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Uptake, allocation, accumulation and ecological implications of ^{85}Sr in bracken (*Pteridium aquilinum* L. Kuhn)

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Abstract

Solutions containing ^{85}Sr were applied to cultivated *Pteridium* (bracken) plants. The radionuclide was applied to either root, rhizome tip or frond tips. Less ^{85}Sr was taken up by the fronds than by the other two plant parts. The fate of the radionuclide differed for different modes of uptake, but for all routes of entry ^{85}Sr was taken up, transported around the plant and behaved as a calcium analogue, in that it accumulated in old and senescent material. Little subsequent recycling to second generation fronds occurred, indicating that ^{90}Sr would accumulate in senescent fronds and be transported into the litter layer, thereby becoming environmentally available. Leaf decay would render ^{90}Sr taken up by bracken environmentally available again far more rapidly than ^{137}Cs in this important component of European ecosystems. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Following the Chernobyl accident in 1986, radiocaesium was found to be the main contaminant of soils and vegetation in Britain (see Tyson, Sheffield & Callaghan, 1999). Radiostrontium was present in smaller amounts than radiocaesium but could be of greater importance if accidentally released in any future accidents. In order to predict the fate of accidentally-released radionuclides it is important to establish their

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individual behaviour, their pathways into and within plants, and the extent to which radionuclides can indicate the likely behaviour of analogous naturally-occurring plant nutrients.

Our investigation into radiocaesium dynamics in bracken (Tyson et al., 1999), found caesium to be a mobile ion which was recycled to the second generation fronds and found in relatively high concentrations in young and meristematic tissues. This mimics the behaviour of potassium in bracken (Ferguson & Armitage, 1944). In plants, strontium is considered to be a relatively immobile element in the phloem, but mobile in the xylem (Handley & Babcock, 1972; Feller, 1986). Strontium can behave as a very close analogue of calcium in plants (Russell, 1963). Calcium is a major plant nutrient whose primary role is usually structural (Marschner, 1986) and it accumulates in woody and senescent tissues (Chen & Lindley, 1981; Hunter, 1953). A study of transfer factors (measures of the amount of contaminants transferred from soil to plants) reported low transfer of ^{90}Sr from soil around Chernobyl after the accident to the rhizomatous marsh fern *Thelypteris palustris* (Lux, Kammerer, Rühm & Wirth, 1995). Transfer factors for ^{90}Sr were not calculated for *Pteridium*, but those for ^{137}Cs were very low. The authors' explanation for this was that the bracken sampled was obtaining nutrients from deep, mineral horizons, where clay minerals bind radionuclides. Bracken frequently grows in organic soils, however, especially in the upland areas of Britain (such as those most affected by fallout from the Chernobyl accident), so it is important to find out whether this highly successful and widespread plant takes up ^{90}Sr if it is available in the substrate, and to determine the subsequent fate of this radionuclide.

The aim of this investigation was therefore to monitor the routes of uptake, transport and accumulation of radiostrontium within bracken. Our goals were to (a) forecast what may happen to radiostrontium in bracken-dominated ecosystems after a nuclear accident, (b) determine the likely patterns of uptake, translocation and accumulation of strontium (and therefore perhaps calcium) in bracken and (c) see how these patterns compare with those obtained in our earlier study for radiocaesium.

2. Materials and methods

The methods of Tyson et al. (1999) used for the tracing of the long-term dynamics of radiocaesium were followed. The same numbers and sizes of rhizome fragments were taken from the same sites and cultivated in perlite watered with nutrient solution. Established plants were excavated in July and subjected to treatments identical to those detailed in the earlier study except that a higher activity of ^{85}Sr than ^{134}Cs was applied, viz. 148 000 Bq of ^{85}Sr in the form of strontium chloride in 7 ml distilled water per treatment, in view of the short half-life of ^{85}Sr (65 days). This was necessary to provide sufficiently active ^{85}Sr by the end of the experiment. The plant parts treated: rhizome tip, frond tip and roots were identical to those used in the earlier study and the same sodium iodide gamma spectrometer connected to a CMTE Electronik GmbH multi-channel data processor (MCA) was used to detect the energy peak (514 keV) for ^{85}Sr in dried material. As for the earlier study, biomass allocated to different plant parts and overall dry weights were similar between replicates and total biomass of plants approximately trebled during the experimental period of 12 months. No attempt was made to determine net uptake or concentrations of ^{85}Sr, as the aim was to monitor routes and compare between plant parts. The results are therefore expressed as mean amounts per plant part sampled. Statistical methods were identical to those used in Tyson et al. (1999).

3. Results

During the experimental period there was an overall decrease in the concentration of ^{85}Sr in living tissues and a corresponding increase in the concentration of ^{85}Sr in senescent and dead material.

All the ^{85}Sr results are shown in tables, giving amounts per plant (cps) and figures expressing these amounts as a percentage per plant part of the total amount detected.

Specific findings for each application method were as follows.

3.1. Root application (see Table 1, Fig. 1)

One month after application (in August) radiostrontium had been taken up by roots and transported to rhizomes and fronds. About 40% of the radionuclide was concentrated in the fronds, with slightly less in the roots. Significantly less ^{85}Sr was found in young fronds and croziers, frond primordia and meristems than in the rhizomes ($p = 0.081$). The lowest ^{85}Sr allocation was to the senescent fronds.

Three months after application (October) there was twice as much ^{85}Sr in fronds than in the first month samples. However, there was little change in the percentage of

Table 1
Mean amounts of ^{85}Sr (c.p.s.) found in organs of bracken during several seasons after root application

Plant part	Month and year									
	Aug. 1990	s.e.	Oct. 1990	s.e.	Jan. 1991	s.e.	April 1991	s.e.	July 1991	s.e.
Dead fronds	—		—		1.38	0.65	3.04	2.48	68.72	56.11
Senescent fronds	3.31	1.96	663.90	339.10	1412.00	147.00	474.50	71.13	295.40	129.30
Fronds	692.10	95.57	1484.00	282.30	—		—		114.10	93.14
Young fronds and croziers	12.09	4.94	0.00		—		0.00		—	
Frond primordia	26.09	9.44	35.75	19.24	10.86	8.86	0.00		0.00	
Meristems	56.33	35.30	44.16	17.08	0.00		0.00		0.00	
Rhizome	773.80	368.80	736.40	134.90	1376.00	49.95	12.08	9.86	24.43	19.95
Roots	441.20	154.20	649.40	116.50	519.50	125.10	100.80	41.46	0.00	
Total	2005.00	647.10	3613.00	568.90	3320.00	74.20	590.40	85.80	502.70	97.30

'—' denotes organ absent; s.e. = standard error; $n = 3$.

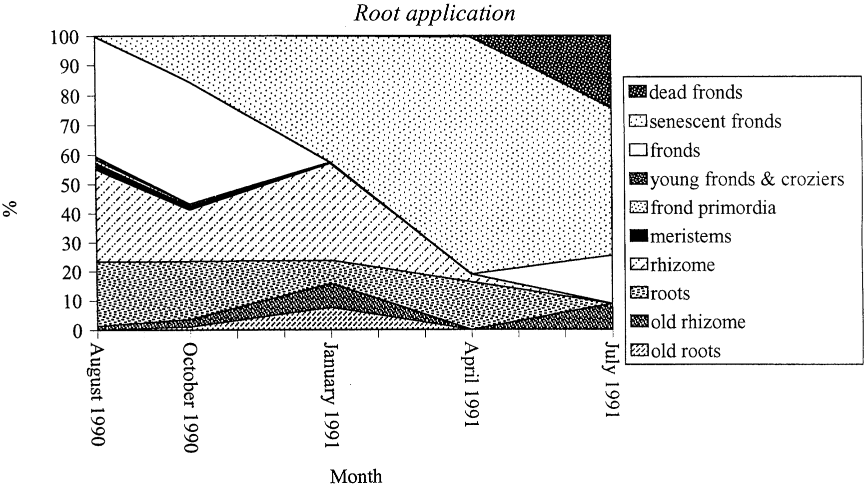

Fig. 1. Relative content (%) of ^{85}Sr in different organs at different times after root application in artificially propagated bracken.

the total ^{85}Sr allocated to the fronds. Amounts in rhizomes were similar to that of the first month. There had been a highly significant increase in radiostrontium allocation to the senescent fronds ($p = 0.081$) between summer and autumn. Allocation of ^{85}Sr to the young fronds and croziers had tailed off and did not recover subsequently, but allocation to the frond primordia, meristems and roots was similar to that during the summer.

By mid-winter (January), there had been a further increase in ^{85}Sr allocation to the senescent fronds, to double that of the autumn allocation ($p = 0.38$). Despite an increase in dry weights there was less ^{85}Sr in frond primordia and ^{85}Sr in meristems had become negligible ($p = 0.081$). ^{85}Sr in roots and rhizomes had increased.

By the following spring (April) the largest amount was found in the senescent fronds, which contained 80% of the ^{85}Sr detected.

Twelve months after application (July) ^{85}Sr was found in the new cohort of fronds. The greatest amount and concentration of ^{85}Sr was still in the senescent fronds, although this was lower than it had been in the spring. The rhizomes had increased greatly in biomass and contained double the ^{85}Sr of plants sampled in spring.

3.2. Rhizome application (Table 2, Fig. 2)

Rhizomes also took up radiostrontium, and one month after application the ^{85}Sr distribution was broadly similar to that of the root-applied plants at the same stage (August). There was slightly more ^{85}Sr (70% of the total detected) in the rhizome than the other plant parts. There was less ^{85}Sr in the fronds, young fronds and croziers, frond primordia and meristems of the rhizome-applied plants than in the root-applied plants. There was very little ^{85}Sr in the roots and none in the old rhizome; this continued for the rest of the experiment.

Table 2
Mean amounts of ^{85}Sr (c.p.s.) found in organs of bracken during several seasons after rhizome application

Plant part	Month and year									
	Aug. (1990)	s.e.	Oct. (1990)	s.e.	Jan. (1991)	s.e.	April (1991)	s.e.	July (1991)	s.e.
Dead fronds	—		—		0.00		0.00		0.00	
Senescent fronds	21.17	15.64	20.08	12.79	1240.00	570.70	713.60	544.50	422.50	333.00
Fronds	1744.00	322.20	554.20	217.10	—		—		59.69	48.74
Young fronds and croziers	63.81	25.31	0.00		—		0.00		—	
Frond primordia	124.20	93.92	0.00		0.00		0.00		0.00	
Meristems	43.87	8.00	0.00		0.00		0.00		0.00	
Rhizome	5809.00	1447.00	2221.00	1047.00	132.60	77.58	2475.00	445.20	256.40	209.40
Roots	188.50	83.13	49.96	35.50	143.70	100.00	0.00		0.00	
Total	7995.00	1331.00	2845.00	1237.00	1517.00	634.40	3.189	957.00	738.60	298.50

'—' denotes organ absent; s.e. = standard error; $n = 3$.

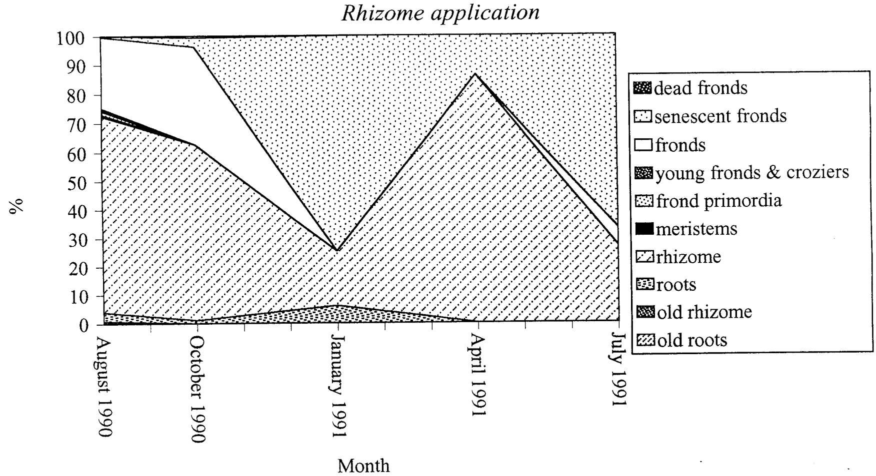

Fig. 2. Relative content (%) of radiation due to ^{85}Sr in different organs at different times after rhizome application in artificially propagated bracken.

After three months (October) the distribution of ^{85}Sr was very different from that of the root-applied plants. There was less ^{85}Sr in senescent fronds, fronds and roots and more in the rhizome. There was no ^{85}Sr detectable in the young fronds and croziers, mirroring the root-applied plants, but there was none detectable in the frond primordia and meristems, unlike the root-applied plants; this continued for the rest of the experiment.

By January a high concentration of ^{85}Sr was found in the senescent fronds ($p = 0.081$). This was far greater than the increase in ^{85}Sr concentration in the senescent fronds of the root-applied plants. Unlike the root-applied plants there was no ^{85}Sr detectable in the dead fronds and this continued for the rest of the experiment.

By the spring (April) levels of ^{85}Sr were higher in the senescent fronds and lower in the rhizome and roots than in the root-applied plants. There was no ^{85}Sr detectable in the roots, in contrast to the root-applied plants (which contained relatively high levels). By summer (July) there had been a large increase in ^{85}Sr in the senescent fronds, bringing the concentration almost back to winter levels. There was less ^{85}Sr in the fronds than the root-applied plants, but a larger amount in the rhizomes than in the root-applied plants.

3.3. Frond application (Table 3, Fig. 3)

Uptake of ^{85}Sr by the fronds was extremely low. Only the data from the first month (August) gave significant levels of detectable ^{85}Sr. Allocation patterns for the frond-applied plants at this point were broadly similar to the other two forms of application.

Table 3
Mean amounts of ^{85}Sr (c.p.s.) found in organs of bracken during several seasons after frond application

Plant part	Month and year									
	Aug. 1990	s.e.	Oct. 1990	s.e.	Jan. 1991	s.e.	April 1991	s.e.	July 1991	s.e.
Dead fronds	—		—		—		0.00		0.00	
Senescent fronds	3.93	1.70	0.00		0.00		0.00		0.00	
Fronds	346.90	56.45	0.00		—		—		0.00	
Young fronds and croziers	47.10	32.90	0.00		—		0.00		—	
Frond primordia	5.10	2.03	0.00		0.00		0.00		0.00	
Meristems	28.92	10.83	0.00		0.00		0.00		0.00	
Rhizome	362.40	133.50	0.00		0.00		0.00		0.00	
Roots	28.26	10.97	0.00		0.00		0.00		0.00	
Total	822.70	191.70	0.00		0.00		0.00		0.00	

'—' denotes organ absent; s.e. = standard error; $n = 3$.

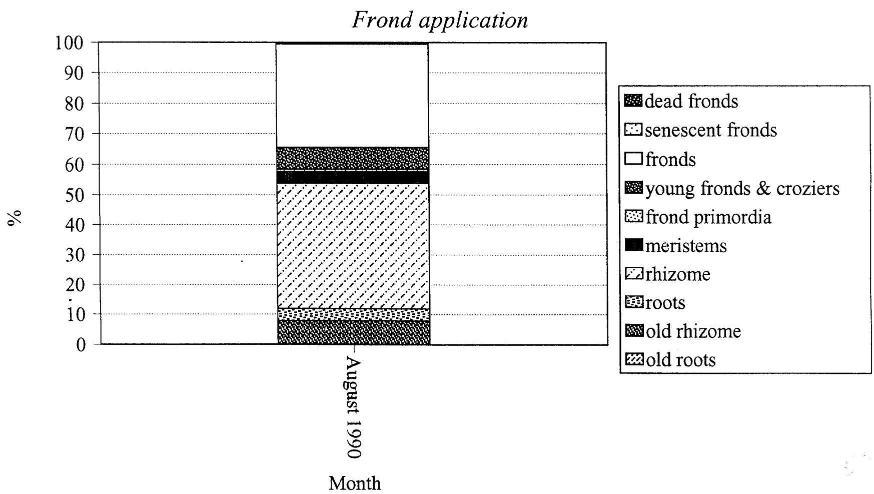

Fig. 3. Relative content (%) of radiation due to ^{85}Sr in different organs at different times after frond application in artificially propagated bracken.

4. Discussion

Although the results confirm the key role of the bracken rhizome tip in nutrient uptake, the behaviour of radiostrontium is very different from that of radiocaesium in this fern (Tyson et al., 1999). Although ^{85}Sr was shown to be taken up by all three plant parts tested and is transported around the plant, it then accumulates in old and senescent material, which does not occur with radiocaesium. The decline in ^{85}Sr from winter (January) onwards in the rhizome of the root-applied plants reflected continued allocation to the senescent fronds. This mirrors the results for radiocaesium and indicates that senescent fronds have functional vascular bundles.

A small amount of ^{85}Sr was shown to be recycled, which has also been shown to be the case for calcium in some studies (e.g. Levi, 1968) but not in others (Biddulph, Biddulph, Cory & Koontz, 1958). Radiostrontium is effectively taken up through the roots and rhizome tip, as with radiocaesium, but not through the fronds. This lack of absorption by leaves is also a feature of calcium (Bukovac & Wittwer, 1957; Levi, 1968) and has been demonstrated in other studies with strontium. This may be because both elements are phloem-immobile. Marschner and Richter (1974) showed that even in high calcium concentrations there was no translocation of calcium to root tips of maize and bean plants, but that when the root tip was removed, calcium was moved downwards, but in the xylem, not in the phloem. When the root tip was calcium-deficient no translocation took place towards the tip, which eventually died. This suggests that calcium must be supplied externally and cannot be recirculated from elsewhere.

Foliar absorption and distribution of ^{89}Sr and ^{137}Cs in plants has been examined by various authors (e.g. Bukovac, Wittwer & Tukey, 1965; Zehnder, Kopp, Oertli, & Feller, 1993; Zehnder, Kopp, Eikenberg, Feller & Oertli, 1995). The rate and amount of absorption were much less for ^{85}Sr than for ^{137}Cs, although the magnitude of the difference between the behaviours of the radionuclides was different for different plants and experiments. Ambler (1964) researching bean and corn plants and Handley, Schultz, Marschner, Overstreet and Longhurst (1967) working with woody plants found that ^{85}Sr translocation from leaves was greater if they were rewetted periodically. It was suggested that this was due to reverse transport through the xylem to other transpiring leaves. High humidity could therefore promote uptake (Pallas, 1960; Clor, Crafts & Yamaguchi, 1962), so that this type of weather after a nuclear accident may increase bracken frond uptake of the radionuclide.

The large amount of ^{85}Sr which accumulated in the senescent fronds and dead fronds of bracken probably reflected immobilisation of strontium in woody and senescent material. Alexakhin, Ginsberg, Mednik and Prokhorov (1994) reported a gradual increase in ^{90}Sr in the wood of a birch and pine forest with time, reaching a maximum after 6–7 years in the former and 10–12 years in the latter (after a nuclear accident in the Urals in 1957). This immobilisation in woody tissue is also found for calcium (Chen & Lindley, 1981; Hunter, 1953; Weirsum, 1966). At maturity, increased lignification of the vascular tissues provides an expanding area for the accumulation of calcium. Frankland (1976) compared the percentage of the elements in the green fronds of bracken with that in the senescing fronds. 94% of the calcium was found in both the standing senescent fronds and dead litter whereas 33% of the potassium was found in standing senescent fronds with only 1% in the dead litter. Similar trends were recorded by Richter (1979) and Sponder (1979), demonstrating the contrasting behaviour of the two elements. Immobile calcium (analogue strontium in this instance) remains in senescent tissues, mobile potassium (analogue caesium in this respect) is recycled. It is therefore likely that the large proportion of radiostrontium which accumulates in senescent fronds would, following a nuclear accident, be shed in the dead fronds to the surrounding environment.

Plants absorb more ^{90}Sr from soils low in calcium than from other soils (Russell, 1963; Menzel, 1954; Roberts & Menzel, 1961; Vose & Koontz, 1959). As bracken largely grows in soil with low levels of calcium (Sheffield, Wolf, Haufler, Ranker & Jermy, 1989) it would be expected that during times of high ^{90}Sr deposition the plant could be exposed to highly available soil ^{90}Sr.

The way radiostrontium is acquired by bracken has implications for its sequestration after a nuclear accident. Unlike caesium, which is taken up by the fronds as well as rhizome and roots, the uptake of strontium is mainly restricted to rhizome and roots and therefore should differ little between summer and winter. The fate of strontium is also affected by its site of uptake. After absorption through the roots, the majority of the radiostrontium is lost to senescent and dead fronds by the second summer after acquisition. Some is recycled to the fronds, and would probably be lost as they died the following winter. A small fraction, however, is sequestered by the old senescent rhizome, and would possibly stay there until released by microbial activity. When radiostrontium is taken up through the rhizome tip, although the majority is probably lost to the senescent fronds, a sizeable minority remains in the rhizome, possibly to be recycled. It is difficult to explain the lack of ^{85}Sr in roots and old rhizomes of plants where entry occurred via the rhizome, however.

Unlike caesium, strontium is allocated to actively growing areas in small amounts. Any radiostrontium contained in the young fronds, frond primordia and meristems had been lost by winter in the root-applied plants, and even earlier (October) in rhizome-applied samples. This indicates that any radiostrontium contained in new tissue (fronds, rhizome, roots, etc.) is transported there at the time of application, after which no recycling takes place. Consequently, genetic damage to apical cells (Tyson et al., 1999) is likely to be lower for radiostrontium than radiocaesium after a nuclear accident. However, strontium is more mobile in soil than caesium (Poiarkov, 1995) and is more readily absorbed from the soil by plant roots (Russell, 1963; Pablo, 1974). Decaying fronds would release radiostrontium into soil where it would be available for uptake by other plants and the originating bracken clone. This would be of ecological significance in the case of ^{90}Sr, which has a physical half-life of 28.78 years and is considered a radionuclide of particularly high radiotoxicity.

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