Determination of Root Uptake to Vegetables Grown in Soil Contaminated for Twenty-five Years

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ABSTRACT

This report presents a re-evaluation of soil to plant transfer factors for different radionuclides and specific crops (cabbage, carrots and potato) based on a lysimeter study carried out at the Health Protection Agency in 2008. The lysimeters used in the study contain radionuclides which have been present for 25 years. The results from the study are therefore representative of soil to plant transfer factors for a long term contamination situation, where the soil has been repeatedly cultivated and where the soil and the radionuclide content have been subject to significant weathering. The main aim of the study was to determine soil to plant transfer factors to identify if there had been any significant changes since the last study carried out with these lysimeters 10 years previously. The HPA's dynamic food chain model FARMLAND contains default soil to plant transfer factors. The results of this study have been compared with the default values in the model.

The measured soil to plant transfer factors were, in general, in good agreement when compared to the compiled values reported by the International Atomic Energy Agency (IAEA) and previous studies carried out at HPA. However, differences have been observed for uptake of americium-241 and strontium-90, where soil to plant transfer values were below or on the lower limit of the range of values published by IAEA and the previous studies carried out at HPA. In contrast, the soil to plant transfer factor for caesum-137 in cabbage was approximately a factor of two higher than the average value of previous studies carried out at HPA and a factor of four higher than the upper limit of the range reported by the IAEA. These differences will be investigated as part of a further study at HPA. The current default values used in the FARMLAND model to carry out radiological dose assessments remain valid.

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CONTENTS

1 INTRODUCTION

The Health Protection Agency has six well established lysimeters of three different soil types representative of UK agricultural soils (Hamble loam, Fyfield sand and Adventures peat). These lysimeters have been used extensively over the last 25 years to investigate the transfer of radionuclides from soil to plant, with a wide variation of vegetables and fruit grown such as carrot, cabbage, barley, strawberry and apples, (see for example Nisbet and Shaw, 1994a and 1994b; Green et al, 1997a and 1997b). In this study the lysimeters were used to grow cabbage, carrots and potatoes to provide additional information on soil to plant transfer factors for these crops and to determine if there has been any change in the magnitude of root uptake over time since previous values were determined.

The soil to plant transfer factor (TF) is the ratio of the concentration of a radionuclide in the plant to the concentration of the radionuclide in the soil at equilibrium, usually measured at the time of harvest. Generally, this concept refers to root uptake and there are strict protocols to follow when obtaining the data to calculate soil to plant transfer factors as described by the International Union of Radioecology (IUR, 1989). The prime use of soil to plant transfer factors is for environmental transfer modelling or simple radiological dose assessments, where the knowledge of the transfer of radionuclides from soil to plants and subsequently animal products is very important. There are many parameters to consider in order to determine soil to plant transfer factors. The most important studied to date are; the type of plant, soil characteristics, chemistry of the radionuclide present, climate, cultivation practice and also how long the radionuclide has been in contact with the soil (Golmakani et al, 2008; Savinkov et al, 2007; IAEA, 2009). Once uptake via the roots has taken place, the radionuclide will be distributed throughout the plant in both the edible and inedible parts. The distribution of the radionuclide between edible and inedible parts was also investigated as part of this study. This distribution is important for radiological assessments as the contribution from different parts of the crops to the intake of activity by people will be dependent on food preparation and their dietary preferences.

In this report the soil to plant transfer factors (TFs) are reported on a dry mass basis in order to avoid inaccuracies associated with different moisture contents of crops, but also to make comparisons with previous data obtained using the lysimeters and the current parameter values used in the FARMLAND model (Brown and Simmonds ,1995).

The TF is defined as:

$$TF = \frac{Bq\,kg^{-1}_{dry\ \ mass\ \ plant}}{Bq\,kg^{-1}_{dry\ \ mass\ \ soil}}$$

FARMLAND is a model that has been developed at the Health Protection Agency to predict the transfer of radionuclides to foods grown in the terrestrial environment. The soil to plant transfer factors used in FARMLAND were derived from previous studies where the radionuclides in the soil had reached an equilibrium established during the growing season. The TFs may change over long periods of time and this study aimed to confirm the suitability of the existing TFs used in FARMLAND for aged soil contamination, and to identify if the TFs had changed significantly since the last study carried out over 10 years previously.

2 EXPERIMENTAL DESIGN

This study was carried out using six very well established lysimeters that were contaminated with strontium-90 (^{90}Sr), caesium-137 (^{137}Cs), plutonium-239-240 ($^{239\text{-}240}$Pu) and americium-241 (^{241}Am) in the winter of 1983/84, as reported in Nisbet and Shaw (1994a). The six lysimeters contain Hamble loam, Fyfield sand and Adventures peat soils, with two lysimeters for each soil type. Cabbage, carrot and potatoes were the crops selected for this study.

2.1 Crop cultivation

In April 2008, all the lysimeters were prepared by weeding, digging the top layer to a depth of approximately 0.4 m and adding a general domestic fertilizer to the top soil. The varieties of the crops planted were: ‘April’ for cabbage, ‘Autumn King’ for carrot and ‘Maris Piper’ for potatoes. The carrots were planted directly into the lysimeters, cabbage was planted from seeds grown indoors and then transferred to the lysimeters and the potatoes were chitted indoors and then planted into the lysimeters. Water was applied as necessary to maintain good growing conditions.

2.2 Collection and preparation of samples

Once all crops reached maturity, they were harvested along with a sample of the associated soil. All the crops of the same species were bulked for each type of soil. The crops and soil samples were prepared for radiochemical analysis immediately after collection. Potatoes and carrots were washed thoroughly to remove all visible soil contamination and were then peeled, collecting both the edible and peel portions. The cabbage was washed and the outer portion separated from the edible hearts. All the crop samples were freeze dried and then passed through a food processor, if necessary, to produce a homogeneous powdered sample. The soil samples were dried in an oven and milled to obtain representative samples for analysis for each lysimeter.

Gamma ray spectrometry was used to quantify the ^{137}Cs in all crop samples and soils, using a calibrated High Purity Germanium detector. Radiochemical analysis was carried out to quantify the activity concentrations of ^{90}Sr, $^{239\text{-}240}$Pu and ^{241}Am. Aliquots of dried samples were first dry ashed in a furnace and leached using nitric acid.

The strontium was separated from the leachate by oxalate precipitation and further purified by precipitation from fuming nitric acid. After the ^{90}Y had reach equilibrium with the strontium, the yttrium was precipitated as oxalate, dried and weighed into a planchet. The source was then counted on a gas flow proportional counter several times over a one week period to check its purity by decay.

The plutonium and americium fractions were separated from the nitric acid phase by ion exchange. The americium was separated by solvent extraction. The plutonium was further purified from a hydrochloric acid phase using anion excahnge. Finally the separated plutonium and americium fractions were electrodeposited onto a stainless steel disk and measured by alpha spectrometry.

3 SOIL TO PLANT TRANSFER FACTORS

The soil to plant TFs estimated in this study for the edible parts of the crops are shown in Table 1. Table 1 also shows average values of previous soil to plant TF values for cabbage and carrot crops cultivated in the same lysimeters in a five year study and reported by Nisbet and Shaw (1994a) and for potatoes grown and reported by Green et al (1997b). Finally, the range of the soil to plant TFs reported by the International Atomic Energy Agency (IAEA, 2009) are also shown.

3.1 Comparison with previous lysimeters studies

It is common that soil to plant TFs for a specific soil and crop vary by up to an order of magnitude due to different factors (Nisbet and Woodman, 2000). This means that even if an experiment is designed to measure TFs for the same crops grown in the same soil, they may vary for a number of reasons which are not necessarily monitored. Examples of these factors could be the amount of irrigation during the growing season which may affect the root uptake of strontium and the amount of fertilizer added that may affect the root uptake of caesium (Nisbet and Shaw, 1996; Sauras Yera et al, 1999; Savinkov et al, 2007; Strebl et al, 2007). Golmakani et al (2008) provides a summary of the main factors affecting the soil to plant TFs of radionuclides from the environment to plant. The most relevant factors for this study are re-mobilisation of mineral nutrients in the soil, particularly calcium and potassium, the content of which might be affected by the different amount of calcium added by the watering during the absence of rain and by the amount of fertilizer added, and also the migration of radionuclides in the soil.

Therefore, if there was a difference of less than an order of magnitude between the soil to plant TF values obtained in this study and averaged results reported in previous studies, the change was not considered to be significant. The soil to plant TFs from this study were compared with the results of Nisbet and Shaw (1994a) for cabbage and carrot and for potatoes with data obtained by Green et al (1997b). All the results met this criterion except in the cases given below.

For the cabbage grown in sandy soil, an approximate order of magnitude reduction in the soil to plant TFs was observed for ^{90}Sr and ^{241}Am.

The ^{137}Cs soil to plant TF for cabbage grown in peat was approximately a factor of two higher than the value reported by Nisbet and Shaw (1994a). Although this is not an order of magnitude difference, it is important to mention this finding because the calculated soil to plant TF for ^{137}Cs in this study and the earlier HPA study are both outside the range of values reported by the IAEA (2009). The high transfer factor in this study could be due to the fact that others crops had been grown previously in the same lysimeters and although fertilizer was added, the amount might not have been enough to compensate for the depleted K^+ and therefore the competition between K^+ and ^{137}Cs was not present as it has been previously.

For carrot there was a reduction of one order of magnitude in the root uptake for ^{90}Sr for loam and sandy soils and very close to an order of magnitude for peat soil.

For potatoes there was a decrease in the soil to plant TF for ^{90}Sr in peat and sandy soils of at least an order of magnitude and a decrease of very close to an order of magnitude for loam.

The soil to plant TFs measured for ^{137}Cs, $^{239\text{-}240}Pu$ and ^{241}Pu, for all the crops grown in the three types of soil , were comparable with the results of earlier studies carried out more than 10 years ago, Nisbet and Shaw (1994a) and Green at al (1997b). However, the soil to plant TFs measured for ^{90}Sr were found to be consistently lower than previously found, by a factor between 5 and 14, for all the crops and soil combinations examined. It is difficult to conclude that this decrease is due to the age of the soil radionuclide mix, but it is nevertheless recommended that a repeat set of experiments are conducted to measure the soil to plant TFs for ^{90}Sr in a few years time.

3.2 Comparison with compilation of soil to plant transfer factors by IAEA

As mentioned in the previous section, differences in the soil to plant TFs values of less than one order of magnitude are not unexpected. However, when comparing the soil to plant transfer from this study to the values reported by IAEA (2009), the approach was to compare the values with the IAEA data range instead of a single value and the soil to plant TFs were considered different if the values from this study were outside the data range reported by IAEA (IAEA, 2009).

For cabbage, most of the soil to plant TFs were outside the range of values published by IAEA. In general, where values were outside of the range reported by IAEA, the values were lower. The exception was for ^{137}Cs in peat where values were a factor of four higher than the highest value reported. It is important to mention that although the largest collection of TFs are reported by IAEA (IAEA, 2009), Nisbet and Woodman (2000) included data from published and unpublished sources and these could also be considered as valid values for comparing with the experimental value from this study. As an example, Nisbet and Woodman (2000) reported a geometric mean of the soil to plant TF for brassicas in organic soil of 2.1 10^{-1}, with an upper limit of 7.5 (95% confidence interval). This upper limit encompasses the high soil to plant TF value of 1.7 for ^{137}Cs in peat soil for cabbage obtained in this study.

For carrots, most of the soil to plant TFs from this study were within the range reported by IAEA except for $^{239\text{-}240}Pu$ and ^{241}Am uptake from sandy soil, where measured values were at least an order of magnitude lower. A comparison cannot be made for actinide uptake for the other soils as values have not been published by IAEA.

For potatoes most of the soil to plant transfer factors were comparable with the ranges of values reported by IAEA except for the peat soil, where the soil to plant TFs for ^{90}Sr and ^{241}Am were a factor of three lower than the lowest value of the range and the $^{239-240}Pu$ value was just outside the lower end of the range.

Table 1 Comparison of transfer factor for each radionuclide measured in cabbage, carrot and potatoes planted in different types of soil with other studies

	Type of soil	Radionuclide	$TF = \dfrac{Bq\,kg^{-1}_{dry\ \ mass\ \ plant}}{Bq\,kg^{-1}_{dry\ \ mass\ \ soil}}$ Current study	Other HPA lysimeter studies[a]	IAEA (2009)
Cabbage[a]	Loam	^{90}Sr	1.1 10^{-1}	9.2 10^{-1}	4.1 10^{-2} - 5.0 10^{0}
		^{137}Cs	4.7 10^{-2}	2.8 10^{-2}	3.0 10^{-4} - 7.3 10^{-1}
		$^{239\text{-}240}Pu$	3.9 10^{-5}	4.6 10^{-5}	-
		^{241}Am	4.0 10^{-5}	6.7 10^{-5}	6.0 10^{-5} - 4.1 10^{-4}
	Peat	^{90}Sr	1.8 10^{-2}	8.8 10^{-2}	1.5 10^{-1} - 3.0 10^{-1}
		^{137}Cs	1.7 10^{0}	9.8 10^{-1}	4.0 10^{-3} - 4.6 10^{-1}
		$^{239\text{-}240}Pu$	7.9 10^{-6}	4.3 10^{-6}	-
		^{241}Am	6.9 10^{-6}	1.6 10^{-5}	4.0 10^{-5} - 2.3 10^{-4}
	Sand	^{90}Sr	1.2 10^{-1}	1.5 10^{0}	6.4 10^{-2} - 7.8 10^{0}
		^{137}Cs	1.2 10^{-1}	4.2 10^{-2}	2.1 10^{-3} - 9.8 10^{-1}
		^{239}Pu	1.1 10^{-5}	3.6 10^{-5}	2.9 10^{-5} - 2.9 10^{-4}
		^{241}Am	1.2 10^{-5}	2.5 10^{-4}	1.7 10^{-4} - 1.5 10^{-3}
Carrots[a]	Loam	^{90}Sr	1.1 10^{-1}	1.4 10^{0}	4.4 10^{-2} - 4.5 10^{0}
		^{137}Cs	5.0 10^{-2}	3.9 10^{-2}	1.0 10^{-3} - 1.6 10^{-1}
		$^{239\text{-}240}Pu$	3.9 10^{-5}	1.5 10^{-4}	-
		^{241}Am	3.9 10^{-5}	2.0 10^{-4}	-
	Peat	^{90}Sr	1.9 10^{-2}	1.5 10^{-1}	-
		^{137}Cs	2.1 10^{-1}	1.4 10^{-1}	1.6 10^{-2} - 8.8 10^{-1}
		$^{239\text{-}240}Pu$	5.1 10^{-6}	1.1 10^{-5}	-
		^{241}Am	3.6 10^{-6}	1.8 10^{-5}	-
	Sand	^{90}Sr	1.4 10^{-1}	1.7 10^{0}	3.0 10^{-2} - 4.8 10^{0}
		^{137}Cs	7.0 10^{-2}	3.3 10^{-2}	8.0 10^{-3} - 4.0 10^{-1}
		^{239}Pu	2.2 10^{-5}	6.3 10^{-5}	7.0 10^{-5} - 5.8 10^{-3}
		^{241}Am	2.0 10^{-5}	1.8 10^{-4}	7.3 10^{-4} - 1.7 10^{-3}
Potatoes[a]	Loam	^{90}Sr	1.9 10^{-2}	1.2 10^{-1}	7.4 10^{-3} - 4.5 10^{-1}
		^{137}Cs	5.1 10^{-2}	5.7 10^{-2}	4.8 10^{-3} - 1.4 10^{-1}
		^{239}Pu	1.3 10^{-5}	5.7 10^{-5}	6.2 10^{-6} - 5.0 10^{-3}
		^{241}Am	1.0 10^{-5}	6.7 10^{-5}	1.1 10^{-5} - 4.7 10^{-3}
	Peat	^{90}Sr	2.6 10^{-3}	3.7 10^{-2}	8.0 10^{-3} - 2.3 10^{-1}
		^{137}Cs	2.6 10^{-1}	6.7 10^{-2}	1.6 10^{-2} - 5.4 10^{-1}
		$^{239\text{-}240}Pu$	1.1 10^{-5}	3.8 10^{-6}	1.3 10^{-5} - 8.0 10^{-4}
		^{241}Am	8.4 10^{-6}	8.6 10^{-6}	2.1 10^{-5} - 1.6 10^{-3}
	Sand	^{90}Sr	2.1 10^{-2}	2.0 10^{-1}	2.6 10^{-2} - 1.6 10^{0}
		^{137}Cs	1.1 10^{-1}	1.1 10^{-1}	4.0 10^{-3} - 6.0 10^{-1}
		$^{239\text{-}240}Pu$	1.7 10^{-5}	2.0 10^{-5}	3.8 10^{-6} - 2.0 10^{-3}
		^{241}Am	1.3 10^{-5}	7.6 10^{-5}	1.1 10^{-5} - 3.4 10^{-2}

Note
(a) Cabbage and carrot data are averaged values taken from Nisbet and Shaw (1994a) from a 5 year study. Values for potatoes are from Green et al (1997b) and are values from a single crop season.

4 DISTRIBUTION OF RADIONUCLIDES IN THE CROPS

The soil to plant TFs were calculated for the edible part of the crop and the peel or outer leaves of the crop and the results are shown in Table A1 in Appendix A. The ratios between the transfer factors for the peel/outer leaves and the edible part of the crop were calculated and are shown in Table 2.

The strontium distribution was found to be different for different crops and soil types. For cabbage and potatoes, the activity concentration was higher in the peel/outer leaves by a factor of between 4 and 10 than in the edible part. For carrot it was homogeneous for crops grown in sand and loam but the peel was a factor of two higher than the edible part for the peat soil. Results were reported for carrot peel and cabbage by Nisbet and Shaw (1994b) and for the carrot the distribution was very homogeneous between the peel and the edible part of the crop and for the cabbage was between a factor of 5 and 7 higher in the peel than the edible part. The results were very similar to the results observed in this study.

The results shown in Table 2 indicate that caesium is concentrated in the edible part of the carrot and potato with ratio of peel:edible portion of between 0.2 and 0.4 and, for cabbage, contamination is homogeneously distributed between the outer leaves and the edible part. Green et al (1977b) found that the caesium was marginally lower in the peel of the potato but concluded that it was reasonable to assume that it was uniformly distributed through the potato. Nisbet and Shaw (1994b) found that for cabbage the ratio for the peel/outer leaves: edible part of the crop was between 1 and 1.5, depending of the type of soil, and between 1.6 and 2.9 for carrot. It is unlikely, due to the high TFs measured for caesium, that the higher concentration of caesium in the edible part of the potato and carrot measured in this study was due to soil contamination, but there is no previous scientific evidence for root uptake to suggest that the edible part of the crop concentrates caesium. Given all the results it remains reasonable to assume that the caesium distribution is very similar between the edible and peel/outer leaves of these crops for dose assessment purposes.

The measurements made in this study support earlier studies that suggested that plutonium and americium concentrate significantly in the peel of the crop. The peel:edible ratio for all types of soils and crops were found to be between 20 and 51, as shown in Table 2. Nisbet and Shaw (1994b) calculated lower values (6 - 24) for the same crops. It is important to mention that the soil to plant TFs for plutonium and americium are very low (around 10^{-5}) and therefore a very small amount of soil contamination left on the peel may influence the results of the partitioning of contamination between the peel and the edible parts. The wide spread of data for the edible:peel ratio obtained in this study may therefore be due to soil contamination on the peel or outer leaves. Nevertheless the fact that the actinides are concentrated in the peel or outer leaves of the crops was supported by the data obtained in this study.

Table 2 Distribution of radionuclides between inedible and edible parts for cabbage, carrot and potatoes cultivated in different types of soils

		Activity concentration in peel/outer leaves / activity concentration in edible part of the crop[a,b]		
Crop	Radionuclide	Loam	Peat	Sand
Cabbage	^{90}Sr	6.5	7.2	10
	^{137}Cs	1.1	1.1	1.2
	$^{239-240}Pu$	9.8	33	28
	^{241}Am	9.5	36	33
Carrots	^{90}Sr	1.5	1.9	1.4
	^{137}Cs	0.18	0.23	0.18
	$^{239-240}Pu$	15	21	42
	^{241}Am	17	26	51
Potatoes	^{90}Sr	4.7	3.6	3.9
	^{137}Cs	0.37	0.40	0.34
	$^{239-240}Pu$	23	19	20
	^{241}Am	29	23	26

Notes:

(a) Values quoted to 2 significant figures, but do not imply this degree of accuracy

(b) Soil to plant TF values are given in the Appendix

5 IMPACT OF THE LATEST SOIL TO PLANT TRANSFER FACTORS ON THE FARMLAND MODEL DEFAULT VALUES

In the FARMLAND model, the crops are divided into six different categories, which include green vegetable, root vegetables and potatoes. For comparative purposes, cabbage is included in the green vegetable category and carrots in the root vegetable category.

The values of the soil to plant TFs for this study and FARMLAND values quoted in dry mass and are shown in Table 3. Values for dry matter content used to convert soil to plant TFs from fresh to dry mass were taken from IAEA (2009).

Table 3 Soil to plant transfer factors for FARMLAND and this study

$$TF = \frac{Bq\,kg^{-1}_{dry\ \ mass\ \ plant}}{Bq\,kg^{-1}_{dry\ \ mass\ \ soil}}$$

Crop Category	Radionuclide	FARMLAND	Data range for 3 types of soils[a,]
Cabbage	^{90}Sr	$2\ 10^{0}$	$2\ 10^{-2}$ - $1\ 10^{-1}$
	^{137}Cs	$8\ 10^{-2}$	$5\ 10^{-2}$ - $2\ 10^{0}$
	$^{239-240}Pu$	$8\ 10^{-5}$	$8\ 10^{-6}$ - $4\ 10^{-5}$
	^{241}Am	$4\ 10^{-4}$	$7\ 10^{-6}$ - $4\ 10^{-5}$
Carrot	^{90}Sr	$2\ 10^{0}$	$2\ 10^{-2}$ - $1\ 10^{-1}$
	^{137}Cs	$5\ 10^{-2}$	$5\ 10^{-2}$ - $2\ 10^{-1}$
	$^{239-240}Pu$	$4\ 10^{-4}$	$5\ 10^{-6}$ - $4\ 10^{-5}$
	^{241}Am	$6\ 10^{-4}$	$4\ 10^{-6}$ - $4\ 10^{-5}$
Potatoes	^{90}Sr	$2\ 10^{-1}$	$3\ 10^{-3}$ - $2\ 10^{-2}$
	^{137}Cs	$3\ 10^{-2}$	$5\ 10^{-2}$ - $3\ 10^{-1}$
	$^{239-240}Pu$	$2\ 10^{-4}$	$1\ 10^{-5}$ - $2\ 10^{-5}$
	^{241}Am	$4\ 10^{-4}$	$8\ 10^{-6}$ - $1\ 10^{-5}$

Note:
(a) Types of soil: loam, peat and sand Types of soil: loam, peat and sand

The soil to plant TFs for ^{90}Sr for cabbage, carrot and potato in FARMLAND are at least an order of magnitude higher than the values obtained in this study. However, they are within the range of the data reported by IAEA (IAEA, 2009). Therefore, the FARMLAND data can be considered appropriate for generic assessments.

The soil to plant TFs used in FARMLAND for ^{137}Cs for cabbage, carrot and potatoes are very similar to the values at the lower end of the range obtained in this study, which correspond to the soil to plant TFs in the loam soil. The higher values of the range are for the peat soil. Further investigation will be undertaken on the ^{137}Cs transfer to crops to provide additional TF values.

For $^{239-240}Pu$ and ^{241}Am, the soil to plant TFs for this study are significantly lower than the FARMLAND values and, in most cases by more than an order of magnitude. The majority of the TF values from this study are, however, within an order of magnitude of the values obtained by Nisbet and Shaw (1994) and Green at al (1997b). The range of TF values for $^{239-240}Pu$ and ^{241}Am reported in the literature is very wide and the IAEA reports values are up to two orders of magnitude higher than the FARMLAND values. Given this large range, it is appropriate to retain the conservative default TF values for these radionuclides in FARMLAND for generic applications.

Although the soil to plant TF values for ^{90}Sr and ^{241}Am were lower for this study compared to the FARMLAND values; the FARMLAND values are within the range of the IAEA values (IAEA, 2009). Therefore it is reassuring that the contribution from these radionuclides will not be underestimated when radiological doses assessments are carried out. It is important, however, that the TF values used are realistic and so a new study is being carried out to determine if lower TFs continue to be seen and whether TF values should be lowered in FARMLAND for typical UK agricultural soils.

6 CONCLUSIONS

The main objective of this study was to measure soil to plant transfer factors for cabbage, carrots and potatoes to identify if there had been any significant changes in uptake since the last study carried out 10 years previously.

For ^{137}Cs, $^{239-240}$Pu and ^{241}Am, no trend was observed between the TF values from measurements made in the mid-1990s and those from this study. However, for ^{90}Sr, the soil to plant transfer factors appear to have decreased for the three soil types studied for cabbage, carrots and potatoes.

For all radionuclides, except ^{90}Sr, the differences between the soil to plant TFs compared to the earlier lysimeter studies were not consistent across all the soil types and therefore it is difficult to attribute any change just to the age of soil contamination. Changes in chemistry of the soil that may have occurred since the time the previous studies were carried out may also be important.

The distribution of radionuclides between edible and inedible parts of the crops supports the findings from the earlier lysimeter studies carried out at HPA.

The soil to plant TFs measured in this study, when compared to other studies, show that the differences found for ^{137}Cs for cabbage grown in peat and ^{90}Sr and ^{241}Am in all crops and soils do not have a major impact in terms of modelling root uptake in the FARMLAND model. Although the soil to plant TF values for ^{90}Sr and ^{241}Am were lower for this study compared to the FARMLAND values and the TF value for ^{137}Cs in peat soil was higher, the FARMLAND values are within the range of the published IAEA values. The current values in FARMLAND are therefore considered to still be appropriate for generic assessments, taking into account the available published data and the importance of not underestimating activity concentrations in foods.

Due to the relatively high TF values for strontium, it is important to investigate further if the decrease in TF values is a real trend and whether it needs to be taken into account in the default values in FARMLAND. A new study is therefore being carried out to further investigate soil to plant transfer of ^{90}Sr in carrots and cabbage. The results of this further study will determine if lower TFs continue to be seen and will inform the choice of default values for use in FARMLAND. Further investigation will also be undertaken on the ^{137}Cs transfer to crops to validate, or otherwise, the higher values observed for peat soils in the study compared to those that had been measured previously.

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APPENDIX A Soil to plant ratio of TFs for inedible and edible parts of the crop

Table A1:Transfer factor[a] for the edible and inedible (peel/outer leaves) part of the crop

Crop	*Soil*	Radionuclide	Edible	Peel / outer leaves	Ratio $TF_{inedible}/TF_{edible}$
Cabbage	Loam	^{90}Sr	1.1 10^{-1}	7.0 10^{-1}	6.5
		^{137}Cs	4.7 10^{-2}	5.0 10^{-2}	1.1
		$^{239-240}Pu$	3.9 10^{-5}	3.9 10^{-4}	9.8
		^{241}Am	4.0 10^{-5}	3.8 10^{-4}	9.5
	Peat	^{90}Sr	1.8 10^{-2}	1.3 10^{-1}	7.2
		^{137}Cs	1.7 10^{0}	1.9 10^{0}	1.1
		$^{239-240}Pu$	7.9 10^{-6}	2.6 10^{-4}	33
		^{241}Am	6.9 10^{-6}	2.5 10^{-4}	36
	Sand	^{90}Sr	1.2 10^{-1}	1.2 10^{0}	10
		^{137}Cs	1.2 10^{-1}	1.3 10^{-1}	1.2
		$^{239-240}Pu$	1.1 10^{-5}	3.2 10^{-4}	28
		^{241}Am	1.2 10^{-5}	3.9 10-^{4}	33
Carrots	Loam	^{90}Sr	1.1 10^{-1}	1.6 10^{-1}	1.5
		^{137}Cs	5.0 10^{-2}	8.9 10^{-3}	0.18
		$^{239-240}Pu$	3.9 10^{-5}	6.1 10^{-4}	15
		^{241}Am	3.9 10^{-5}	6.6 10^{-4}	17
	Peat	^{90}Sr	1.9 10^{-2}	3.6 10^{-2}	1.9
		^{137}Cs	2.1 10^{-1}	4.8 10^{-2}	0.23
		$^{239-240}Pu$	5.1 10^{-6}	1.1 10^{-4}	21
		^{241}Am	3.6 10^{-6}	9.3 10^{-5}	26
	Sand	^{90}Sr	1.4 10^{-1}	2.0 10^{-1}	1.4
		^{137}Cs	7.0 10^{-2}	1.3 10^{-2}	0.18
		$^{239-240}Pu$	2.2 10^{-5}	9.2 10^{-4}	42
		^{241}Am	2.0 10^{-5}	1.0 10^{-3}	51
Potatoes	Loam	^{90}Sr	1.9 10^{-2}	8.9 10^{-2}	4.7
		^{137}Cs	5.1 10^{-2}	1.9 10^{-2}	0.37
		$^{239-240}Pu$	1.3 10^{-5}	3.0 10^{-4}	23
		^{241}Am	1.0 10^{-5}	3.0 10^{-4}	29

Crop	*Soil*	Radionuclide	Edible	Peel / outer leaves	Ratio $TF_{inedible}/TF_{edible}$
Potatoes	Peat	^{90}Sr	$2.6\ 10^{-3}$	$9.6\ 10^{-3}$	3.6
		^{137}Cs	$2.6\ 10^{-1}$	$1.0\ 10^{-1}$	0.40
		^{239}Pu	$1.1\ 10^{-5}$	$2.1\ 10^{-4}$	19
		^{241}Am	$8.4\ 10^{-6}$	$2.0\ 10^{-4}$	23
	Sand	^{90}Sr	$2.1\ 10^{-2}$	$8.1\ 10^{-2}$	3.9
		^{137}Cs	$1.1\ 10^{-1}$	$3.9\ 10^{-2}$	0.34
		^{239}Pu	$1.7\ 10^{-5}$	$3.3\ 10^{-4}$	20
		^{241}Am	$1.3\ 10^{-5}$	$3.4\ 10^{-4}$	26

Note: (a) $TF = \dfrac{\text{Bq kg}^{-1}\text{ dry mass plant}}{\text{Bq kg}^{-1}\text{ dry mass soil}}$