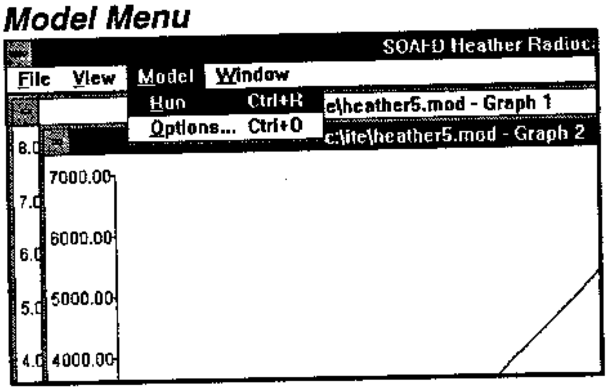
View Menu



This has the following options

- Copy. Copies the contents of the current window into the windows clipboard from where they can be pasted into other windows applications (e.g. Word, Excel etc).
- X-axis. Configure the X-axis (only available for graphs). This can also be done by double clicking to the left of the axis.
- Y-axis. Configure the Y-axis (only available for graphs). This can also be done by double clicking below the axis.

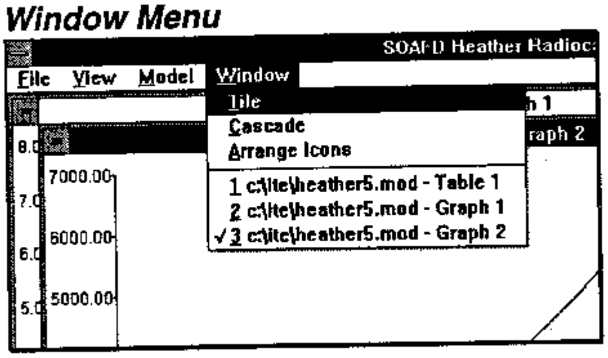
Model Menu



This has two options

- Run. This actually runs the model, using your current options
- Options. This sets the various radioecological options for running the model. This is described below.

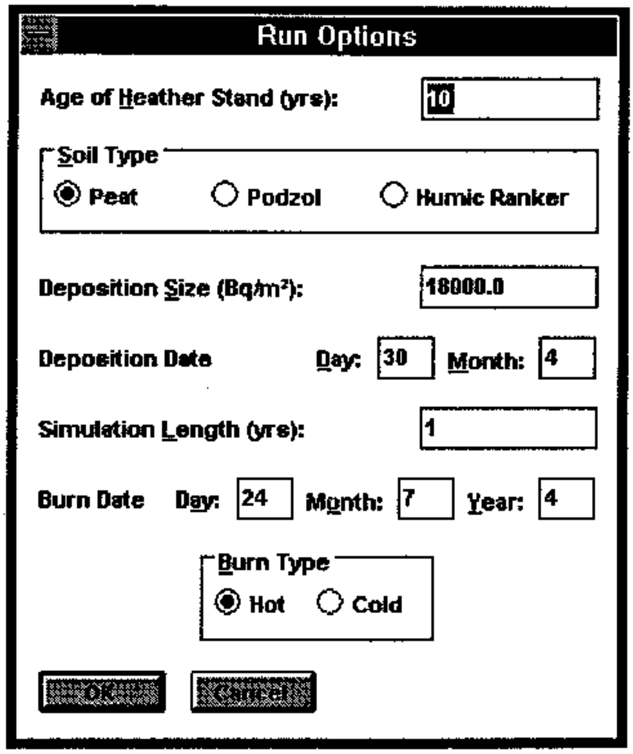
Window Menu



This is the standard windows MDI options menu which enables yuo to arrange the program windows and select between them as required.

Options Dialog Box

The radioecological options are set from the options dialog box which is shown below.



- Age of Heather Stand refers to the age of the heather at the begining og the year in which deposition occurs.
- Soil Type can be selected from three options.
- Deposition Size is simply the amount of radiocaesium deposited per unit ground area.
- Deposition Date can be used to control at when the deposition event occurs.
- Simulation Length simply controls how many simulated years the model will run for.
- Burn date controls when (relative to the start of the simulation) any heather burning will occur.
- Burn type enables the user to switch between cool and hot burns.