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Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments

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HANDBOOK OF PARAMETER VALUES FOR THE PREDICTION OF RADIONUCLIDE TRANSFER IN TERRESTRIAL AND FRESHWATER ENVIRONMENTS

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FOREWORD

For many years, the IAEA has published materials aimed at supporting the assessment of radiation impacts on human beings and the environment. Two major publications, Sediment K_ds and Concentration Factors for Radionuclides in the Marine Environment (Technical Reports Series No. 247), published in 1985, and the Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments (Technical Reports Series No. 364), published in 1994, together provided a full set of available transfer parameter values for the marine, freshwater and terrestrial environments. For many years, these two publications have served as key references for radioecologists, modellers and authorities, providing data for use in environmental impact assessments.

Since the publication of these two collections of data, a number of publications on transfer parameter values have been produced and merit consideration. Therefore, in 2000 the IAEA initiated a revision of Technical Reports Series No. 247 which resulted in the publication, in 2004, of Sediment Distribution Coefficients and Concentration Factors for Biota in the Marine Environment (Technical Reports Series No. 422), covering newly obtained data as well as changes in the regulatory framework.

In 2003, within the framework of the Environmental Modelling for Radiation Safety (EMRAS) programme, the IAEA undertook a revision of Technical Reports Series No. 364. The current publication was prepared by the members of Working Group 1 of the EMRAS programme, chaired by P. Calmon (IRSN, France). This publication focuses on transfer parameter values; the models in which they are used generally are not described here. It is therefore supported by IAEA-TECDOC-1616, which accompanies this report and contains the full collection of the reviewed data and provides radioecological concepts and models facilitating the use of these values in specific situations. This publication is intended to supplement existing IAEA reports on environmental assessment methodologies.

The IAEA wishes to express its gratitude to all the experts who contributed to this report, and to the International Union of Radioecologists for its support.

The IAEA officer responsible for this publication was S. Fesenko of the Agency’s Laboratories (Seibersdorf and Headquarters).

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The impacts of planned discharges of radionuclides to the environment are assessed by means of mathematical models that approximate the transfer of radionuclides through the compartments of the environment [1]. These models can be used as tools to evaluate the effectiveness of countermeasures applied to reduce the impacts of accidental releases of radionuclides and to predict the future impact of releases from underground waste repositories. In all these applications, the reliability of the predictions of the models depends on the quality of the data used to represent radionuclide transfer through the environment. Ideally, such data should be obtained by measurements made in the environment being assessed. However, this is often impracticable or overly costly, and thus there is heavy reliance on data obtained from the literature. Often such data can provide an estimate of the radiological impact of a planned release to satisfy regulatory requirements. Only when the estimated radiation doses to humans approach nationally established regulatory limits is a more site specific approach needed. Similarly, the potential impact of accidental releases and of releases in the far future can usually be adequately assessed using such generic data sets.

The International Atomic Energy Agency (IAEA) has for many years supported efforts to develop models for radiological assessments [1, 2] and to assemble sets of transfer parameter data, and in 1994 it published a collection of data for estimating radionuclide transfer in the terrestrial and freshwater environments (Technical Reports Series No. 364) [3]. The IAEA also published a similar collection relevant to transfer in the marine environment, which was updated in 2004 [4]. These data collections draw upon data from many countries of the world and have come to be regarded as international reference values.

Since the publication of TRS-364 [3], new data sets have become available, and an update of the report was considered appropriate. The present publication supersedes TRS-364 [3] and includes considerably expanded information on ecosystems other than temperate ecosystems, on radionuclides, and on processes to be taken into account in the assessment of the radiation impact of radionuclide discharges to the terrestrial and freshwater environments.

The data included here relate mainly to equilibrium conditions, that is, they relate to the conditions where equilibrium has been established between the movements of radionuclides into and out of the compartments of the environment. Such a situation may exist during the controlled and continuous release of radionuclides to the environment from a nuclear facility. In the case of short term releases, as might occur in the event of an accident, equilibrium cannot be assumed, and the rate of transfer between compartments must be assumed to vary with time. Some data relevant to time dependent radionuclide transfer in the environment are also included in this publication, for example, data on weathering and translocation for foliar uptake, on the long term dynamic of transfer factors for root uptake, and on some processes in semi-natural ecosystems.

The data contained here are generally presented as ranges of observed values; where the available data permit, mean values determined by statistical methods are also included. The statistical approach is described in Section 2. The data can be used for various purposes, in particular:

(a) To derive transfer parameters for screening purposes, that is, to evaluate, in a preliminary and approximate way, the radiological significance of a planned environmental release. For this purpose, modelling assumptions and data are chosen conservatively so that there is only a small probability of underestimation of detrimental environmental effects. If regulatory targets are met by using this approach, then usually no further assessment is needed. This is the approach described in Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment (IAEA Safety Reports Series No. 19) [1]. The conservative values of the transfer parameters used in that publication were mainly obtained from the upper end of the ranges of data given in TRS-364 [3].

(b) To obtain realistic estimates of the radiation dose to humans by using the mean of the observed values and realistic modelling assumptions. However, it must be noted that generic data sets are no substitute for site specific data for obtaining realistic estimates of radiation dose.

A specific task of the revision of TRS-364 [3] was to provide the transfer parameter values that are the most commonly used in radiological assessment models. However, some important details and recommendations on how to use these parameters were omitted from TRS-364, which constrained its usefulness in helping assessors to make appropriate choices of necessary transfer parameters. Moreover, the data sets reviewed for the purpose of producing the present publication are very extensive, and in some topic areas the tables contain only summaries of the available data. Therefore this handbook is supported by the accompanying TECDOC-1616 [5], which contains the full collection of the reviewed data and the methods used to obtain the tabulated data values. This TECDOC also gives necessary clarifications of how the tabulated values were derived and provides radioecological concepts and models facilitating the use of these values in specific situations.

1.2. OBJECTIVE

This publication is primarily intended to provide IAEA Member States with data for use in the radiological assessment of routine discharges of radionuclides to the environment. Some of the data may also be useful for assessing the impact of accidental releases and of releases in the far future.

1.3. SCOPE

This report covers radionuclide transfer in the terrestrial and freshwater environments. The data collected here are relevant to the transfer of radionuclides through food chains to humans and are not specifically addressed to radionuclide transfers to non-human species. However, in many situations they are also applicable for assessments of radionuclide transfer to non-human species. The data relate mainly to equilibrium conditions, that is, conditions where equilibrium has been established between the movements of radionuclides into and out of the compartments of the environment. However, some data relevant to time dependent radionuclide transfer in the environment are also included.

The focus of this publication is on transfer parameter values; the models in which they are used generally are not described here. Typical models applied in the context of the control of routine releases are described in Ref. [1].

1.4. STRUCTURE

This report consists of 12 sections and 2 appendices. Definitions and units, classifications used and necessary details of data analysis are given in Section 2. The nine sections that follow provide data relevant to parameters for a range of different environmental transfer processes. Sections 3, 4 and 5 address contamination of plants, focusing on foliar uptake, mobility in soil and uptake from soil by plants, respectively. Section 6 considers radionuclide transfers to agricultural animal products. Parameters for modelling radionuclide transfer to products from semi-natural extensive ecosystems (forests, uplands and polar ecosystems) are given in Sections 7 and 8. Section 9 is devoted to the transfer of radionuclides to food products in freshwater ecosystems. For some radionuclides, in particular for H, ^{14}C and ^{36}Cl, transfer parameters and models are normally formulated in terms of specific activity concepts. Therefore, data for these radionuclides were treated separately and are presented in Section 10. Section 11 gives information on the impact of different methods of food processing on decontamination of food. Finally, the application of analogue approaches to filling data gaps is described in Section 12. The appendices provide reference information applicable to one or more of the preceding sections. The accompanying TECDOC [5] is included on the CD-ROM at the end of this publication.

2. DEFINITIONS AND DATA ANALYSIS

2.1. BASIC DEFINITIONS

Generic quantities and units used throughout this publication are given in Table 1. Generic quantities and terms are as defined in the International Commission on Radiation Units and Measurements (ICRU) report on quantities and units [6], as used by the IAEA, or are those in common usage. The definitions of specific terms are also given in each section.

2.2. DATA ANALYSIS

International databases of bibliographical references, reports from scientific institutions and a number of relevant national databases were consulted to derive values for radionuclide transfer in the environment. Priority was given to data from original publications rather than to data from review sources, although the latter were used in some cases.

In this publication, transfer parameters are normally given for dry weight. When these parameters are expressed relative to fresh weight, the fresh weight/dry weight conversion factors given in Appendix I have been applied.

The data presented here are derived from TECDOC-1616 on Quantification of Radionuclide Transfers in Terrestrial and Freshwater Environments for Radiological Assessments [5], where the available data were analysed to (a) estimate a representative value for a given parameter and (b) obtain an indication of the extent of uncertainty about this estimate. International databases of bibliographical references and some national databases were consulted by using relevant key words. Such bibliographical searches were limited to (a) published documents within the international scientific literature and, depending on their accessibility, (b) reports from different scientific institutions. Priority was given to data from original publications and all the information that they contained, rather than to summaries of such information. During the second step, databases were elaborated, where necessary (see Ref. [5] for details).

TABLE 1. GENERIC QUANTITIES AND UNITS USED IN THIS PUBLICATION

Symbol	Name	Definition	Unit
Foliar uptake			
α	Interception coefficient	The ratio of the initial mass activity density on the plant (A_m, in Bq kg^{-1}) to the unit area activity density (A_α, in Bq m^{-2}) on the terrestrial surface (soil plus vegetation).	m^2 kg^{-1}
f_{tr}	Translocation ratio, translocation factor, translocation coefficient	The mass activity density (A_m, in Bq kg^{-1}) in one tissue, typically an edible tissue, divided by the mass activity density (A_m, in Bq kg^{-1}) in another tissue of the same plant or crop. The translocation ratio can be calculated as the mass activity density in the edible tissue (Bq kg^{-1}) divided by the activity contained on the mass foliage covering a square metre of land surface (Bq m^{-2}).	Dimensionless, m^2 kg^{-1}
K_s	Resuspension factor	The ratio of the volumetric activity density (A_v, in Bq m^{-3}) measured in air or water to the areal activity density (A_α, in Bq m^{-2}) measured on the soil or sediment surface.	m^{-1}
Soil mobility			
K_d	Distribution coefficient	The ratio of the mass activity density (A_m, in Bq kg^{-1}) of the specified solid phase (usually on a dry mass basis) to the volumetric activity density (A_v, in Bq L^{-1}) of the specified liquid phase.	L kg^{-1}
Soil to plant transfer			
F_v	Concentration ratio	The ratio of the activity concentration of radionuclide in the plant (Bq kg^{-1} dm) to that in the soil (Bq kg^{-1} dm).	Dimensionless
Herbage to animal transfer			
F_1	Absorbed fraction	The fraction of the intake by an animal that is transferred to a specified receptor tissue.	Dimensionless
F_m, F_f	Feed transfer coefficient	The mass or volumetric activity density in the receptor animal tissue or animal product (Bq kg^{-1} fresh weight or Bq L^{-1}) divided by the daily intake of radionuclide (in Bq d^{-1}).	d kg^{-1} or d L^{-1}, where d is the time in days
Transfer in semi-natural ecosystems			
T_{ag}	Aggregated transfer factor	The ratio of the mass activity density (Bq kg^{-1}) in a specified object to the unit area activity density (A_a, in Bq m^{-2}).	m^2 kg^{-1}
Transfer in freshwater ecosystems			
CR	Concentration ratio, water–biota	The ratio of the radionuclide concentration in the receptor biota tissue (fresh weight) from all exposure pathways (including water, sediment and ingestion/dietary pathways) mass relative to that in water.	Dimensionless
$CR_{s\text{-}b}$	Concentration ratio, sediment–biota	The ratio of the concentration of a radionuclide in biota tissue (fresh weight) to that in the sediment (C_{sed}) (fresh weight).	Dimensionless

TABLE 1. GENERIC QUANTITIES AND UNITS USED IN THIS PUBLICATION (cont.)

Symbol	Name	Definition	Unit
Specific activity approaches			
$CR_{s\text{-}a}$	Concentration ratio, soil water to air moisture for HTO	The ratio of the tritiated water (HTO) concentration in soil water to that in air moisture.	Dimensionless
R_p, R_f	Partition factor	R_p for plants is the ratio of the concentration of non-exchangeable organically bound tritium (OBT) in the combustion water of plant dry matter to the concentration of tissue free water tritium in plant leaves. R_f for fish is the ratio of OBT concentration in the combustion water of fish dry matter to the HTO concentration in fish flesh.	Dimensionless
CR_a^{HTO}, CR_a^{OBT}	Concentration ratio	CR_a^{HTO} is the ratio of the total tritium concentration (HTO + OBT) in an animal product to the average HTO concentration in the water taken in by the animal via feed, drinking water and inhaled air. CR_a^{OBT} is the ratio of the total tritium concentration in the animal product to the average OBT concentration in the animal's feed.	Bq kg^{-1} fresh weight/(Bq L^{-1}) for HTO intake; Bq kg^{-1} fresh weight/(Bq kg^{-1} dry weight) for OBT intake
Food processing			
F_r	Food processing retention factor	The ratio of the total amount of a radionuclide in a given food item when ready for consumption to the total amount of the radionuclide in the original raw food before processing and preparation.	Dimensionless
P_f	Processing factor	The ratio of the radionuclide activity concentration in a given food item when ready for consumption to the activity concentration before processing and preparation.	Dimensionless
P_e	Processing efficiency	The ratio of the fresh weight of processed food to the weight of the original raw material.	Dimensionless

Estimations of the transfer parameter values and the extent of uncertainty about each such value were carried out by applying statistical analysis, where possible. In the ideal case, where three or more values were available ($N > 2$), a geometric mean was given in the tables as the mean value. The uncertainties assigned to the geometric mean were estimated by using the geometric standard deviation. If only two values were available, the parameters were shown in reported ranges with minimum and maximum values, along with the arithmetic mean and the standard deviation.

Thus, depending on the number of values used for the statistical analysis, the mean given in the tables included here may be a geometric mean or an arithmetic mean, with the corresponding uncertainties. The number of data is also reported. In some cases, the values were given without a statement of uncertainty or a range, because of the limited data available. The values in such cases should be used with a great caution.

2.3. TIME DEPENDENCE OF RADIONUCLIDE TRANSFER FACTORS

By definition, concentration ratios and aggregated transfer factors assume that the activity concentration of the radionuclide in the organism is in equilibrium with that in the relevant environmental medium (soil, sediment or water). However, for many radionuclides, transfer to foodstuffs will change over time as a result of changes in the extent of uptake due to soil fixation (‘ageing’) processes and to migration of radionuclides into the soil profile and finally out of the rooting zone. The rate of increase in the extent of radionuclide activity concentrations in animal tissue will depend not only on ingestion quantities but also on the rate of uptake and loss from tissues. Such changes over time in radionuclide activity concentrations in environmental compartments are often termed biological or ecological half-lives.

The biological half-life, $T_{1/2}^{bio}$, is a measure of the rate at which radionuclides are excreted from an organism, and it is defined as the time required for a twofold decrease of the radionuclide activity concentration in a given organ (or tissue) resulting from the action of all possible factors except radioactive decay. For example, if a sheep contaminated with radiocaesium is fed uncontaminated feed for a period of time, the radiocaesium in the sheep’s body will decline at a rate determined by the biological half-life. If the initial concentration of radionuclide in the sheep is $C(0)$, then after time t the activity concentration $C(t)$ of radionuclide in the body of sheep is given by:

$$C(t) = C(0)\exp[-(\lambda_r + \lambda_{bio})t] \tag{1}$$

where λ_r is the radioactive decay constant and λ_{bio} is the rate of excretion of the radionuclide from the organism. Then, $T_{1/2}^{bio}$ can be calculated as:

$$T_{1/2}^{bio} = \frac{\ln 2}{\lambda_{bio}} \tag{2}$$

In most cases, however, animals (or plants) remain in the contaminated environment, ingesting contaminated food, so they continue to take in radionuclides. Thus, long term declines in activity concentrations in plants and animals occur at rates slower than the biological half-life, being controlled by soil ‘ageing’ and redistribution processes. The long term, time dependent behaviour of radionuclides in the environment is often quantified using the ecological half-life, $T_{1/2}^{eco}$, which is an integral parameter that lumps together all processes (except radioactive decay) that cause a reduction of activity in a specific medium. The processes involved in determining the value of the ecological half-life are specific to the medium considered; for example, for the reduction of activity in game, losses of radionuclides from the root layer of the soil, fixation to soil particles and uptake by plants are the most relevant processes. Assuming that the decline in radioactivity concentration C from an initial concentration $C(0)$ is exponential:

$$C(t) = C(0) \cdot e^{-(\lambda_r + \lambda_{eco})t} \tag{3}$$

The rate of decline, λ_{eco}, is related to the ecological half-life, $T_{1/2}^{eco}$, which can be calculated as follows:

$$T_{1/2}^{eco} = \frac{\ln 2}{\lambda_{eco}} \tag{4}$$

If radioactive decay (characterized by physical half-life T_r) is included in the reduction of the content or concentration of a particular radionuclide in a system, then the effective ecological half-life T^{eff} is given by:

$$\frac{1}{T^{eff}} = \frac{1}{T^{eco}} + \frac{1}{T_r} \tag{5}$$

Environmental compartments often exhibit declining parameter values (e.g. T_{ag} values, concentrations) that cannot be described by a single term exponential function; often, two exponential models are needed to describe the data adequately. The time dependence of the aggregated transfer coefficient (or any other quantities, such as the radionuclide concentrations in some environmental compartments) then can be expressed as:

$$\begin{aligned} T_{ag}(t) &= T_{ag}(0) \cdot \left(a_1 \cdot e^{-\frac{\ln 2}{T_1^{eff}} \cdot t} + (1 - a_1) \cdot e^{-\frac{\ln 2}{T_1^{eff}} \cdot t} \right) \\ &= T_{ag}(0) \cdot e^{-\frac{\ln 2}{T_r} \cdot t} \cdot \left(a_1 \cdot e^{-\frac{\ln 2}{T_1^{eco}} \cdot t} + (1 - a_1) \cdot e^{-\frac{\ln 2}{T_2^{eco}} \cdot t} \right) \end{aligned} \tag{6}$$

where T_1^{eff} is the fast loss component, T_2^{eff} is the slow loss component, $T_{ag}(0)$ is the initial value of the aggregated transfer coefficient and a_1 is the initial fraction of this coefficient associated with the fast loss term. The estimates for the fast loss term depend on the definition of time zero, and care must be taken when comparing results from different studies.

2.4. SOIL AND PLANT CLASSIFICATIONS

It is often possible to reduce the uncertainty in the estimate of the expected value by categorizing parameters according to food type, soil group, type of deposition or environmental conditions. Where possible, this has been done in this handbook; however, where data were few, or are not specified in sufficient detail to permit such grouping, only general categories were used to derive a transfer parameter value.

The transfer of radionuclides through the food chain varies considerably, depending on soil properties [7]. In the soil classification of the Food and Agriculture Organization of the United Nations (FAO)/United Nations Educational, Scientific and Cultural Organization (UNESCO), there are 28 units and 125 subunits [8]. F_v values are not available for all units or subunits, even for the most extensively studied radionuclides. Therefore, a more broadly based classification is adopted here that permits some distinction on the basis of texture and organic matter content, while ensuring that a reasonable amount of data is available for each category. For this handbook of parameter values, four soil groups were defined: sand, loam, clay and organic (Table 2).

Soils were grouped according to the percentages of sand and clay in the mineral matter, and the organic matter (OM) content in the soil. This defined the 'texture/OM' criterion, which is similar to the criterion followed in TRS-364 [3]. For the mineral soils, the following three groups were created according to the percentages of sand and clay in the mineral matter [9]: sand (sand fraction ≥65%, clay fraction <18%), clay (clay fraction ≥35%) and loam (all other mineral soils). A soil was included in the 'organic' group if the organic matter content was ≥20%. Finally, an 'unspecified' soil group was created for soils without characterization data, and for mineral soils with unknown sand and clay contents. More details of the typical textures of the mineral soil classes are given in the accompanying TECDOC [5].

TABLE 2. TYPICAL RANGES OF VALUES OF SELECTED SOIL PARAMETERS FOR THE FOUR SOIL GROUPS

Soil group	pH	Organic matter content (%)	Cation exchange capacity (cmol_c/kg)	Sand content in the mineral matter fraction (%)	Clay content in the mineral matter fraction (%)
Sand	3.5–6.5	0.5–3.0	3.0–15.0	≥65	<18
Loam	4.0–6.0	2.0–6.5	5.0–25.0	65–82	18–35
Clay	5.0–8.0	3.5–10.0	20.0–70.0	—	≥35
Organic	3.0–5.0	≥20	20.0–200.0	—	—

Based on the analyses of available information on radionuclide transfer to plants [5, 9, 10], 14 plant groups were identified (Table 3).

The individual plants assigned to these groups are shown in Appendix II; plant compartments are shown in Table 3.

TABLE 3. PLANT GROUPS AND PLANT COMPARTMENTS

Plant group	Plant compartment
Cereals	Grains, seeds and pods
	Stems and shoots
Maize	Grains, seeds and pods
	Stems and shoots
Rice	Grains, seeds and pods
	Stems and shoots
Leafy vegetables	Leaves
Non-leafy vegetables	Fruits, heads, berries and buds
Leguminous vegetables	Grains, seeds and pods
Root crops	Roots
Tubers	Tubers
Fruits	Fruits, heads, berries and buds
Grasses (cultivated species)	Stems and shoots
Leguminous fodder (cultivated species)	Stems and shoots
Pasture (species mixture — natural or cultivated)	Stems and shoots
Herbs	Leaves
	Grains, seeds and pods
	Fruits, heads, berries and buds
Other crops	Grains, seeds and pods
	Leaves
	Stems and shoots
	Fruits, heads, berries and buds
	Roots
	Tubers

3. AGRICULTURAL ECOSYSTEMS: FOLIAR UPTAKE

The deposition of radionuclides on vegetation and soil represents the starting point of their transfer in the terrestrial environment and in food chains. There are two principal deposition processes for the removal of pollutants from the atmosphere: dry deposition is the direct transfer to and absorption of gases and particles by natural surfaces such as vegetation, whereas wet deposition is the transport of a substance from the atmosphere to the ground in snow, hail or rain. Once deposited on vegetation, radionuclides are lost from plants due to removal by wind and rain, either through leaching or by cuticular abrasion. The increase of biomass during growth does not cause a loss of activity, but it does lead to a decrease of activity concentration due to effective dilution. There is also systemic transport (translocation) of radionuclides in the plant subsequent to foliar uptake, leading to the redistribution of a chemical substance deposited on the aerial parts of a plant to the other parts that have not been contaminated directly.

3.1. INTERCEPTION

3.1.1. Definitions and parameters

There are several possible ways to quantify the interception of deposited radionuclides (see also Section 1). The simplest is the interception fraction, f (dimensionless), which is defined as the ratio of the activity initially retained by the standing vegetation immediately subsequent to the deposition event, A_i, to the total activity deposited, A_t:

$$f = \frac{A_i}{A_t} \tag{7}$$

The interception fraction is dependent on the stage of development of the plant. To take account of this, in some experiments and models the interception fraction is normalized to the standing biomass B (kg m^{-2}, dry mass). This quantity is denoted as the mass interception fraction f_B (m^2 kg^{-1}):

$$f_B = \frac{f}{B} \tag{8}$$

Since the leaf area represents the main interface between the atmosphere and the vegetation, the interception fraction is sometimes normalized to the leaf area index, which is defined as the ratio of the (single sided) leaf area to the soil area.

Chamberlain and Chadwick [11] defined the interception fraction (Eq. (7)) for dry deposition in terms of a dependence on the standing biomass and the empirically derived mass interception coefficient:

$$f = 1 - \exp(-\alpha \cdot B) \tag{9}$$

The mass interception fraction (Eq. (8)) is then derived to take into account the dependence of the interception fraction on the biomass using:

$$f_B = \frac{1 - \exp(-\alpha \cdot B)}{B} \tag{10}$$

For low density standing biomass, there is little difference between f_B and α.

3.1.2. Interception fractions

The interception of radionuclides is the result of the interaction of various factors, including the stage of development of the plant, the capacity of the canopy to retain water, elemental properties of the radionuclide, and the amount of rain during a rainfall event and the intensity of the precipitation.

The interception of rain by vegetation is closely linked to the water storage capacity of the plant canopy. The interception increases during a rainfall event until the water storage capacity is reached and the weight of more rain overcomes the surface tension holding the water on the plants.

Water storage capacity is quantified in terms of the thickness of the water film (in millimetres) that covers the foliage. Since the capacity of the plant canopy to retain water is limited, the interception fraction decreases in general with increasing amounts of rainfall in a rainfall event. The interception of a radionuclide deposited by wet deposition is controlled by the storage capacity of water and the interaction of the radionuclide with the leaf surface, which strongly depends on the chemical form of the deposit.

The differences in interception between different elements are due to their different valences. As plant surfaces are negatively charged, they have the properties of a cation exchanger. Therefore, the initial retention of anions such as iodide is less than that of polyvalent cations, which seem to be effectively retained on the plant surface. More details on processes governing interception of radionuclides by plants, including all available information sources, are given in the accompanying TECDOC [5]; summaries of available interception fraction values for wet and dry depositions are given in Tables 4 and 5, respectively.

TABLE 4. INTERCEPTION FRACTION VALUES FOR WET DEPOSITION

Element	Crop	Standing biomass (kg m^{-2})	Amount of rainfall (mm)	Interception fraction (f)	Mass interception fraction (f_B, m^2 kg^{-1})	References
Chernobyl deposits						[12–15]
Ba	Grass	n.a.[a]			1.7	
Cs	Grass				1.1	
I	Grass				0.7	
Ru	Grass				0.48	
Simulated rain						[16–18]
Be			1		3.2 ± 0.91	
			10		1.4 ± 0.86	
I	Grass		1		4.3	
	Clover				8.7	
	Grass		2		1.6	
	Clover				4.1	
	Grass		4		1.1	
	Clover				2.5	
Sr	Grass		1		7.6	
	Clover				8.2	
	Grass		2		5.1	
	Clover				8.0	
	Grass		4		4.8	
	Clover				8.2	
Pure water[b]	Grass		1		6.2	
	Clover				11.1	
	Grass		2		4.3	
	Clover				5.9	
	Grass		4		1.8	
	Clover				4.0	
Be	Mean of 5 species	n.a.	8.5		1.8	[19]
Cd					1.8	
Cr					1.3	
Sr					1.0	
Ce					0.94	
S					0.35	
I					0.27	

TABLE 4. INTERCEPTION FRACTION VALUES FOR WET DEPOSITION (cont.)

Element	Crop	Standing biomass (kg m^{-2})	Amount of rainfall (mm)	Interception fraction (f)	Mass interception fraction (f_B, m^2 kg^{-1})	References
Cs[c]	Wheat	n.a.	0.4	0.03[d]	1.4	[20]
			0.7	0.074	3.5	
			1.5	0.029	1.4	
			4.4	0.024	1.2	
			8.9	0.014	0.5	
	Beans	n.a.	0.34	0.059	2.1	
			0.68	0.031	1.1	
			1.4	0.039	1.4	
			4.1	0.01	0.4	
			8.2	0.013	0.5	
	Grass	n.a.	0.45	0.18	4.6	
			0.9	0.21	5.5	
			1.8	0.11	2.8	
			5.4	0.036	0.9	
			10.8	0.027	0.7	
Simulated very fine drizzle, no water run-off from the foliage						[21–23]
Mixture of nuclides	Rice	0.079	0.03–0.04	0.48	6.0	[21]
		0.39		0.79	2.1	
		0.93		0.88	0.95	
		1.04		0.87	0.84	
		1.7		0.94	0.55	
		1.9		0.94	0.49	
	Soybean	0.021		0.34	17	[22]
		0.13		0.83	6.6	
		0.44		0.93	2.1	
		0.74		0.88	1.2	
		0.79		0.84	1.1	
		0.63		0.45	0.71	
	Chinese cabbage	0.005		0.16	30	[23]
		0.032		0.59	19	
		0.10		0.77	7.8	
		0.15		0.83	5.6	
		0.29		0.87	3.0	
	Radish	0.011		0.18	16	[21]
		0.044		0.67	15	
		0.089		0.82	9.3	
		0.15		0.86	5.9	
		0.17		0.86	5.2	

[a] n.a.: not available.
[b] Retention of radionuclide free water.
[c] Rainfall intensity: 4.4 mm h^{-1}.
[d] LAIF: Interception fraction per unit leaf area.

TABLE 5. INTERCEPTION FRACTION VALUES FOR DRY DEPOSITION

Deposited material	Particle diameter (μm)	Crop	f or f_B ($m^2\ kg^{-1}$), or (α) or (f_{LAI})[a] (arithmetic mean ± SD)	Reference
Lycodium spores	32	Grass	3.1 ± 0.15 (α)	[11]
		Wheat, dry	3.2 ± 0.5 (α)	[11]
		Wheat, moist	9.6 ± 3.7 (α)	[11]
Quartz particles	44–88	Grass	2.7 ± 0.3 (α)	[24]
Sand particles	40–63	Grass, dry	0.44 ± 0.15 (α)	[25]
		Grass, wet	0.88 ± 0.13 (α)	[25]
	63–100	Grass, dry	0.23 ± 0.07 (α)	[25]
		Grass, wet	0.69 ± 0.16 (α)	[25]
	100–200	Grass, dry	0.24 ± 0.07 (α)	[25]
		Grass, wet	0.46 ± 0.11 (α)	[25]
Pu particles	≈1	Corn	3.6 ± 0.05 (α)	[26]
I vapour		Grass	2.8 ± 0.14 (α)	[26]
Pb vapour		Artificial grass	13 (α)	[27]
Ba, Cs, Sr[b]	3.5	Beans: 30 d[c]	1–1.2 (α)	[28]
		45 d[c]	1.1 (α)	[28]
		65 d[c]	0.85–0.93 (α)	[28]
Ba, Cs, Sr, Te[b]		85 d[c]	0.3 (α)	[28]
Ba, Cs, Sr, Te[b]	3.5	Grass	0.84 ± 0.06 (f)	[28]
			3.27 ± 1.15 (α)	[28]
Cs, Sr[b]		Wheat	$f = 1 - \exp(-0.316 \cdot LAI)$	[3]
			$f = 0.85 \cdot (1 - \exp(-13.1 \cdot B))$[d]	[3]
Spherical porous silica particles	4	Lettuce	0.71 ± 0.1 (f)	[29]
	10		0.88 ± 0.07 (f)	[29]
	18		0.88 ± 0.08 (f)	[29]
	22		0.81 ± 0.23 (f)	[29]
	4	Wheat	0.56 ± 0.29 (f)	[29]
	22		0.65 ± 0.13 (f)	[29]
Spherical porous silica particles	4	Wheat	1.6 (f)	[30]
	22		1.2 (f)	[30]
Uranium particles (wind tunnel)	0.82	Spruce (LAI[e] = 3.1)	0.97 (f)	[31]
Cs, Sr		Rice	0.04–0.12 (f_{LAI}), n = 6	[32]
		Wheat	0.05–0.09 (f_{LAI}), n = 2	[32]
		Carrot	0.1–0.3 (f_{LAI}), n = 2	[32]
		Cabbage	0.18–0.2 (f_{LAI}), n = 2	[32]
		Tomato	0.08–0.9 (f_{LAI}), n = 2	[32]

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[a] f: Interception fraction; f_B: mass interception fraction.

[b] Dissolution in rainwater after 2 h: Cs, Ba — 95%; Sr — 75%, Te — 8%.

[c] Days after sowing.

[d] B: Yield (kg m^{-2} dry mass).

[e] LAI: Leaf area index.

For dry deposition, particle size is the other key parameter. Interception is more effective for small particles and reactive gases. Interception of radionuclides deposited by wet depostion is a result of the complex interaction of the chemical form of the element, the development of the plant and the amount of rainfall. Rainfall intensity appears to be of minor importance in determining interception.

3.1.3. Application of data

For the interception of dry and wet deposits by vegetation, the development of the plant canopy is a key factor [18]. The biomass density or the leaf area index may be used to quantify plant development. During vegetative growth, both approaches are equally appropriate, whereas during the generative phase, the leaf area index is a more suitable basis for interception modelling. In this phase, the biomass increases whereas the leaf area declines. Variations in the degree of interception of both dry and wet deposits can be reduced if interception is normalized to the standing biomass or to the leaf area index.

The existing data show that the interception of both dry and wet deposits depends on the chemical form of the deposit and its interaction with the plant surface and the canopy structure. Deeper knowledge of the processes involved would considerably improve the predictive power of the models applied so far. For wet deposits, the amount of rainfall is a key factor.

The values for α, f, f_B and f_{LAI} have all been determined from single experiments; before they are used, it should be checked whether the experimental conditions are consistent with the conditions of the deposition under consideration. The parameter f represents absolute interception, whereas α and f_B are normalized to the biomass and f_{LAI} is normalized to the leaf area index; therefore the variability of the last three parameters is less pronounced.

The interception of wet deposits decreases with increasing amounts of rainfall, during which the deposition occurs. For wet deposits, this dependence on rainfall is taken into account in the approach described by Müller and Pröhl (see Ref. [128]), who model the interception fraction for wet deposits as a function of: the leaf area index, LAI; the storage capacity of the plant, S; an element-dependent factor, k, that quantifies the ability of the element to be attached to the leaves; and the total amount of rainfall, R, that falls during a single event:

$$f = \min\left(1; \frac{LAI \cdot k \cdot S}{R}\left[1 - e^{-\frac{\ln(2)}{3 \cdot k \cdot S} \cdot R}\right]\right) \tag{11}$$

For *k*, values of 0.5, 1 and 2 are assumed for anions (iodide, sulphate), monovalent cations (e.g. Cs) and polyvalent cations, respectively. For water storage capacity, 0.2 mm is assumed for grass, cereals and corn, and 0.3 mm is assumed for all other crops.

For continuous depositions, the amount of rainfall per precipitation event is needed. Such data are not readily available; an upper limit can be obtained by dividing the total monthly rainfall by the number of days with precipitation >0.1 mm. Those values are given in climate statistics.

For continuous releases, average values for the standing biomass or for the leaf area indices should be applied for both dry and wet deposits. If the growth function is for a specific crop at a specific site, the use of monthly averages for biomass and leaf area index could be used.

3.2. WEATHERING

3.2.1. Definitions and parameters

Weathering is the loss of material from leaf surfaces after wet or dry deposition. In radioecological models, weathering is normally described by a single exponential function characterized by a first-order rate constant, λ_w, or a weathering half-life, T_w:

$$\lambda_w = \frac{\ln(2)}{T_w} \tag{12}$$

3.2.2. Weathering half-lives

Results from numerous studies show limited differences between cationic species (Mn, Co, Sr, Ru, Cs) for most plant species, but also show that T_w values are dependent on plant characteristics such as the plant growth stage at the time of deposition [33]. The available data, summarized based on information presented in the accompanying TECDOC [5] for different elements and plant groups, are given in Table 6.

3.2.3. Application of data

The magnitude of the weathering loss of a radionuclide depends on many factors, including its solubility, strength of adsorption to the plant surface, degree

TABLE 6. WEATHERING HALF-LIVES OF SELECTED ELEMENTS AND FOR GENERIC PLANT TYPES[a] (d) [12]

Element	Plant group	*N*	Arithmetic mean	Minimum	Maximum
Cs	Cereal	1	35		
Cs	Grass	4	10	7.9	11.1
I	Grass	9	13	8.3	29
I	Rice	1	14		
Sr	Grass	4	24	12.8	49
Sr	Cereals	1	21		
Mn-Ce	Cereals	1	30		
Pu	Cereals	1	12		
Pu	Fruits	1	43		

[a] Including growth dilution.

of penetration into the inner flesh and ability to leach from the interior. Biological factors such as the structure of the epidermis, plant senescence and defoliation, and shedding of old epicuticular wax also play a part in the weathering process. It can be inferred that the highly complex interaction of these factors may be the cause of the observed differences in weathering loss among radionuclides, and among plant species and their growth stages.

3.3. TRANSLOCATION

3.3.1. Definitions and parameters

Translocation is the process leading to the redistribution of a chemical substance deposited on the aerial parts of a plant to other parts that have not been contaminated directly. Translocation factors have been defined differently by different authors. Here, the translocation factor is defined as the ratio of the activity, on a ground area basis, of the edible part of a crop at harvest time (Bq m^{-2}) to the foliage activity of the crop at the time of deposition (Bq m^{-2}), expressed as a percentage.

3.3.2. Translocation

The direct contamination of plants by radionuclides or other elements and the transfer of these contaminants from the foliage to edible parts of the plants depend on many physical, chemical and biological factors [18, 34]. Physical factors include characteristics of the deposition regime, the contaminants (rain duration, size of particles) and the plant (foliage layout, leaf size and cuticular structure). Chemical factors include the speciation of the element water composition and cuticle composition [35–37]. Biological factors are mainly associated with the vegetative cycle at the time of the foliar deposit [38–41].

Experimental protocols for measurement of translocation have not yet been standardized; hence they vary widely and results remain very heterogeneous. The main contamination scenarios include:

(a) Simulations of sprinkling irrigation of contaminated water or contaminated rain at various timescales and intensities over the whole vegetation cover, with or without soil protection, followed or not by non-contaminated rain. This operating mode is the most realistic for investigation purposes.
(b) Sprays of contaminated solution over the foliage, followed or not, after drying, by non-contaminated rain.
(c) Foliar contamination by a deposit of dry or wet aerosols, followed or not, after drying, by non-contaminated rain.
(d) Deposit of droplets over part or all of the plant foliage, with a view to detecting translocation and mobility mechanisms within the plant. This method cannot be used to determine a translocation factor as defined in this document.

Few authors specify the plant growth stage at the time of deposit. The data given in this section were derived from the database with all available literature information. More details on source data and data analysis, as well as a description of the factors governing translocation, are given in the accompanying TECDOC [5]. Translocation factor values, as defined above, for cereals, root crops, tubers and fruits are presented in Tables 7–11.

TABLE 7. TRANSLOCATION FACTORS (f_{tr}) FOR CAESIUM IN CEREALS (GRAIN) (%)

Plant growth stage	*N*	Mean	Minimum	Maximum
Wheat, barley and rye				
Leaf development/tillering	21	0.6	0.06	7.9
Stem elongation	21	4.6	0.45	24.3
Earing/flowering	15	6.1	1.1	27.0
Grain growth	11	5.5	1.1	27.1
Ripening	11	2.7	1.1	7.7
Rice				
Leaf development/tillering	2	2.3	1.2	3.4
Stem elongation	1	4.3		
Earing/flowering	1	8.4		
Grain growth	1	11		
Ripening	1	2.2		

TABLE 8. TRANSLOCATION FACTORS (f_{tr}) FOR STRONTIUM IN CEREALS (GRAIN) (%)

Plant growth stage	*N*	Mean	Minimum	Maximum
Wheat, barley and rye				
Leaf development/tillering	2	0	0	0
Stem elongation	13	0.1	0.008	1.6
Earing/flowering	5	0.4	0.1	1.3
Grain growth	6	2.0	0.6	8.5
Ripening	8	1.2	0.3	5.1
Rice				
Leaf development/tillering	2	0.02	0.021	0.024
Stem elongation	1	0.02		
Earing/flowering	1	0.6		
Grain growth	1	1.3		
Ripening	1	1		

TABLE 9. TRANSLOCATION FACTORS (f_{tr}) FOR OTHER ELEMENTS IN CEREALS (GRAIN) (%)

Element	Plant growth stage	*N*	Mean	Minimum	Maximum
Wheat, barley and rye					
Mn	Leaf development/tillering	3	0.3	0.08	1.6
	Stem elongation	8	2.1	0.21	10.7
	Earing/flowering	6	2.3	0.47	12.7
	Grain growth	6	2.0	0.46	8.6
	Ripening	6	1.0	0.2	4.9
Co	Leaf development/tillering	5	0.5	0.06	3.4
	Stem elongation	3	1.0	0.24	4.6
	Earing/flowering	4	2.0	0.3	18.0
	Grain growth	4	2.8	0.3	29.0
	Ripening	3	1.5	0.5	6.6
Zn	n.a.[a]	6	15.8	7.6	32
Fe	Leaf development/tillering	4	0.8	0.65	1.2
	Stem elongation	3	1.0	0.57	1.5
	Earing/flowering	3	1.9	1.3	2.6
	Grain growth	3	2.7	1.0	7.5
	Ripening	3	1.5	0.35	9.2
Ru	n.a.	8	0.11	0.04	1.18
Ce	Stem elongation	8	0.1	0.02	0.8
	Grain growth	4	0.6	0.1	7.8
	Ripening	4	1.3	0.3	6.0

TABLE 9. TRANSLOCATION FACTORS (f_{tr}) FOR OTHER ELEMENTS IN CEREALS (GRAIN) (%) (cont.)

Element	Plant growth stage	*N*	Mean	Minimum	Maximum
Sb	Leaf development/tillering	5	0.02	0.002	0.6
	Stem elongation	3	0.1	0.034	1.0
	Earing/flowering	3	1.2	0.3	5.2
	Grain growth	3	2.2	1.0	7.5
	Ripening	2	0.6	0.3	1.3
Cd	n.a.	6	0.7	0.025	3.8
Ba	n.a.	6	0.2	0.001	4.3
Hg	n.a.	6	0.5	0.01	8
Na	n.a.	6	2.0	0.17	7.0
Cr	n.a.	7	1.0	0.02	7.4
Be	n.a.	6	0.2	0.001	2.7
Pb	n.a.	3	2.0	0.2	8.2
Rice					
Mn	Leaf development/tillering	2	0.05	0.04	0.052
	Stem elongation	1	0.03		
	Earing/flowering	1	0.6		
	Grain growth	1	1.6		
	Ripening	1	0.7		
Co	Leaf development/tillering	2	0.2	0.06	0.2
	Stem elongation	1	1.6		
	Earing/flowering	1	4		
	Grain growth	1	6.6		
	Ripening	1	0.8		
Ru	Leaf development/tillering	2	0.005	0.005	0.006
	Stem elongation	1	0.02		
	Earing/flowering	1	0.12		
	Grain growth	1	0.38		
	Ripening	1	0.35		

[a] n.a.: not available.

3.3.3. Application of data

The majority of the available data relate to caesium and strontium. Other radionuclides have been insufficiently investigated, and it is difficult to obtain reliable values even for the most important plants.

Many radioecological models use values based on inadequately justified extrapolations or chemical analogies. This method is arbitrary insofar as chemical analogy refers only to the chemical properties of the elements; it does not, for example, necessarily imply that the elements will behave similarly inside the

TABLE 10. TRANSLOCATION FACTORS (f_{tr}) FOR ROOT VEGETABLES AND TUBERS[a] (%)

Element	*N*	Mean	Minimum	Maximum
Root crops				
Cs	17	4.6	0.7	13.0
Sr	14	0.5	0.2	1.6
Mn	5	0.24	0.2	0.4
Co	5	8	4.9	12
Ru	5	0.15	0.1	0.4
Te	1	0.8		
Ba	1	2.2		
Tubers				
Cs	23	11.6	1.3	46.0
Sr	9	0.1	0.02	0.5

[a] Plant growth stages are not given; it can be assumed that the values are for mature vegetables.

TABLE 11. TRANSLOCATION FACTORS (f_{tr}) FOR FRUITS[a] (%)

Element	Type of fruit	*N*	Mean	Minimum	Maximum
Cs	Apples, beans, grapes, tomatoes, strawberries	53	4.6	0.1	29.0
Sr	Apples, beans, grapes, tomatoes, strawberries	35	0.44	0.01	12.1
Ba	Beans	4	0.13	0.04	1.6
Zn	Tomatoes	2	4.3	2.6	7.0
Am	Beans	1	0.0005		
Pu	Beans	1	0.0003		

[a] Plant growth stages are not given; it can be assumed that the values are for mature fruits.

plant, as has been shown for calcium and strontium [42], and for caesium, potassium and rubidium [43]. Moreover, it does not take into account the various physiological and physicochemical mechanisms inside the plant that govern the translocation processes.

Moreover, some authors do not make a distinction between plant types and recommend a single default value, whatever the element and plant type. Data given without a growth stage indication should be used with caution, as its absence indicates a wide range of associated uncertainty.

3.4. RESUSPENSION

Resuspension occurs when the wind exerts a force exceeding the adherence of particles to the surface material. The forces in action are the weight of the particle, the adherence and the aerodynamic loads related to the flow of wind. According to wind erosion models, three types of process are used to describe the dispersion of particular contaminants deposited on surface soil [44–46]: surface creep, saltation and (re)suspension. Another process for resuspension is the mixed effect of wind and rain on particle detachment. Rain splash transport of soil particles in windless conditions has been studied in detail. The overall result of these studies is that the contribution of rain splash transport alone is small compared with that of overland flow transport [47–49].

3.4.1. Definitions and parameters

Resuspension is the process by which previously deposited radionuclides are re-entrained into the atmosphere by the action of wind on soil and vegetation surfaces. The resuspension factor K is the ratio of the volumetric air concentration ($C_v(t)$, Bq m^{-3}) above the soil/vegetation surface to the initial surface soil contamination ($C_{S,0}$, Bq m^{-2}):

$$K(t) = \frac{C_v(t)}{C_{S,0}} \quad (\mathrm{m}^{-1}) \tag{13}$$

The resuspension factor approach makes it possible to directly obtain the radionuclide concentration in the air.

3.4.2. Resuspension factor

Resuspension of radionuclides from accidentally contaminated sites has been documented with in situ measurements concerning plutonium and caesium contamination from the Chernobyl accident. The characterization of resuspension factors is a complicated task because of the number of processes involved. The extent of the resuspension depends on the material (particle size, shape, adherence), the surface type (roughness, humidity), the time elapsed since deposition and the intensity of soil processing.

As with measurements, resuspension models can be distinguished according to the environmental context. It is recommended that models tested on the data collected after the accident at Chernobyl be used in the context of accidental releases to air. However, other types of model may be more appropriate in other contexts, for example, in assessing the radiological impacts of contaminated land at sites that currently or formerly handle(d) or process(ed) radioactive materials [50].

For rural conditions, the model suggested for use is that of Garland et al. [51]:

$$K_s(t) = 1.2 \cdot 10^{-6}\, t^{-1} \quad (\mathrm{m}^{-1}) \tag{14}$$

where t is the time in days since deposition.

In this and subsequent models discussed in this section, the model formulations are not independent of the unit in which time is expressed. Generally, time is given in days unless otherwise stated. Garland et al. [51] advised that this formula be applied to deposits older than 1 day.

For urban environments, the Linsley model [52] provided the best results in the intercomparison exercises:

$$K_s(t) = 10^{-6} \exp(-0.01 \cdot t) + 10^{-9} \quad (\mathrm{m}^{-1}) \tag{15}$$

This expression yields a resuspension factor that lies within the range of those estimated in in situ experiments. However, it tends to overestimate short term concentrations and to underestimate the long term values. Moreover, the exponential decrease with time is difficult to justify because it is rarely measured in experiments.

For arid and desert conditions, it is recommended that the model discussed in Ref. [45] be used. This model gives values that are intermediate between those observed for urban and rural environments in the long term. The model form is:

$$K_s(t) = 10^{-6} \exp(-0.15\sqrt{t}) + 10^{-9} \quad (\mathrm{m}^{-1}) \tag{16}$$

In the first days and months that follow deposition, the value of the resuspension factor generally ranges between 10^{-5} m^{-1} in residential areas, on sites undergoing cleanup operations and on arid sites, and 10^{-6} m^{-1} on rural sites [46, 53, 54]. In humid or semi-humid climates, resuspension is generally more important under urban conditions than in rural systems. However, this might not be the case in desert or semi-desert environments. More details about processes governing resuspension as well as main achievements in resuspension modelling are given in the accompanying TECDOC [5].

3.4.3. Application of data

The values and models presented here are adapted for impact studies focusing on the resuspension of radionuclides deposited accidentally in the natural environment. The measurements carried out in the context of the Chernobyl accident provide a relatively homogeneous base for estimating the resuspension factor. The order of magnitude established is suitable for the estimation of average values over long periods of time and in a large area.

Some of the data sources cited here are well established, and the parameter values represent our best quantitative understanding of the processes considered. However, before using any of these parameters, it is advisable to consult the original publication(s) to ensure that the way the parameter values were originally obtained is compatible with the way they are to be used in assessment calculations. This is particularly important with regard to the consistent use of the units in which individual parameters are expressed.

4. RADIONUCLIDE INTERACTION IN SOILS

4.1. CONCEPTS AND PROCESSES

4.1.1. The solid-liquid distribution coefficient concept

Dissolved radionuclide ions can bind to solid surfaces by a number of processes that are often classified under the broad term of sorption. The behaviour and ultimate radiological impacts of radionuclides in soils are largely controlled by their chemical form and speciation, which strongly affect their mobility, the residence time within the soil rooting zone and uptake by biota.

The degree of radionuclide sorption on the solid phase is often quantified using the solid-liquid distribution coefficient, K_d, which can be used when making assessments of the overall mobility and likely residence times of radionuclides in soils. K_d is the ratio of the concentration of radionuclide sorbed on a specified solid phase to the radionuclide concentration in a specified liquid phase [55]:

$$K_d = \frac{\text{activity concentration in solid phase}}{\text{activity concentration in liquid phase}} \left(\frac{\text{Bq kg}^{-1}}{\text{Bq L}^{-1}} \right) \ (\text{L kg}^{-1}) \qquad (17)$$

The K_d approach takes no explicit account of sorption mechanisms but assumes that the radionuclide on the solid phase is in equilibrium with the radionuclide in solution and that exchange between these phases is reversible.

However, the time elapsed since the incorporation of the radionuclide in the soil is known to affect the magnitude of K_d, since a fraction of the incorporated radionuclide may become fixed by the solid phase (an aging effect related to sorption dynamics) [56, 57].

K_d values for specific radionuclides are commonly obtained from field and laboratory studies. Since radionuclides in the field may have been present in the soil for a long period of time (e.g. from atmospheric nuclear weapons testing or from the Chernobyl accident), K_d values determined in situ may be higher than those determined in short term laboratory experiments [55].

For some well studied radionuclides the influence of specific co-factors on K_d values can be evaluated. Co-factors are soil properties involved in the mechanisms responsible for radionuclide sorption [58–64], and they can be used to group K_d values and can reduce the variability of these values when the grouping is based on fundamental properties, such as soil texture and organic matter. More details concerning the use of co-factors in K_d grouping are provided in the the accompanying TECDOC [5].

4.1.2. Vertical transfer of radionuclides in undisturbed soil profiles

The basic processes controlling the mobility of radionuclides (and other trace elements) in soil include convective transport by flowing water, dispersion caused by spatial variations of convection velocities, diffusive movement within the fluid, and physicochemical interactions with the soil matrix. In addition to abiotic processes, soil fauna may contribute to the transport of radionuclides in soils [65], and their action under general conditions results in the dispersion of radionuclides within the soil profile [66].

Two approaches are widely applied for modelling the migration of radionuclides in soils:

(1) The serial compartment model;
(2) The convection-dispersion equation (CDE).

Results from the serial compartment models for describing vertical migration in soil are generally expressed as migration rates (cm a^{-1}). In contrast, the CDE approach considers that the input of the radionuclide can be approximated by a single pulse-like function. In this case, for a large time t, the first two moments of the depth distribution function are asymptotically approximated by:

$$E[z] \cong v_s \cdot t \qquad (18)$$

$$\mathrm{var}[z] \cong 2 \cdot D_s \cdot t \tag{19}$$

where D_s is the effective (or apparent) dispersion coefficient (cm² a^{-1}), and v_s is the convection velocity (cm a^{-1}) [67]. The parameters v_s and D_s are estimated from the position of the peak concentration in soil, z_M, and the distance, Δz, between z_M and the depth where the concentration reduces to approximately $0.6 = 1/\sqrt{e}$ of its maximum:

$$v_s = \frac{z_M}{t} \tag{20}$$

$$D_s = \frac{(\Delta z)^2}{2t} \tag{21}$$

Values of D_s and v_s can be used in the CDE for a chosen time t to produce a vertical profile of the radionuclide. In some cases, authors reported not only v_s and D_s but also the migration rate, derived from the peak of the vertical distribution (or half-depth, i.e. the soil depth above which 50% of the total activity is present) at a given time t.

This migration rate is directly comparable with that resulting from compartment model calculations. Therefore, both kinds of migration rate may be combined (see Table 16).

4.1.3. Relationship between K_d and other parameters characterizing radionuclide mobility

4.1.3.1. Relationship between K_d *and vertical migration*

In a porous medium such as soil, the radionuclide diffusion process differs from diffusion in free water. An effective diffusion coefficient, D_e(m^2 s^{-1}), should therefore be defined. Only those pores that contribute to the transport of the dissolved radionuclide species have to be considered, although in most cases (mainly when the relative saturation tends to 1, and for cationic radionuclides), the total porosity, ε, is an adequate approximation. In the case of radionuclides with significant sorption, an apparent diffusion coefficient, D_a (m^2 s^{-1}), can be calculated from the diffusion profile of the sample.

The apparent diffusion coefficient takes into account the retardation of the radionuclide due to interactions with the porous material:

$$D_a = \frac{D_e}{f_{ret}} \tag{22}$$

where f_{ret} is the retardation factor. If we hypothesize a linear sorption pattern, with a constant K_d in the range of concentrations studied, f_{ret} can be defined as:

$$f_{ret} = 1 + \left(\frac{\rho}{\varepsilon}\right) \cdot K_d \tag{23}$$

where ρ (kg m^{-3}) is the dry bulk density of the soil.

If sorption of a radionuclide on soil is instantaneous, reversible and independent of its concentration (i.e. the K_d concept applies), this process is reflected in the CDE model by the following relations of the model parameters of a sorbing and a non-sorbing trace substance, respectively:

$$D_s = \frac{D}{f_{ret}} \tag{24}$$

$$v_s = \frac{v_w}{f_{ret}} \tag{25}$$

where D_s and v_s are respectively the effective dispersion coefficient and the convective velocity of the radionuclide showing sorption, D is the dispersion coefficient of a non-sorbing trace substance, v_w is the mean pore water velocity and f_{ret} is the retardation factor.

4.1.3.2. Relationship between K_d *and root uptake*

Soil to plant radionuclide transfer is assessed by measuring the soil to plant transfer factor or concentration factor, F_v, defined as the ratio of the radionuclide content in the plant (or in part of the plant) to that in the soil (Bq kg^{-1} dry weight plant tissue/Bq kg^{-1} dry weight soil). The concentration factor can be assumed to be controlled mostly by root uptake, since other sources of plant contamination (i.e. foliar uptake, soil adhesion by resuspension) are often of less significance.

The radionuclide concentration in the plant, C_v, is assumed to be linearly correlated to the radionuclide level in the soil solution, C_{ss}. This relationship is controlled by the selectivity of the plant root system, represented by the bioaccumulation factor, B_p:

$$C_v = C_{ss} \cdot B_p \tag{26}$$

where B_p refers to the radionuclide plant to soil solution ratio (Bq kg^{-1} dry weight plant tissue/Bq L^{-1} soil solution). The process of ion uptake from the soil solution to the plant by its roots includes physiological aspects of the plant related to nutrient uptake and selectivity, and depends on both the plant and the element considered.

Therefore, the soil solution–plant bioaccumulation factor is assumed to be dependent on the concentrations of radionuclide competitive species in the soil solution [68], as has been fully described for the K-Cs pair [69–71].

Concentrating on soil chemical factors, C_{ss} may be written as:

$$C_{ss} = C_s f_{rev} / K_d \tag{27}$$

where C_s is the radionuclide concentration in the soil (Bq kg^{-1}, dry weight soil) and f_{rev} is the reversibly sorbed radionuclide fraction (dimensionless), which also refers to the time dependent potential of the soil to fix the radionuclide to the solid phase.

Combining these equations results in the following:

$$F_v = C_v / C_s = C_{ss} \cdot B_p / C_s = f_{rev}\, B_p / K_d \tag{28}$$

Attempts to correlate field data on F_v to any one of the parameters in Eq. (28) should be made with caution and are rarely justified.

However, for a given radionuclide and in the medium term after the contamination event, the reversibly sorbed fraction can be expected to be reasonably similar for a given set of soils, except when the set contains soils of contrasting properties (e.g. high clay content soils and peat soils) [72, 73]. In any case, the range of variation will be much narrower than that of K_d. Therefore, radionuclide availability may be quantified solely in terms of K_d.

To summarize, when comparing the concentration factors in the medium term for a set of similar soils, Eq. (28) may be simplified as follows:

$$F_v = B_p / K_d \tag{29}$$

After a log transformation of this equation, the result is:

$$\log F_v = \log B_p - \log K_d \tag{30}$$

The resulting log equation has been successfully used to predict radiocaesium and radiostrontium transfer factors from K_d, both measured in contaminated soils and calculated from soil properties [70, 74]. For other radionuclides — for example, actinides and transuranides — this approach may not be valid and should be tested further.

4.2. SOLID-LIQUID DISTRIBUTION COEFFICIENT VALUES

The K_d values were classified on the basis of four main soil groups (sand, loam, clay and organic) defined according to the sand and clay mineral percentages, referred to as the mineral matter, and the organic matter content in the soil (see Section 2.4 for details).

Table 12 provides K_d values for selected radionuclides grouped according to this criterion; K_d values for the same radionuclides are grouped according to co-factors in Table 13. Table 14 provides a compendium of K_d values for a large number of elements, grouped according to the ‘texture/OM’ criterion [9].

Although the texture/OM criterion defines five soil groups, soil groups in Tables 12–14 have been combined when differences between values were not statistically significant. However, independent values for mineral and organic soils are given in most cases.

4.3. VERTICAL MIGRATION IN UNDISTURBED SOIL PROFILES

The data compilation in Table 15 takes into account data from the literature on the vertical migration of radionuclides in undisturbed meadow soils (agricultural and semi-natural) [75–77]. Most data refer to ^{137}Cs and ^{90}Sr from fallout from the Chernobyl accident and weapons fallout. Other radionuclides are covered in very few literature sources.

Values for deeper layers, derived by compartment models, are excluded from this compilation because there is evidence that such data are artefacts and overestimate the real velocities of radionuclides in soil [75] (for details, see the accompanying TECDOC [5]). Table 16 gives values for the parameters of the CDE model, mostly for radiocaesium and radiostrontium, derived from undisturbed grassland soil profiles.

Text cont. on p. 37.

TABLE 12. K_d VALUES FOR SELECTED RADIONUCLIDES IN SOILS GROUPED ACCORDING TO THE TEXTURE/ORGANIC MATTER CRITERION (L kg^{-1})

Element	Soil group	*N*	Mean	GSD[a]	Minimum	Maximum
Sr	All soils	255	5.2×10^1	5.9	4.0×10^{-1}	6.5×10^3
	Sand	65	2.2×10^1	6.4	4.0×10^{-1}	2.4×10^3
	Loam + clay + organic	176	6.9×10^1	5.4	2.0	6.5×10^3
Cs	All soils	469	1.2×10^3	7.0	4.3	3.8×10^5
	Sand	114	5.3×10^2	5.8	9.6	3.5×10^4
	Loam + clay	227	3.7×10^2	3.6	3.9×10^1	3.8×10^5
	Organic	108	2.7×10^2	6.8	4.3	9.5×10^4
U	All soils	178	2.0×10^2	12	7.0×10^{-1}	6.7×10^4
	Mineral	146	1.8×10^2	13	7.0×10^{-1}	6.7×10^4
	Organic	9	1.2×10^3	6.1	3.3×10^2	7.6×10^3
Th	All soils	46	1.9×10^3	10	1.8×10^1	2.5×10^5
	Mineral	25	2.6×10^3	10	3.5×10^1	2.5×10^5
	Organic	5	7.3×10^2	44	1.8×10^1	8.0×10^4
I	All soils	250	6.9	5.4	1.0×10^{-2}	5.8×10^2
	Mineral	196	7.0	5.2	1.0×10^{-2}	5.4×10^2
	Organic	11	3.2×10^1	3.3	8.5	5.8×10^2
Cd	All soils	61	1.5×10^2	9.4	2.0	7.0×10^3
	Mineral	39	1.1×10^2	8.1	2.0	2.7×10^3
	Organic	13	6.5×10^2	6.0	9.6	7.0×10^3
Co	All soils	118	4.8×10^2	16	2.0	1.0×10^5
	Sand + loam	89	6.4×10^2	16	2.0	1.0×10^5
	Clay	10	3.8×10^3	5.7	5.4×10^2	9.9×10^4
	Organic	17	8.7×10^1	9.5	4.0	5.8×10^3
Ni	All soils	64	2.8×10^2	7.0	3.0	7.2×10^3
	Sand + loam	40	1.4×10^2	7.8	3.0	7.2×10^3
	Clay + organic	20	9.8×10^2	2.1	2.5×10^2	5.0×10^3
Zn	All soils	92	9.5×10^2	11	9.0×10^{-1}	1.5×10^5
	Sand	17	1.1×10^2	23	9.0×10^{-1}	2.8×10^4
	Loam + clay	56	2.4×10^3	3.6	2.1×10^2	1.5×10^5
	Organic	12	5.6×10^2	7.6	9.7	7.6×10^4

[a] GSD: Geometric standard derivation.

TABLE 13. K_d VALUES FOR SELECTED RADIONUCLIDES FOR SOILS GROUPED ACCORDING TO THE CO-FACTOR CRITERION (L kg^{-1})

Element	Soil group	*N*	Mean	GSD[a]	Minimum	Maximum
Sr	CEC[b]/M_{ss}[c]<15	25	4.2	2.4	4×10^{-1}	1.5×10^{1}
	15<CEC/M_{ss}<150	28	2.2×10^{1}	2.5	4.0	1.1×10^{2}
	150<CEC/M_{ss}<500	18	1.7×10^{2}	1.5	7.7×10^{1}	2.7×10^{2}
	CEC/M_{ss}>500	25	3.2×10^{2}	2.0	8.1×10^{1}	1.8×10^{3}
Cs	RIP[d]<150	47	7.4×10^{1}	2.4	1.0×10^{1}	7.3×10^{2}
	150<RIP<1000	78	3.2×10^{2}	5.6	1.0×10^{1}	3.4×10^{4}
	1000<RIP<2500	72	2.4×10^{3}	4.1	6.2×10^{1}	9.5×10^{4}
	RIP>2500	60	7.2×10^{3}	4.0	2.2×10^{2}	3.8×10^{5}
U	pH<5	36	7.1×10^{1}	11	7.0×10^{-1}	6.7×10^{3}
	5≤pH<7	78	7.4×10^{2}	8.0	2.6	6.7×10^{4}
	pH≥7	60	6.5×10^{1}	8.3	9.0×10^{-1}	6.2×10^{3}
Th	pH<5	11	1.3×10^{3}	15	1.8×10^{1}	1.0×10^{5}
	5≤pH<8	26	3.3×10^{3}	8.0	1.3×10^{2}	2.5×10^{5}
	pH≥8	6	3.1×10^{2}	7.1	3.5×10^{1}	3.2×10^{4}
I	OM<2	75	2.3	6.1	1.0×10^{-2}	5.7×10^{1}
	2≤OM<5	106	9.1	3.4	6.0×10^{-1}	5.4×10^{2}
	OM≥5	46	2.3×10^{1}	3.6	2.0	5.8×10^{2}
Cd[e]	pH<6.5	19	1.5×10^{1}	3.5	2.0	2.5×10^{2}
	pH≥6.5	24	3.8×10^{2}	6.2	3.7	4.4×10^{3}
Co[e]	pH<5	21	1.2×10^{1}	4.7	2.0	1.5×10^{2}
	5≤pH<6.5	50	1.9×10^{3}	5.2	2.9×10^{1}	9.9×10^{4}
	pH≥6.5	26	4.6×10^{3}	4.2	5.5×10^{2}	1.0×10^{5}
Ni[e]	pH<5	10	1.4×10^{1}	2.2	3.0	4.8×10^{1}
	5≤pH<6.5	11	5.8×10^{1}	4.2	7.0	1.1×10^{3}
	pH≥6.5	30	8.2×10^{2}	3.1	4.0×10^{1}	7.2×10^{3}
Zn[e]	pH<5	9	8.2	7.9	0.9×10^{-1}	3.0×10^{2}
	5≤pH<6.5	49	1.6×10^{3}	5.7	6.2	3.0×10^{4}
	pH≥6.5	17	4.3×10^{3}	3.8	4.4×10^{2}	1.5×10^{5}

[a] GSD: Geometric standard deviation.

[b] CEC: Cation exchange capacity.

[c] M_{ss}: Sum of Ca and Mg concentrations in soil solution.

[d] RIP: Radiocaesium interception potential.

[e] Mean values are for mineral soils only.

TABLE 14. K_d VALUES FOR RADIONUCLIDES IN SOILS GROUPED ACCORDING TO THE TEXTURE/ORGANIC MATTER CRITERION (L kg^{-1})

Element	Soil group	*N*	Mean	GSD[a]	Minimum	Maximum
Ac	All soils[b]	4	1.7×10^{3}	2.8	4.5×10^{2}	5.4×10^{3}
	Mineral	3	1.2×10^{3}	2.4	4.5×10^{2}	2.4×10^{3}
	Organic	1	5.4×10^{3}	—	—	—
Ag	All soils	9	3.8×10^{2}	7.1	3.6×10^{1}	1.5×10^{4}
	Mineral	5	1.4×10^{2}	3.0	3.6×10^{1}	7.0×10^{2}
	Organic	2	9.7×10^{3}	—	4.4×10^{3}	1.5×10^{4}
Am	All soils	62	2.6×10^{3}	6.1	5.0×10^{1}	1.1×10^{5}
	Sand	17	1.0×10^{3}	6.7	6.7×10^{1}	3.7×10^{4}
	Loam + clay	32	4.3×10^{3}	5.6	5.0×10^{1}	4.8×10^{4}
	Organic	13	2.5×10^{3}	4.6	2.1×10^{2}	1.1×10^{5}
As	All soils	7	5.5×10^{2}	5.5	2.5×10^{1}	3.0×10^{3}
Ba	All soils	1	4.0×10^{-1}	—	—	—
Be	All soils	5	9.9×10^{2}	2.5	2.4×10^{2}	3.0×10^{3}
	Mineral[b]	3	6.3×10^{2}	2.8	2.4×10^{2}	1.3×10^{3}
	Organic[b]	1	3.0×10^{3}	—	—	—
Bi	All soils	6	4.8×10^{2}	2.3	1.2×10^{2}	1.5×10^{3}
	Mineral	4	3.5×10^{2}	2.1	1.2×10^{2}	6.7×10^{2}
	Organic[b]	1	1.5×10^{3}	—	—	—
Br	All soils[b]	4	5.5×10^{1}	2.8	1.5×10^{1}	1.8×10^{2}
	Mineral	3	4.0×10^{1}	2.3	1.5×10^{1}	7.4×10^{1}
	Organic	1	1.8×10^{2}	—	—	—
Ca	All soils	34	8	3.4	7.0×10^{-1}	1.1×10^{2}
	Mineral	33	7	3.2	7.0×10^{-1}	8.9×10^{1}
	Organic	1	1.1×10^{2}	—	—	—
Ce	All soils	11	1.2×10^{3}	5.1	1.2×10^{2}	2.0×10^{4}
	Sand	3	4.0×10^{2}	1.2	3.2×10^{2}	4.9×10^{2}
	Loam + clay	7	1.8×10^{3}	6.4	1.2×10^{2}	2.0×10^{4}
	Organic[b]	1	3.0×10^{3}	—	—	—
Cl	All soils	22	3.0×10^{-1}	3.0	4.0×10^{-2}	1.2
Cm	All soils	18	9.3×10^{3}	3.8	1.9×10^{2}	5.2×10^{4}
Cr	All soils	31	4.0×10^{1}	20	1.0	7.9×10^{3}
	Mineral	23	1.8×10^{1}	15	1.0	1.6×10^{3}
	Organic	6	1.6×10^{2}	10	8.3	2.9×10^{3}
Cu	All soils	11	5.3×10^{2}	3.0	7.6×10^{2}	2.7×10^{3}
	Sand + loam	3	2.7×10^{2}	2.0	1.3×10^{2}	4.8×10^{2}
	Clay	2	2.1×10^{3}	—	1.4×10^{3}	2.7×10^{3}
	Organic	4	3.2×10^{2}	3.0	7.6×10^{2}	8.8×10^{2}
Dy	All soils	2	1.5×10^{3}	—	8.2×10^{2}	2.1×10^{3}
Fe	All soils	23	8.8×10^{2}	2.3	2.2×10^{2}	4.9×10^{3}
	Sand	4	3.2×10^{2}	1.3	2.2×10^{2}	4.2×10^{2}
	Loam	12	8.9×10^{2}	2.0	2.9×10^{2}	2.2×10^{3}
	Clay	4	1.6×10^{3}	1.4	1.2×10^{3}	2.2×10^{3}

For footnotes see p. 36.

TABLE 14. K_d VALUES FOR RADIONUCLIDES IN SOILS GROUPED ACCORDING TO THE TEXTURE/ORGANIC MATTER CRITERION (L kg^{-1}) (cont.)

Element	Soil group	*N*	Mean	GSD[a]	Minimum	Maximum
Fe	Organic	3	1.4×10^{3}	3.1	5.2×10^{2}	4.9×10^{3}
Ga	All soils	2	3.0×10^{2}	—	2.8×10^{2}	3.1×10^{2}
H	All soils	1	1.0×10^{-1}	—	—	—
Hf	All soils	6	2.5×10^{3}	2.8	4.5×10^{2}	8.5×10^{3}
	Mineral	4	1.5×10^{3}	2.4	4.5×10^{2}	3.3×10^{3}
	Organic[b]	1	5.4×10^{3}	—	—	—
Hg	All soils	1	6.3×10^{3}	—	—	—
Ho	All soils[b]	4	9.3×10^{2}	2.9	2.4×10^{2}	3.0×10^{3}
	Mineral	3	6.3×10^{2}	2.4	2.4×10^{2}	1.3×10^{3}
	Organic	1	3.0×10^{3}	—	—	—
In	All soils	2	4.8×10^{2}	—	2.4×10^{2}	7.3×10^{2}
Ir	All soils	15	3	—	1	1.1×10^{1}
K	All soils	237	1.3×10^{1}	4.3	7.0×10^{-1}	9.1×10^{2}
	Sand	60	3.4	2.6	7.0×10^{-1}	1.8×10^{2}
	Loam + clay	93	2.2×10^{1}	3.6	1.8	9.1×10^{2}
	Organic	76	1.9×10^{1}	2.8	2.5	1.3×10^{2}
La	All soils	1	5.3×10^{3}	—	—	—
Lu	All soils	1	5.1×10^{3}	—	—	—
Mg	All soils	30	3.8	3.5	4.0×10^{-1}	4.5×10^{1}
Mn	All soils	83	1.2×10^{3}	9.4	3.6×10^{1}	7.9×10^{4}
	Mineral	79	1.3×10^{3}	9.4	4.0×10^{1}	7.9×10^{4}
	Organic	3	1.6×10^{2}	3.8	3.6×10^{1}	4.9×10^{2}
Mo	All soils	9	4.0×10^{1}	2.8	7	1.3×10^{2}
Na	All soils	30	3.4	3.1	2.0×10^{-1}	2.6×10^{1}
Nb	All soils	11	1.5×10^{3}	3.7	1.6×10^{2}	8.4×10^{3}
	Sand	2	1.7×10^{2}	—	1.6×10^{2}	1.9×10^{2}
	Loam + clay	8	2.5×10^{3}	2.5	5.4×10^{2}	8.4×10^{3}
	Organic[b]	1	2.0×10^{3}	—	—	—
Np	All soils	26	3.5×10^{1}	6.1	1.3	1.2×10^{3}
	Mineral	22	2.0×10^{1}	3.6	1.3	1.2×10^{2}
	Organic	4	8.1×10^{2}	1.4	5.0×10^{2}	1.2×10^{3}
P	All soils	6	9.0×10^{1}	5.2	9.0	7.6×10^{2}
Pa	All soils[b]	4	2.0×10^{3}	2.8	5.4×10^{2}	6.6×10^{3}
	Mineral	3	1.4×10^{3}	2.3	5.4×10^{2}	2.7×10^{3}
	Organic	1	6.6×10^{3}	—	—	—
Pb	All soils	23	2.0×10^{3}	9.9	2.5×10^{1}	1.3×10^{5}
	Sand	9	2.2×10^{2}	3.6	2.5×10^{1}	1.3×10^{3}
	Loam + clay	7	1.3×10^{4}	3.6	3.6×10^{3}	1.3×10^{5}
	Organic	5	2.5×10^{3}	2.5	8.8×10^{2}	1.0×10^{4}
Pd	All soils	6	1.8×10^{2}	2.3	5.5×10^{1}	6.7×10^{2}
	Mineral	4	1.4×10^{2}	2.0	5.5×10^{1}	2.7×10^{2}
	Organic[b]	1	6.7×10^{2}	—	—	—

TABLE 14. K_d VALUES FOR RADIONUCLIDES IN SOILS GROUPED ACCORDING TO THE TEXTURE/ORGANIC MATTER CRITERION (L kg^{-1}) (cont.)

Element	Soil group	*N*	Mean	GSD[a]	Minimum	Maximum
Pm	All soils	2	4.5×10^{2}	—	4.5×10^{2}	4.5×10^{2}
Po	All soils	44	2.1×10^{2}	5.4	1.2×10^{1}	7.0×10^{3}
	Mineral	43	1.9×10^{2}	5.1	1.2×10^{1}	7.0×10^{3}
	Organic[b]	1	6.6×10^{3}	—	—	—
Pt	All soils	15	2.4×10^{1}	—	1.2×10^{1}	8.3×10^{1}
Pu	All soils	62	7.4×10^{2}	4.0	3.2×10^{1}	9.6×10^{3}
	Sand	11	4.0×10^{2}	4.0	3.3×10^{1}	6.9×10^{3}
	Loam + clay	37	1.1×10^{3}	3.3	1.0×10^{2}	9.6×10^{3}
	Organic	6	7.6×10^{2}	3.7	9.0×10^{1}	3.0×10^{3}
Ra	All soils	51	2.5×10^{3}	13	1.2×10^{1}	9.5×10^{5}
	Sand + loam	39	1.9×10^{3}	12	1.2×10^{1}	1.2×10^{5}
	Clay	6	3.8×10^{4}	12	7.0×10^{2}	9.5×10^{5}
	Organic	2	1.3×10^{3}	—	2.0×10^{2}	2.4×10^{3}
Rb	All soils[b]	4	2.1×10^{2}	2.8	5.5×10^{1}	6.7×10^{2}
	Mineral	3	1.4×10^{2}	2.3	5.5×10^{1}	2.7×10^{2}
	Organic	1	6.7×10^{2}	—	—	—
Rh	All soils	12	4.0	—	6.0×10^{-1}	2.9×10^{1}
Ru	All soils	15	2.7×10^{2}	8.1	5.0	6.6×10^{4}
	Sand	3	3.6×10^{1}	6.1	5.0	1.7×10^{2}
	Loam + clay	7	4.0×10^{2}	2.5	8.2×10^{1}	9.9×10^{2}
	Organic[b]	1	6.6×10^{4}	—	—	—
Sb	All soils	152	6.2×10^{1}	3.9	6.0×10^{-1}	2.1×10^{3}
	Sand	19	1.7×10^{1}	6.4	6.0×10^{-1}	4.7×10^{2}
	Loam	92	6.1×10^{1}	3.1	4.0	2.1×10^{3}
	Clay	18	1.4×10^{2}	2.3	3.8×10^{1}	6.1×10^{2}
	Organic	3	7.5×10^{1}	8.4	8.0	5.4×10^{2}
Sc	All soils	2	2.1×10^{3}	—	6.7×10^{2}	3.5×10^{3}
Se	All soils	172	2.0×10^{2}	3.3	4.0	2.1×10^{3}
	Sand	15	5.6×10^{1}	5.2	4.0	1.6×10^{3}
	Loam + clay	134	2.2×10^{2}	3.0	1.2×10^{1}	2.1×10^{3}
	Organic	2	1.0×10^{3}	—	2.3×10^{2}	1.8×10^{3}
Si	All soils[b]	4	1.3×10^{2}	2.8	3.3×10^{1}	4.0×10^{2}
	Mineral	3	8.7×10^{1}	2.4	3.3×10^{1}	1.8×10^{2}
	Organic	1	4.0×10^{2}	—	—	—
Sm	All soils[b]	4	9.3×10^{2}	2.9	2.4×10^{2}	3.0×10^{3}
	Mineral	3	6.3×10^{2}	2.4	2.4×10^{2}	1.3×10^{3}
	Organic	1	3.0×10^{3}	—	—	—
Sn	All soils	12	1.6×10^{3}	6.2	1.3×10^{2}	3.1×10^{4}
	Mineral	4	2.8×10^{2}	2.2	1.3×10^{2}	6.7×10^{2}
	Organic[b]	1	1.6×10^{3}	—	—	—
Ta	All soils	5	7.8×10^{2}	2.7	2.4×10^{2}	3.0×10^{3}
	Mineral	4	5.6×10^{2}	2.1	2.4×10^{2}	1.3×10^{3}
	Organic[b]	1	3.0×10^{3}	—	—	—

For footnotes see p. 36.

TABLE 14. K_d VALUES FOR RADIONUCLIDES IN SOILS GROUPED ACCORDING TO THE TEXTURE/ORGANIC MATTER CRITERION (L kg^{-1}) (cont.)

Element	Soil group	*N*	Mean	GSD[a]	Minimum	Maximum
Tb	All soils	2	6.0×10^3	—	5.4×10^3	6.6×10^3
Tc	All soils	33	2.3×10^{-1}	9.3	1.0×10^{-2}	1.1×10^1
	Mineral	22	6.3×10^{-2}	3.7	1.0×10^{-2}	1.2
	Organic	11	3.1	2.9	9.2×10^{-1}	1.1×10^1
Te	All soils	2	4.8×10^2	—	1.8×10^2	7.9×10^2
Tm	All soils	1	3.3×10^2	—	—	—
V	All soils	2	3.0×10^2	—	1.8×10^2	4.1×10^2
Y	All soils	7	4.7×10^1	4.0	1.0×10^1	3.8×10^2
	Mineral	5	2.2×10^1	1.9	1.0×10^1	4.7×10^1
	Organic	2	3.2×10^2	—	2.6×10^2	3.8×10^2
Zr	All soils	11	4.1×10^2	21	2	1.0×10^4
	Sand	4	3.2×10^1	16	2	6.0×10^2
	Loam + clay	4	5.0×10^3	2.1	2.2×10^3	1.0×10^4
	Organic	2	3.7×10^3	—	2.3×10^1	7.3×10^3

[a] GSD: Geometric standard deviation.

[b] K_d value from TRS-364 [3].

TABLE 15. MIGRATION RATES (cm a^{-1}) FOR ^{137}Cs AND ^{90}Sr IN UNDISTURBED MEADOW SOIL PROFILES, DERIVED BY VARIOUS CALCULATION METHODS

(calculation methods include compartment models, half-depth, repeated measurements, convection dispersion equation approaches)

Case study	Soil group	*N*	Mean/value	GSD[a]	Minimum	Maximum
			^{137}Cs			
Chernobyl fallout	All soils	103	0.31	2.7	0.07	10.0
	Sand	43	0.23	1.9	0.08	1.2
	Loam	34	0.35	2.5	0.07	2.0
	Clay	7	0.17	1.9	0.08	0.6
	Organic	11	0.82	3.2	0.14	8.7
	Unspecified	8	1.07	3.0	0.38	10.0
Weapons fallout	All soils	19	0.28	2.0	0.09	0.85
	Sand	6	0.30	2.6	0.09	0.85
	Loam	9	0.30	1.8	0.09	0.50
	Clay	1	0.20	—	—	—
	Organic	1	0.30	—	—	—
	Unspecified	2	0.19	2.9	0.09	0.40
			^{90}Sr			
Chernobyl fallout	All soils	16	0.48	2.0	0.12	1.54
Weapons fallout	All soils	12	0.80	1.6	0.46	1.36
Artificial contamination	All soils	24	0.89	2.5	0.20	9.50

[a] GSD: Geometric standard deviation.

TABLE 16. PARAMETERS OF THE CONVECTION DISPERSION EQUATION MODEL FOR ^{137}Cs AND ^{90}Sr FROM DIFFERENT SOURCES OF CONTAMINATION

Case study	Parameter	Soil group	*N*	Mean/value	GSD[a]	Minimum	Maximum
^{137}Cs	D (cm^2 a^{-1})	All soils	31	0.22	3.1	0.02	1.9
Chernobyl fallout		Sand	11	0.11	2.3	0.03	0.6
		Loam	4	0.20	4.6	0.02	0.8
		Organic	3	0.94	1.8	0.63	1.9
		Unspecified	12	0.27	2.6	0.04	0.8
^{137}Cs	D (cm^2 a^{-1})	All soils	12	0.22	4.3	0.04	2.9
Weapons fallout		Sand	3	0.13	5.9	0.04	1.0
		Loam	2	1.06	4.1	0.39	2.9
		Organic	1	1.60	—	—	—
		Unspecified	6	0.12	2.2	0.05	0.4
^{137}Cs	v (cm a^{-1})	All soils	31	0.18	3.3	0.00	0.9
Chernobyl fallout		Sand	11	0.15	1.7	0.07	0.6
		Loam	4	0.06	18	0.00	0.6
		Organic	3	0.69	1.6	0.40	0.9
		Unspecified	12	0.22	1.6	0.09	0.5
^{137}Cs	v (cm a^{-1})	All soils	11	0.09	3.3	0.01	0.7
Weapons fallout		Sand	2	0.20	6.1	0.06	0.7
		Loam	2	0.01	3.6	0.01	0.1
		Organic	1	0.10	—	—	—
		Unspecified	6	0.13	1.4	0.09	0.2
^{90}Sr	D (cm^2 a^{-1})	All soils	10	0.38	2.9	0.05	1.73
Chernobyl fallout	v (cm a^{-1})	All soils	10	0.22	2.2	0.06	0.92
^{106}Ru	D_s (cm^2 a^{-1})	All soils	105	2.6×10^{-1}	2.7		
	v_s (cm a^{-1})	All soils	55			3.5×10^{-1}	3.1×10^{-1}
^{125}Sb	D_s (cm^2 a^{-1})	All soils	87	2.6×10^{-1}	3.0		
	v_s (cm a^{-1})	All soils	53			2.9×10^{-1}	2.7×10^{-1}
^{110m}Ag	D_s (cm^2 a^{-1})	All soils	10	3.1×10^{-1}	3.5		
	v_s (cm a^{-1})	All soils	4			8.4×10^{-1}	4.7×10^{-1}
^{144}Ce	D_s (cm^2 a^{-1})	All soils	4	7.6×10^{-1}	10		
	v_s (cm a^{-1})	All soils	3			6.8×10^{-1}	8.4×10^{-1}

[a] GSD: Geometric standard deviation.

4.4. APPLICATION OF DATA

The data for K_d are from a variety of different sources; these include field and laboratory experiments with various contamination sources, and references, mostly from 1990 onwards, including TRS-364 [3] and related reports, reviewed papers, and ‘grey literature’ (PhD theses, reports).

Data originating from experiments using other materials (e.g. sediments, pure soil phases such as clays or Fe–Mn–Al oxides, rock materials) or stable elements have not been considered. Data from radioisotopes of the same radioelement have been pooled.

There are still evident gaps in K_d values for a large number of radionuclides and soil types, which restricts the possibility of proposing expected values for individual soil groups in most cases. When expected values are proposed, they must be considered only as approximate values that are suitable for screening purposes but not for specific risk assessments. For these gaps, the use of analogues (data on other elements or media such as pure soil phases or sediments) can be considered, although such analogues must be used with care.

The wide ranges of K_d values obtained for similar soil and radionuclide combinations arise both because of the inherent variability derived from grouping the soils according to soil properties not directly related to the mechanisms governing the soil–radionuclide interaction and because of the large number of approaches and contrasting experimental conditions used.

There is a need for information on the reversibility of sorption and on how the sorption rate may change over time. The dynamics of the soil–radionuclide interaction is especially significant for radionuclides such as radiostrontium and radiocaesium.

Soil–radionuclide interactions are governed by multiple factors that depend on the radionuclide and on various soil properties. As the quality and quantity of the mineral matter are among the key soil properties affecting sorption, classification of K_d values according to soil groups based on soil texture and organic matter content is a satisfactory approach to establish K_d values for a large number of radionuclides. However, it is recommended that additional soil and radionuclide properties (co-factors) that govern soil–radionuclide interactions also be considered to the extent possible.

The main soil parameters controlling the interaction should be measured and monitored to improve the prediction of K_d, and they should also be included in models of environmental decision support systems. Modellers can choose to use the geometric mean values derived from soils grouped according to texture and organic matter or, where available, according to other criteria such as specific soil properties (cation exchange capacity, radiocaesium interception potential, pH). Moreover, modellers and end users can also consider using existing single and multiple correlations between soil properties and K_d, especially in those cases where the mechanisms behind radionuclide interaction are well known.

Regarding vertical migration parameters, soil characteristics, including texture composition, have a distinct influence on the migration behaviour of radionuclides; thus they need to be considered in parameter selection.

Some studies have pointed out the time dependence of migration rates. The fixation of radionuclides to soil components like clay minerals or humus takes some time, and migration rates tend to decrease with increasing time due to irreversible fixation of part of the radionuclide content.

The presence of hot particles can have a significant influence on the migration velocity of radionuclides into the soil profile, as radionuclides contained in hot particles are protected against leaching until they are released from the particles by weathering (for details, see the accompanying TECDOC [5]).

No data are currently available for *v* and *D* in tropical meadow soils. Only a few values have been derived from Arctic soils and for subtropical climate conditions. Therefore, at present it is not possible to give separate values for different ecosystems, although distinct differences may exist in the ecological conditions driving vertical migration of radionuclides in soil.

Results from recent studies show that mathematical constraints exist that can lead to artefacts when compartment models are applied to describe vertical distributions of radionuclides in soil profiles. In particular, the arbitrarily chosen thickness of layers can yield unrealistic results. Therefore, literature values of migration rates derived from compartment models should be considered as rough estimates that are valuable as a means to compare radionuclides in different soil types but not as a first choice for predictive purposes. For the modelling of vertical migration in undisturbed soils, reliance on CDE approaches or other innovative calculation methods is strongly preferred, because these approaches and methods offer a more realistic representation of the observed processes.

5. ROOT UPTAKE OF RADIONUCLIDES IN AGRICULTURAL ECOSYSTEMS

The transfer of radionuclides along food chains has been studied extensively over the past 50 years, following nuclear weapons testing, releases from military sites and civilian uses of nuclear energy. Based on information from these studies, extensive databases of soil to plant transfer factors from the literature worldwide were compiled to obtain the values and ranges included in the tables presented here, while basic details of the data selection and processing are given in the accompanying TECDOC [5].

5.1. DEFINITIONS AND PROCESSES

The transfer factor, F_v, for the uptake of any radionuclide from soil to plant is defined as the ratio of the dry weight concentration in the plants to the dry weight concentration in the specified soil layer. The dry weight concentration was used for all plants, with the exception of fruits (see Section 5.2.2.), in order to reduce uncertainty. When the transfer factor (concentration ratio) values or the plant concentrations reported in the literature were expressed relative to fresh weight, the fresh weight to dry weight conversion factors given in Appendix I were applied.

Fresh weight to dry weight ratios will vary somewhat around the adopted values, making this an additional source of uncertainty in the data. In some cases, foodstuff fresh weight is used in dose assessment calculations; in these situations, the fresh weight to dry weight conversion factors (see Appendix I) can be applied to convert the dry weight based values given here.

In defining soil to plant transfer factors, this publication follows the International Union of Radioecologists (IUR) [10] standardization of rooting depth. Thus, instead of the real rooting depth, a standardized soil layer is adopted. All roots and all activity present in the actual rooting zone are assumed to be present in the standardized zone. For grass, this soil depth value is 10 cm; for all other crops (including fruit trees), it is 20 cm. When applying the transfer factors presented here, estimates of the activity concentration in the standardized soil layer should therefore be used.

Soil to plant transfer is influenced by several factors: the physicochemical characteristics of the radionuclides, the form of the fallout or the waste, the time after fallout, soil properties, the type of crop, and the soil management practices [78, 79].

Different types of radioactive material in routine or accidental releases from the nuclear fuel cycle can be identified according to their mobility in soil–plant systems [9, 79–84]. The transfer factor values given here apply to the soluble form of radionuclides.

Radionuclides in the particulate state (usually oxides or carbonates) often have low solubility [85, 86]. Leaching of ^{137}Cs from fuel matrices can be a significant factor affecting the bioavailability of the radionuclide over time after deposition [85–88]. The recommended F_v values given here address the soluble form of radionuclides. Information on ^{137}Cs and ^{90}Sr transfer to plants when fuel particles are present in the environment is given elsewhere [9, 85–88].

The accumulation of radionuclides in farm crops varies considerably for different soils [89, 90]. The difference in transfer factors to farm crops for different soils may be one or two orders of magnitude. Soil properties that are likely to affect radionuclide transfer values include mineralogical and granulometric composition, organic matter content, pH and fertility [9, 79, 89–92].

The biological variability inherent in plants and distinctions between different varieties and species are also a likely source of much of the variability in transfer factors. Other sources of the variability in transfer factor values are: (a) the chemical nature of the radionuclide; (b) variations in metabolic and biochemical mechanisms of radionuclide uptake by plants; (c) detoxification mechanisms; (d) hydrological conditions within the soil; and (e) plant available concentrations in soil within the rhizosphere [5, 9, 78, 79, 90].

Soil fertility, the duration of the vegetative period and the character of the root distribution in soil also influence radionuclide transfer factors. Radionuclide accumulation across the root interface can vary among species by a factor of 100 [93]. Radionuclides often transfer in greater concentrations to leaves and stems, and in much lower concentrations to the generative parts of plants [5, 78, 93].

Cultivation of agricultural crops is based on the application of various methods of soil processing, different doses and combinations of fertilizers, irrigation in dry areas and drainage in boggy territories. Crop cultivation technologies can change soil properties or lead to redistribution of radionuclides in the root zone, and consequently change radionuclide accumulation in crops [9, 79, 94].

A decrease in the radionuclide content in farm crops over time is a phenomenon typically observed in agricultural ecosystems [79, 85–89, 94–96]. A variety of processes are involved, including fixation to soil minerals, incorporation by microorganisms and migration within the rooting zone [30]. As a result, the biological availability of radionuclides for incorporation into food chains is reduced. A detailed discussion of the properties and factors governing root uptake of radionuclides is given in the accompanying TECDOC [5].

5.2. TEMPERATE ENVIRONMENTS

5.2.1. Radionuclide transfer to plants

Over 1100 information sources on radionuclide transfer to plants in temperate environments were used in the development of this handbook, including books, journals, conference proceedings, institutional reports, and international and national databases including the IAEA's Classification of Soil Systems on the Basis of Transfer Factors of Radionuclides from Soil to Reference Plants [9] and the IUR-1989 database [96] used in TRS-364 [3]. The most extensive information obtained relates to cereals, vegetables and pasture grasses. With respect to soil groups, most of the information found was for sand and loam soils. Information on organic soils was rather limited.

To minimize artefacts and misinterpretations, the recommendations given in TRS-364 [3] have been retained and used for data selection. In particular, these recommendations included the following:

(a) Measures to ensure sufficient equilibrium between the radionuclide applied and the corresponding stable nuclides present in the soil;
(b) Application of fertilizers at rates used in routine agriculture;
(c) Use of data from lysimeters or pot experiments only if other data are unavailable.

Soil to plant transfer factor values for the temperate environment are given in Table 17. In comparison with TRS-364 [3], the present publication contains many more data for radionuclide transfers to crops of various plant groups and for the four different soil types used here; it also allows better differentiation between site specific contamination scenarios.

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Ag	Leafy vegetables	Leaves	All	5	1.8×10^{-4}	3.3	5.9×10^{-5}	1.3×10^{-3}
			Sand	2	1.7×10^{-4}		9.6×10^{-5}	2.5×10^{-4}
			Loam	3	2.0×10^{-4}	5.0	5.9×10^{-5}	1.3×10^{-3}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	5	6.4×10^{-4}	2.3	2.5×10^{-4}	2.0×10^{-3}
			Sand	2	1.6×10^{-3}		1.1×10^{-3}	2.0×10^{-3}
			Loam	3	3.7×10^{-4}	1.4	2.5×10^{-4}	4.7×10^{-4}
	Root crops	Roots	All	6	1.3×10^{-3}	2.0	5.7×10^{-4}	3.9×10^{-3}
			Sand	3	1.7×10^{-3}	2.4	6.8×10^{-4}	3.9×10^{-3}
			Loam	3	1.0×10^{-3}	1.7	5.7×10^{-4}	1.7×10^{-3}
Am	Cereals	Grain	All	83	2.2×10^{-5}	11.0	7.4×10^{-7}	3.4×10^{-2}
			Sand	66	2.7×10^{-5}	4.1	2.7×10^{-6}	8.0×10^{-3}
			Loam	7	4.0×10^{-4}	2.0×10^{2}	1.0×10^{-6}	3.4×10^{-2}
			Clay	9	1.6×10^{-5}	2.5×10^{1}	7.4×10^{-7}	4.0×10^{-3}
			Organic	1	1.5×10^{-7}			
		Stems and shoots	All	5	7.9×10^{-5}	81.5	3.0×10^{-7}	5.8×10^{-2}
			Sand	1	5.8×10^{-2}			
			Clay	4	1.5×10^{-5}	14.9	3.0×10^{-7}	1.0×10^{-4}
	Maize	Stems and shoots	All	64	2.6×10^{-4}	5.5	1.1×10^{-5}	1.2×10^{-2}
			Sand	64	2.6×10^{-4}	5.5	1.1×10^{-5}	1.2×10^{-2}

Text continues on p. 63.

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Am	Leafy vegetables	Leaves	All	10	2.7×10^{-4}	3.3	4.0×10^{-5}	1.5×10^{-3}
			Sand	5	5.3×10^{-4}	2.7	1.7×10^{-4}	1.5×10^{-3}
			Loam	2	1.6×10^{-4}		6.0×10^{-5}	4.1×10^{-4}
			Organic	2	1.5×10^{-7}		1.3×10^{-4}	2.3×10^{-4}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	9	3.6×10^{-4}	5.0	2.3×10^{-5}	1.9×10^{-3}
			Sand	8	3.9×10^{-4}	5.5	2.3×10^{-5}	1.9×10^{-3}
	Leguminous vegetables	Seeds and pods	All	12	3.8×10^{-4}	2.6	2.2×10^{-5}	7.9×10^{-4}
			Sand	12	3.8×10^{-4}	2.6	2.2×10^{-5}	7.9×10^{-4}
	Root crops	Roots	All	4	6.7×10^{-4}	2.4	2.0×10^{-4}	1.7×10^{-3}
			Sand	3	1.0×10^{-3}	1.6	7.3×10^{-4}	1.7×10^{-3}
	Tubers	Tubers	All	78	2.1×10^{-4}	6.0	1.1×10^{-5}	3.4×10^{-2}
			Sand	65	2.1×10^{-4}	5.5	1.1×10^{-5}	3.4×10^{-2}
			Loam	8	1.5×10^{-4}	9.0	1.1×10^{-5}	4.7×10^{-3}
			Clay	2	3.3×10^{-3}		9.0×10^{-5}	6.5×10^{-3}
			Organic	2	8.1×10^{-4}		2.1×10^{-5}	1.6×10^{-3}
	Grasses	Stems and shoots	All	7	3.3×10^{-2}	9.0	4.2×10^{-4}	2.6×10^{-1}
			Sand	7	3.3×10^{-2}	9.0	4.2×10^{-4}	2.6×10^{-1}
	Leguminous fodder	Stems and shoots	All	20	6.5×10^{-4}	2.7	1.8×10^{-4}	3.1×10^{-3}
			Sand	12	9.9×10^{-4}	2.5	1.9×10^{-4}	2.9×10^{-3}
			Loam	1	3.1×10^{-3}			
			Clay	7	2.5×10^{-4}	1.4	1.8×10^{-4}	4.8×10^{-4}
	Pasture	Stems and shoots	All	27	1.5×10^{-3}	4.1	1.0×10^{-4}	4.8×10^{-2}
			Sand	10	5.1×10^{-3}	2.6	1.3×10^{-3}	2.9×10^{-2}
			Loam	11	1.0×10^{-3}	5.0	5.3×10^{-4}	2.0×10^{-2}
			Clay	5	1.7×10^{-4}	2.2	1.0×10^{-4}	3.0×10^{-4}
Ba	Cereals	Grain	All	1	1.0×10^{-3}			
	Leafy vegetables	Leaves	All	1	5.0×10^{-3}			
	Non-leafy vegetables	Fruits, heads, berries, buds	All	1	5.0×10^{-3}			
	Root crops	Roots	All	1	5.0×10^{-3}			
	Tubers	Tubers	All	1	5.0×10^{-3}			
	Grasses	Stems and shoots	All	3	2.0	1.3	1.2	3.6
			Sand	1	1.3			
			Loam	1	1.2			
			Organic	1	3.6			
	Leguminous fodder	Stems and shoots	All	3	9.1×10^{-1}	1.0	2.8×10^{-1}	2.1
			Sand	1	3.7×10^{-1}			
			Loam	1	2.8×10^{-1}			
			Organic	1	2.1			
Be	Pasture	Stems and shoots	All	1	4.2×10^{-1}			

For footnote see p. 62.

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	*N*	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Ca	Cereals	Stems and shoots	All	6	8.7	3.7	2.3	3.8×10^{1}
			Sand	3	3.0×10^{1}	1.2	2.5×10^{1}	3.8×10^{1}
			Loam	3	2.6	1.1	2.3	2.9
	Leguminous vegetables	Stems and shoots	All	6	2.0×10^{1}	3.7	5.9	7.5×10^{1}
			Sand	3	6.5×10^{1}	1.2	5.3×10^{1}	7.5×10^{1}
			Loam	3	6.2	1.0	5.9	6.5
Cd	Cereals	Grain	All	11	8.8×10^{-1}	2.7	1.4×10^{-1}	2.×9
			Sand	5	1.2	2.1	4.8×10^{-1}	2.5
			Loam	4	1.3	2.2	5.6×10^{-1}	2.9
			Clay	2	2.1×10^{-1}		1.4×10^{-1}	2.8×10^{-1}
		Stems and shoots	All	24	2.1	2.2	1.9×10^{-1}	5.4
			Sand	8	3.2	1.4	2.2	5.1
			Loam	12	2.2	2.1	5.8×10^{-1}	5.4
			Clay	4	7.1×10^{-1}	2.4	1.9×10^{-1}	1.3
	Maize	Grain	All	1	5.0×10^{-2}			
		Stems and shoots	All	2	1.3		3.5×10^{-1}	2.2
			Sand	1	2.2			
			Clay	1	3.5×10^{-1}			
	Leguminous vegetables	Seeds and pods	All	1	2.7×10^{-1}	2.7×10^{-1}	8.0×10^{-2}	4.6×10^{-1}
			Sand	2	4.6×10^{-1}			
			Clay	1	8.0×10^{-2}			
	Tubers	Tubers	All	1	1.5			
Ce	Cereals	Grain	All	20	3.1×10^{-3}	3.7	2.4×10^{-4}	2.0×10^{-2}
			Sand	5	1.1×10^{-2}	2.6	2.0×10^{-3}	2.0×10^{-2}
			Loam	7	2.8×10^{-3}	3.3	2.4×10^{-4}	7.0×10^{-3}
			Clay	6	1.6×10^{-3}	4.1	2.8×10^{-4}	6.0×10^{-3}
			Organic	1	8.0×10^{-4}			
		Stems and shoots	All	13	3.9×10^{-2}	5.5	3.0×10^{-3}	6.8×10^{-1}
			Sand	4	2.8×10^{-1}	2.5	8.0×10^{-2}	6.8×10^{-1}
			Loam	6	7.0×10^{-3}	2.4	7.0×10^{-3}	6.0×10^{-2}
			Clay	3	3.0×10^{-3}	3.0	3.0×10^{-3}	2.7×10^{-2}
	Leafy vegetables	Leaves	All	1	6.0×10^{-3}			
	Leguminous vegetables	Seeds and pods	All	2	1.3×10^{-2}		6.0×10^{-3}	2.0×10^{-2}
			Sand	1	2.0×10^{-2}			
			Loam	1	6.0×10^{-3}			
	Root crops	Roots	All	1	6.0×10^{-3}			
	Tubers	Tubers	All	1	4.0×10^{-3}			
	Grasses	Stems and shoots	All	2	2.0×10^{-2}		1.0×10^{-2}	3.0×10^{-2}
			Loam	2	2.0×10^{-2}		1.0×10^{-2}	3.0×10^{-2}

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Ce	Leguminous fodder	Stems and leaves	All	4	8.0×10^{-3}	2.1	4.0×10^{-3}	2.0×10^{-2}
			Loam	4	8.0×10^{-3}	2.1	4.0×10^{-3}	2.0×10^{-2}
	Pasture	Stems and shoots	All	10	3.7×10^{-1}	5.0	2.0×10^{-2}	3.5
			Sand	1	9.6×10^{-1}			
			Loam	4	4.0×10^{-1}	3.3	1.2×10^{-1}	1.2
			Clay	3	2.9×10^{-1}	3.3	1.4×10^{-1}	1.2
			Organic	1	3.5			
Cm	Cereals	Grain	All	67	2.3×10^{-5}	3.3	1.4×10^{-6}	2.0×10^{-4}
			Sand	66	2.3×10^{-5}	3.3	1.4×10^{-6}	2.9×10^{-4}
	Leafy vegetables	Leaves	All	7	1.4×10^{-3}	4.5	2.0×10^{-4}	8.1×10^{-3}
			Sand	6	1.9×10^{-3}	3.7	3.0×10^{-4}	8.1×10^{-3}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	8	3.2×10^{-4}	4.5	3.6×10^{-5}	1.4×10^{-3}
			Sand	8	2.9×10^{-4}	4.5	3.6×10^{-5}	1.4×10^{-3}
	Leguminous vegetables	Seeds and pods	All	17	7.5×10^{-4}	1.5	4.2×10^{-4}	1.6×10^{-3}
			Sand	17	7.5×10^{-4}	1.5	4.2×10^{-4}	1.6×10^{-3}
	Root crops	Roots	All	6	8.5×10^{-4}	3.0	2.0×10^{-4}	3.9×10^{-3}
			Sand	5	1.1×10^{-3}	2.5	4.1×10^{-4}	3.9×10^{-3}
	Tubers	Tubers	All	66	1.5×10^{-4}	3.7	1.1×10^{-5}	2.1×10^{-3}
			Sand	65	1.5×10^{-4}	4.1	1.1×10^{-5}	2.1×10^{-3}
	Pasture	Stems and shoots	All	17	1.0×10^{-3}	2.4	1.0×10^{-4}	3.6×10^{-3}
			Sand	6	2.1×10^{-3}	1.7	1.1×10^{-3}	3.6×10^{-3}
			Loam	8	8.3×10^{-4}	1.4	4.6×10^{-4}	1.4×10^{-3}
			Clay	2	2.5×10^{-4}		1.0×10^{-4}	4.0×10^{-4}
	Maize	Stems and shoots	All	71	2.0×10^{-4}	5.0	5.7×10^{-6}	4.4×10^{-3}
			Sand	71	2.0×10^{-4}	5.0	5.7×10^{-6}	4.4×10^{-3}
Co	Cereals	Grain	All	61	8.5×10^{-3}	5.5	4.0×10^{-4}	7.2×10^{-1}
			Sand	30	1.4×10^{-2}	6.0	1.0×10^{-3}	7.2×10^{-1}
			Loam	16	4.9×10^{-3}	5.0	4.0×10^{-4}	6.0×10^{-2}
			Clay	12	5.4×10^{-3}	4.1	8.0×10^{-4}	3.0×10^{-2}
			Organic	2	3.4×10^{-3}		1.7×10^{-3}	5.0×10^{-3}
		Stems and shoots	All	27	1.1×10^{-1}	5.0	1.0×10^{-2}	4.9
			Sand	8	5.8×10^{-1}	4.1	1.1×10^{-1}	4.9
			Loam	12	6.4×10^{-2}	3.3	1.0×10^{-2}	2.9×10^{-1}
			Clay	7	3.6×10^{-2}	1.4	2.0×10^{-2}	5.0×10^{-2}
	Maize	Grain	All	40	1.0×10^{-2}	4.1	9.0×10^{-4}	5.6×10^{-1}
			Sand	26	1.5×10^{-2}	4.5	3.0×10^{-3}	5.6×10^{-1}
			Loam	10	7.2×10^{-3}	1.9	1.6×10^{-3}	1.6×10^{-2}
			Clay	4	2.0×10^{-3}	2.0	9.0×10^{-4}	4.0×10^{-3}
		Stems and shoots	All	37	3.5×10^{-2}	2.2	6.0×10^{-3}	2.0×10^{-1}
			Sand	36	3.4×10^{-2}	2.2	6.0×10^{-3}	2.0×10^{-1}
			Loam	1	5.0×10^{-2}			

For footnote see p. 62.

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	*N*	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Co	Leafy vegetables	Leaves	All	185	1.7×10^{-1}	2.7	1.3×10^{-2}	1.0
			Sand	66	2.5×10^{-1}	2.4	1.7×10^{-2}	1.0
			Loam	85	1.5×10^{-1}	2.5	1.8×10^{-2}	8.6×10^{-1}
			Clay	33	9.7×10^{-2}	3.0	1.3×10^{-2}	6.9×10^{-1}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	7	1.4×10^{-1}	1.6	5.7×10^{-2}	2.3×10^{-1}
			Sand	2	1.4×10^{-1}		5.7×10^{-2}	2.3×10^{-1}
			Clay	4	1.6×10^{-1}	1.2	1.3×10^{-1}	1.9×10^{-1}
	Leguminous vegetables	Seeds and pods	All	105	3.6×10^{-2}	2.3	5.0×10^{-3}	5.0×10^{-1}
			Sand	43	5.7×10^{-2}	2.1	2.2×10^{-2}	5.0×10^{-1}
			Loam	40	2.8×10^{-2}	2.3	5.0×10^{-3}	2.2×10^{-1}
			Clay	22	2.2×10^{-2}	1.9	6.0×10^{-3}	5.3×10^{-2}
	Root crops	Roots	All	14	1.1×10^{-1}	2.2	4.7×10^{-2}	7.2×10^{-1}
			Sand	7	1.4×10^{-1}	2.7	5.5×10^{-2}	7.2×10^{-1}
			Loam	4	6.5×10^{-2}	1.4	4.7×10^{-2}	9.9×10^{-2}
			Clay	2	1.0×10^{-1}		1.0×10^{-1}	1.0×10^{-1}
		Leaves	All	2	2.4×10^{-1}		2.4×10^{-1}	2.4×10^{-1}
			Clay	2	2.4×10^{-1}		2.4×10^{-1}	2.4×10^{-1}
	Tubers	Tubers	All	56	5.4×10^{-2}	3.0	1.0×10^{-2}	6.7×10^{-1}
			Sand	39	8.0×10^{-2}	3.0	1.1×10^{-2}	6.7×10^{-1}
			Loam	11	2.1×10^{-2}	1.7	1.0×10^{-2}	6.3×10^{-2}
			Clay	5	2.2×10^{-2}	2.0	1.2×10^{-2}	7.0×10^{-2}
	Grasses	Stems and shoots	All	4	7.7×10^{-2}	2.2	4.0×10^{-2}	1.7×10^{-1}
			Sand	1	1.3×10^{-1}			
			Loam	1	1.7×10^{-1}			
			Clay	2	4.0×10^{-2}		4.0×10^{-2}	4.0×10^{-2}
	Leguminous fodder	Stems and shoots	All	38	6.6×10^{-2}	3.3	1.0×10^{-3}	7.2×10^{-1}
			Sand	15	1.4×10^{-1}	2.2	4.4×10^{-2}	7.2×10^{-1}
			Loam	10	2.9×10^{-2}	6.0	1.0×10^{-3}	1.8×10^{-1}
			Clay	9	6.9×10^{-2}	1.5	3.7×10^{-2}	1.2×10^{-1}
			Organic	4	2.8×10^{-2}	1.6	1.9×10^{-2}	5.3×10^{-2}
	Pasture	Stems and shoots	All	88	4.5×10^{-2}	3.7	2.1×10^{-3}	8.4×10^{-1}
			Sand	49	8.6×10^{-2}	3.0	1.4×10^{-2}	8.4×10^{-1}
			Loam	36	1.7×10^{-2}	2.7	2.1×10^{-3}	1.3×10^{-1}
			Clay	2	1.3×10^{-1}	6.4×10^{-2}	8.0×10^{-2}	1.7×10^{-1}
Cr	Cereals	Grain	All	1	2.0×10^{-4}			
	Leafy vegetables	Leaves	All	1	1.0×10^{-3}			
	Non-leafy vegetables	Fruits, heads, berries, buds	All	1	1.0×10^{-3}			
	Root crops	Roots	All	1	1.0×10^{-3}			
	Tubers	Tubers	All	1	5.0×10^{-4}			

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	*N*	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Cr	Pasture	Stems and shoots	All	1	2.0×10^{-3}			
Cs	Cereals	Grain	All	470	2.9×10^{-2}	4.1	2.0×10^{-4}	9.0×10^{-1}
			Sand	156	3.9×10^{-2}	3.3	2.0×10^{-3}	6.6×10^{-1}
			Loam	158	2.0×10^{-2}	4.1	8.0×10^{-4}	2.0×10^{-1}
			Clay	110	1.1×10^{-2}	2.7	2.0×10^{-4}	9.0×10^{-2}
			Organic	28	4.3×10^{-2}	2.7	1.0×10^{-2}	7.3×10^{-1}
		Stems and shoots	All	130	1.5×10^{-1}	5.0	4.3×10^{-3}	3.7
			Sand	35	2.1×10^{-1}	3.3	4.1×10^{-2}	1.9
			Loam	36	1.1×10^{-1}	4.5	6.5×10^{-3}	1.5
			Clay	37	5.6×10^{-2}	3.7	4.3×10^{-3}	5.3×10^{-1}
	Maize	Grain	All	67	3.3×10^{-2}	3.0	3.0×10^{-3}	2.6×10^{-1}
			Sand	47	4.9×10^{-2}	2.4	8.0×10^{-3}	2.6×10^{-1}
			Loam	14	1.6×10^{-2}	2.7	3.2×10^{-3}	7.0×10^{-2}
			Clay	11	1.2×10^{-2}	3.3	3.0×10^{-3}	7.0×10^{-2}
		Stems and shoots	All	101	7.3×10^{-2}	3.0	3.0×10^{-3}	4.9×10^{-1}
			Sand	77	1.0×10^{-1}	2.3	1.4×10^{-2}	4.9×10^{-1}
			Loam	10	1.5×10^{-2}	2.5	3.0×10^{-3}	5.2×10^{-2}
			Clay	11	2.2×10^{-2}	2.1	7.8×10^{-3}	6.0×10^{-2}
			Organic	3	1.4×10^{-1}	1.3	1.0×10^{-1}	1.6×10^{-1}
	Leafy vegetables	Leaves	All	290	6.0×10^{-2}	6.0	3.0×10^{-4}	9.8×10^{-1}
			Sand	96	1.2×10^{-1}	4.1	2.1×10^{-3}	9.8×10^{-1}
			Loam	119	7.4×10^{-2}	5.0	3.0×10^{-4}	7.3×10^{-1}
			Clay	67	1.8×10^{-2}	6.7	5.0×10^{-4}	7.2×10^{-1}
			Organic	7	2.3×10^{-2}	7.4	4.0×10^{-3}	4.6×10^{-1}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	38	2.1×10^{-2}	4.1	7.0×10^{-4}	7.3×10^{-1}
			Sand	17	3.5×10^{-2}	4.1	1.2×10^{-2}	7.3×10^{-1}
			Loam	5	3.3×10^{-2}	5.5	6.3×10^{-3}	3.0×10^{-1}
			Clay	14	9.1×10^{-3}	2.2	7.0×10^{-4}	1.6×10^{-2}
	Leguminous vegetables	Seeds and pods	All	126	4.0×10^{-2}	3.7	1.0×10^{-3}	7.1×10^{-1}
			Sand	66	8.7×10^{-2}	2.5	3.5×10^{-3}	7.1×10^{-1}
			Loam	42	2.0×10^{-2}	3.3	1.0×10^{-3}	4.2×10^{-1}
			Clay	18	1.3×10^{-2}	3.0	2.0×10^{-3}	8.1×10^{-2}
	Root crops	Roots	All	81	4.2×10^{-2}	3.0	1.0×10^{-3}	8.8×10^{-1}
			Sand	37	6.2×10^{-2}	2.5	8.0×10^{-3}	4.0×10^{-1}
			Loam	21	3.0×10^{-2}	3.7	1.0×10^{-3}	1.6×10^{-1}
			Clay	17	2.4×10^{-2}	2.2	5.0×10^{-3}	6.0×10^{-2}
			Organic	5	5.9×10^{-2}	5.0	1.6×10^{-2}	8.8×10^{-1}

For footnote see p. 62.

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Cs	Root crops	Leaves	All	12	3.5×10^{-2}	3.0	6.0×10^{-3}	4.5×10^{-1}
			Sand	3	1.1×10^{-1}	3.3	5.1×10^{-2}	4.5×10^{-1}
			Loam	2	2.6×10^{-2}		9.0×10^{-3}	4.3×10^{-2}
			Clay	7	2.6×10^{-2}	2.1	6.0×10^{-3}	4.7×10^{-2}
	Tubers	Tubers	All	138	5.6×10^{-2}	3.0	4.0×10^{-3}	6.0×10^{-1}
			Sand	69	9.3×10^{-2}	3.0	4.0×10^{-3}	6.0×10^{-1}
			Loam	40	3.5×10^{-2}	2.3	4.8×10^{-3}	1.4×10^{-1}
			Clay	21	2.5×10^{-2}	2.2	5.0×10^{-3}	9.0×10^{-2}
			Organic	7	5.8×10^{-2}	3.7	1.6×10^{-2}	5.4×10^{-1}
	Grasses	Stems and shoots	All	64	6.3×10^{-2}	36.6	4.8×10^{-3}	9.9×10^{-1}
			Sand	41	8.4×10^{-2}	3.3	1.0×10^{-2}	9.9×10^{-1}
			Loam	10	4.8×10^{-2}	2.3	1.2×10^{-2}	2.1×10^{-1}
			Clay	9	1.2×10^{-2}	2.1	4.8×10^{-3}	4.3×10^{-2}
			Organic	4	2.8×10^{-1}	1.2	2.1×10^{-1}	3.4×10^{-1}
	Leguminous fodder	Stems and shoots	All	85	1.6×10^{-1}	3.3	1.0×10^{-2}	1.8
			Sand	29	2.4×10^{-1}	3.7	1.8×10^{-2}	1.8
			Loam	51	1.5×10^{-1}	3.0	1.0×10^{-2}	1.2
			Clay	4	4.6×10^{-2}	4.1	1.3×10^{-2}	3.0×10^{-1}
	Pasture	Stems and shoots	All	401	2.5×10^{-1}	4.1	1.0×10^{-2}	5.0
			Sand	169	2.9×10^{-1}	4.1	1.0×10^{-2}	4.8
			Loam	124	1.9×10^{-1}	4.1	1.0×10^{-2}	2.6
			Clay	75	1.8×10^{-1}	3.7	1.0×10^{-2}	1.2
			Organic	31	7.6×10^{-1}	2.2	3.0×10^{-1}	5.0
	Herbs	Stems and leaves	All	4	6.6×10^{-2}	14.9	4.8×10^{-3}	2.8
	Other crops		All	9	3.1×10^{-1}	4.5	3.6×10^{-2}	2.2
Cu	*Not specified*		*All*	*1*	*0.8*			
Fe	Cereals	Grain	All	1	2.0×10^{-4}			
		Stems and shoots	All	1	2.9×10^{-1}		2.2×10^{-1}	3.5×10^{-1}
	Leafy vegetables	Leaves	All	1	1.0×10^{-3}			
	Non-leafy vegetables	Fruits, heads, berries, buds	All	3	1.0×10^{-3}			
	Leguminous vegetables	Stems and shoots	All	1	3.7×10^{-1}		3.0×10^{-1}	4.8×10^{-1}
	Root crops	Roots	All	1	1.0×10^{-3}			
	Tubers	Tubers	All	1	5.0×10^{-4}			
	Pasture	Stems and shoots	All	1	2.0×10^{-3}			

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
	Cereals	Grain	All	13	6.3×10^{-4}	2.3	1.0×10^{-4}	1.1×10^{-2}
			Sand	2	5.8×10^{-3}		1.0×10^{-3}	1.1×10^{-2}
			Loam	5	3.6×10^{-4}	2.5	1.0×10^{-4}	1.2×10^{-3}
			Clay	6	5.7×10^{-4}	2.3	2.0×10^{-4}	1.6×10^{-3}
		Stems and shoots	All	16	5.2×10^{-2}	3.3	7.0×10^{-3}	7.5×10^{-1}
			Sand	2	4.3×10^{-1}		1.1×10^{-1}	7.5×10^{-1}
			Loam	7	3.6×10^{-2}	3.3	7.0×10^{-3}	2.0×10^{-1}
			Clay	7	4.5×10^{-2}	2.5	1.0×10^{-2}	1.9×10^{-1}
	Leafy vegetables	Leaves	All	12	6.5×10^{-3}	3.7	1.1×10^{-3}	1.0×10^{-1}
			Sand	1	4.0×10^{-2}			
			Loam	8	4.1×10^{-3}	1.9	1.1×10^{-3}	8.0×10^{-3}
			Clay	2	4.6×10^{-3}		1.6×10^{-3}	1.3×10^{-2}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	1	1.0×10^{-1}			
	Leguminous vegetables	Seeds and pods	All	23	8.5×10^{-3}	7.4	2.0×10^{-4}	1.4×10^{-1}
			Sand	2	3.5×10^{-3}		3.3×10^{-3}	3.7×10^{-3}
			Loam	3	4.4×10^{-4}	1.5	3.0×10^{-4}	7.0×10^{-4}
			Clay	2	2.5×10^{-4}		2.0×10^{-4}	3.0×10^{-4}
	Root crops	Roots	All	28	7.7×10^{-3}	3.0	1.4×10^{-3}	4.7×10^{-2}
			Sand	9	2.3×10^{-2}	1.5	1.2×10^{-2}	4.7×10^{-2}
			Loam	12	4.7×10^{-3}	2.1	1.5×10^{-3}	1.6×10^{-2}
			Clay	7	4.5×10^{-3}	3.0	1.4×10^{-3}	2.8×10^{-2}
	Tubers	Tubers	All	1	1.0×10^{-1}			
	Pasture	Stems and shoots	All	12	3.7×10^{-3}	6.0	9.0×10^{-4}	5.0×10^{-1}
			Sand	9	1.8×10^{-3}	2.1	9.0×10^{-4}	8.5×10^{-3}
			Clay	2	8.7×10^{-3}		8.4×10^{-3}	9.0×10^{-3}
K	Cereals	Grain	All	2	7.4×10^{-1}		7.3×10^{-1}	7.4×10^{-1}
		Stems and shoots	All	2	1.1		9.3×10^{-1}	1.2
	Leafy vegetables	Leaves	All	2	1.3		1.2	1.3
	Pasture	Stems and shoots	All	1	7.3×10^{-1}			
La	Cereals	Grain	All	1	2.0×10^{-5}			
	Maize	Stems and shoots	All	2	8.8×10^{-5}		7.6×10^{-5}	9.9×10^{-5}
	Leafy vegetables	Leaves	All	7	5.7×10^{-3}	2.7	1.1×10^{-3}	1.5×10^{-2}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	2	6.0×10^{-3}		5.9×10^{-3}	6.0×10^{-3}
	Leguminous vegetables	Seeds and pods	All	4	4.2×10^{-4}	3.0	1.6×10^{-4}	1.8×10^{-3}
	Root crops	Roots	All	9	1.6×10^{-3}	2.7	4.5×10^{-4}	6.0×10^{-3}

For footnote see p. 62.

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
La	Tubers	Tubers	All	8	3.9×10^{-4}	3.7	7.0×10^{-5}	4.0×10^{-3}
	Grasses	Stems and shoots	All	4	1.8×10^{-5}	2.3	6.0×10^{-6}	4.7×10^{-5}
	Pasture	Stems and shoots	All	1	2.0×10^{-2}			
Mn	Cereals	Grain	All	78	2.8×10^{-1}	3.3	1.4×10^{-2}	2.7
			Sand	33	3.4×10^{-1}	3.3	1.4×10^{-2}	2.7
			Loam	22	2.0×10^{-1}	2.6	5.6×10^{-2}	1.1
			Clay	15	2.2×10^{-1}	4.1	2.4×10^{-2}	1.0
			Organic	6	6.5×10^{-1}	2.1	2.7×10^{-1}	1.7
		Stems and shoots	All	30	2.2	4.1	2.0×10^{-1}	2.7×10^{1}
			Sand	9	9.0	1.9	4.8	2.7×10^{1}
			Loam	16	1.2	3.0	2.0×10^{-1}	6.2
			Clay	5	9.8×10^{-1}	4.1	2.0×10^{-1}	8.3
	Maize	Grain	All	19	7.5×10^{-2}	2.1	1.8×10^{-2}	3.0×10^{-1}
			Sand	7	1.4×10^{-1}	1.8	6.4×10^{-2}	3.0×10^{-1}
			Loam	9	5.6×10^{-2}	1.6	3.1×10^{-2}	1.1×10^{-1}
			Clay	3	4.5×10^{-2}	2.4	1.8×10^{-2}	9.9×10^{-2}
	Leafy vegetables	Leaves	All	103	4.1×10^{-1}	2.4	5.2×10^{-2}	3.0
			Sand	35	8.5×10^{-1}	1.8	2.5×10^{-1}	3.0
			Loam	49	3.4×10^{-1}	1.9	7.4×10^{-2}	1.0
			Clay	18	1.7×10^{-1}	2.3	5.2×10^{-2}	7.7×10^{-1}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	3	3.1×10^{-1}	4.1	1.0×10^{-1}	1.5
	Leguminous vegetables	Seeds and pods	All	92	2.2×10^{-1}	2.5	2.2×10^{-2}	2.8
			Sand	37	5.0×10^{-1}	1.9	1.6×10^{-1}	2.8
			Loam	43	1.4×10^{-1}	1.6	5.0×10^{-2}	3.4×10^{-1}
			Clay	12	7.8×10^{-2}	2.3	2.2×10^{-2}	6.0×10^{-1}
	Root crops	Roots	All	13	4.2×10^{-1}	5.5	1.5×10^{-2}	3.9
			Sand	8	1.3	2.4	3.9×10^{-1}	3.9
			Loam	4	6.7×10^{-2}	3.7	1.5×10^{-2}	3.1×10^{-1}
	Tubers	Tubers	All	23	4.7×10^{-2}	2.2	1.2×10^{-2}	3.0×10^{-1}
			Sand	9	8.1×10^{-2}	2.2	2.6×10^{-2}	3.0×10^{-1}
			Loam	9	3.6×10^{-2}	1.6	1.6×10^{-2}	7.6×10^{-2}
			Clay	4	2.4×10^{-2}	2.2	1.2×10^{-2}	7.3×10^{-2}
	Leguminous fodder	Stems and shoots	All	32	1.5	3.3	2.4×10^{-1}	1.2×10^{1}
			Sand	15	2.7	3.0	3.4×10^{-1}	1.2×10^{1}
			Loam	6	1.4	4.1	3.9×10^{-1}	8.4
			Clay	7	6.3×10^{-1}	2.2	2.4×10^{-1}	1.3
			Organic	4	9.2×10^{-1}	2.1	4.9×10^{-1}	2.6

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	*N*	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Mn	Pasture	Stems and shoots	All	83	6.4×10^{-1}	1.9	1.1×10^{-1}	2.7
			Sand	42	9.7×10^{-1}	1.5	4.0×10^{-1}	2.7
			Loam	40	4.3×10^{-1}	1.7	1.1×10^{-1}	1.8
Mo	Cereals	Grain	All	1	8.0×10^{-1}			
	Maize	Stems and shoots	All	3	7.3×10^{-1}		1.0×10^{0}	3.8×10^{1}
	Leafy vegetables	Leaves	All	1	5.1×10^{-1}		2.1×10^{-1}	8.0×10^{-1}
	Root crops	Roots	All	3	3.2×10^{-1}		2.3×10^{-2}	4.2×10^{-1}
	Leguminous fodder	Stems and shoots	All	1	5.4×10^{0}			
Na	Cereals	Grain	All	1	1.0×10^{-2}			
	Leafy vegetables	Leaves	All	1	3.0×10^{-2}			
	Non-leafy vegetables	Fruits, heads, berries, buds	All	1	3.0×10^{-2}			
	Root crops	Roots	All	1	3.0×10^{-2}			
	Tubers	Tubers	All	1	3.0×10^{-2}			
	Pasture	Stems and shoots	All	1	1.0×10^{-1}			
Nb	Cereals	Grain	All	2	1.4×10^{-2}		2.0×10^{-3}	2.5×10^{-2}
	Leafy vegetables	Leaves	All	2	1.7×10^{-2}		8.0×10^{-3}	2.5×10^{-2}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	1	8.0×10^{-3}			
	Root crops	Roots	All	2	1.7×10^{-2}		8.0×10^{-3}	2.5×10^{-2}
	Tubers	Tubers	All	1	4.0×10^{-3}			
	Pasture	Stems and shoots	All	1	2.0×10^{-2}			
Nd	*Not specified*		*All*	*1*	2.0×10^{-2}			
Ni	Cereals	Grain	All	44	2.7×10^{-2}	2.7	3.1×10^{-3}	1.7×10^{-1}
			Sand	26	3.7×10^{-2}	2.4	8.2×10^{-3}	1.7×10^{-1}
			Loam	4	7.6×10^{-3}	1.7	4.9×10^{-3}	1.6×10^{-2}
			Clay	9	3.2×10^{-2}	2.4	6.3×10^{-3}	9.3×10^{-2}
			Organic	4	6.1×10^{-3}	1.6	3.1×10^{-3}	1.0×10^{-2}
	Grasses	Stems and shoots	All	38	1.7×10^{-1}	2.6	1.8×10^{-2}	5.8×10^{-1}
			Sand	18	2.6×10^{-1}	1.6	8.2×10^{-2}	5.1×10^{-1}
			Loam	5	1.1×10^{-1}	1.6	5.6×10^{-2}	1.7×10^{-1}
			Clay	10	2.5×10^{-1}	1.8	1.1×10^{-1}	5.8×10^{-1}
			Organic	5	2.4×10^{-2}	1.5	1.8×10^{-2}	5.0×10^{-2}

For footnote see p. 62.

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Ni	Leguminous fodder	Stems and shoots	All	27	4.0×10^{-1}	2.5	7.3×10^{-2}	2.6
			Sand	14	6.5×10^{-1}	1.8	2.8×10^{-1}	2.6
			Loam	3	2.5×10^{-1}	2.6	1.2×10^{-1}	7.4×10^{-1}
			Clay	6	3.2×10^{-1}	2.4	1.1×10^{-1}	7.3×10^{-1}
			Organic	4	1.5×10^{-1}	3.3	7.3×10^{-2}	9.1×10^{-1}
Np	Cereals	Grain	All	85	2.9×10^{-3}	5.0	2.3×10^{-5}	7.1×10^{-2}
			Sand	79	3.5×10^{-3}	4.1	2.5×10^{-4}	7.1×10^{-2}
			Loam	2	8.5×10^{-4}		2.9×10^{-4}	1.4×10^{-3}
			Clay	2	3.9×10^{-5}		2.3×10^{-5}	5.4×10^{-5}
			Organic	1	9.7×10^{-5}			
	Maize	Grain	All	2	4.8×10^{-3}		1.0×10^{-4}	9.4×10^{-3}
		Stems and shoots	All	58	1.9×10^{-2}	3.3	1.4×10^{-3}	1.1×10^{-1}
			Sand	58	1.9×10^{-2}	3.3	1.4×10^{-3}	1.1×10^{-1}
	Leafy vegetables	Leaves	All	5	2.7×10^{-2}	3.0	5.0×10^{-3}	8.0×10^{-2}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	9	1.8×10^{-2}	2.4	4.0×10^{-3}	5.7×10^{-2}
	Leguminous vegetables	Seeds and pods	All	17	1.7×10^{-2}	1.8	4.0×10^{-3}	3.8×10^{-2}
			Sand	17	1.7×10^{-2}	1.8	4.0×10^{-3}	3.8×10^{-2}
	Root crops	Roots	All	7	2.2×10^{-2}	2.0	5.0×10^{-3}	3.6×10^{-2}
			Sand	6	2.9×10^{-2}	1.2	2.1×10^{-2}	3.6×10^{-2}
	Tubers	Tubers	All	57	5.7×10^{-3}	2.5	7.1×10^{-4}	2.7×10^{-2}
			Sand	56	5.8×10^{-3}	2.5	7.1×10^{-4}	2.7×10^{-2}
	Grasses	Stems, leaves	All	3	3.1×10^{-2}	3.7	7.2×10^{-3}	8.6×10^{-2}
	Leguminous fodder	Stems and shoots	All	34	2.5×10^{-2}	3.3	2.0×10^{-3}	1.2×10^{-1}
			Sand	23	4.6×10^{-2}	1.8	1.6×10^{-2}	1.2×10^{-1}
			Loam	2	6.1×10^{-2}		5.9×10^{-2}	6.3×10^{-2}
			Clay	9	4.1×10^{-3}	1.5	2.0×10^{-3}	8.1×10^{-3}
	Pasture	Stems and shoots	All	16	6.1×10^{-2}	2.7	1.3×10^{-2}	4.7×10^{-1}
			Sand	5	2.1×10^{-1}	2.0	8.9×10^{-2}	4.7×10^{-1}
			Loam	10	3.4×10^{-2}	1.7	1.3×10^{-2}	5.7×10^{-2}
P	Cereals	Grain	All	1	2.0×10^{-1}			
	Leafy vegetables	Leaves	All	1	1.0			
	Non-leafy vegetables	Fruits, heads, berries, buds	All	1	1.0			
	Root crops	Roots	All	1	1.0			
	Tubers	Tubers	All	1	5.0×10^{-1}			
	Pasture	Stems and shoots	All	1	2.0			
Pb	Cereals	Grain	All	9	1.1×10^{-2}	3.6	1.9×10^{-3}	4.8×10^{-2}
		Stems and shoots	All	4	2.3×10^{-2}	3.5	5.1×10^{-3}	9.6×10^{-2}

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Pb	Maize	Grain	All	9	1.2×10^{-3}	2.3	5.2×10^{-4}	3.8×10^{-3}
		Stems and shoots	All	3	2.8×10^{-3}	6.6	6.0×10^{-4}	2.3×10^{-2}
	Leafy vegetables	Leaves	All	31	8.0×10^{-2}	1.3×10^{1}	3.2×10^{-3}	2.5×10^{1}
			Sand	4	7.3×10^{-2}	1.5	4.9×10^{-2}	1.1×10^{-1}
			Loam	3	8.2×10^{-1}	1.0	7.9×10^{-1}	8.6×10^{-1}
			Clay	7	2.8×10^{-2}	4.1	4.1×10^{-3}	1.2×10^{-1}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	5	1.5×10^{-2}	2.6×10^{1}	1.5×10^{-3}	3.9
		Stems and shoots	All	2	8.8×10^{-3}		5.8×10^{-3}	1.2×10^{-2}
	Leguminous vegetables	Seeds and pods	All	17	5.3×10^{-3}	1.2×10^{1}	4.6×10^{-4}	4.9
			Sand	3	2.7×10^{-3}	3.2	6.5×10^{-4}	8.9×10^{-3}
			Loam	5	1.4×10^{-3}	4.4	6.5×10^{-4}	8.9×10^{-3}
			Clay	4	8.0×10^{-4}	1.0	4.6×10^{-4}	1.0×10^{-2}
		Stems and shoots	All	1	8.0×10^{-4}			
	Root crops	Roots	All	27	1.5×10^{-2}	1.6×10^{1}	2.4×10^{-4}	3.3
			Sand	5	6.4×10^{-2}	1.6	4.2×10^{-2}	1.2×10^{-1}
			Loam	5	2.3×10^{-3}	4.7	2.4×10^{-4}	1.7×10^{-2}
		Stems and shoots	All	12	6.3×10^{-2}	1.5×10^{1}	3.0×10^{-3}	1.6×10^{1}
	Tubers	Tubers	All	30	1.5×10^{-3}	7.4	1.5×10^{-4}	2.6
			Sand	5	6.4×10^{-3}	3.5	1.6×10^{-3}	3.9×10^{-2}
			Loam	17	5.2×10^{-4}	2.4	1.5×10^{-4}	2.3×10^{-3}
	Grasses	Stems and shoots	All	17	3.1×10^{-1}	1.8	1.1×10^{-1}	1.0
	Pasture	Stems and shoots	All	34	9.2×10^{-2}	4.8	2.2×10^{-3}	1.0
	Leguminous fodder	Stems and shoots	All	1	1.6×10^{-2}			
Pm	Cereals	Grain	All	17	1.4×10^{-2}	6.0	1.7×10^{-3}	2.4×10^{-1}
			Sand	10	6.6×10^{-3}	6.0	1.7×10^{-3}	2.4×10^{-1}
			Loam	6	4.6×10^{-2}	2.7	1.0×10^{-2}	1.3×10^{-1}
			Clay	1	2.0×10^{-2}			
		Stems and shoots	All	19	2.3×10^{-1}	4.1	2.2×10^{-2}	1.4
			Sand	10	1.2×10^{-1}	5.0	2.2×10^{-2}	1.4
			Loam	7	5.8×10^{-1}	1.8	2.9×10^{-1}	1.2
			Clay	2	2.8×10^{-1}		1.3×10^{-1}	4.2×10^{-1}
	Leguminous vegetables	Seeds and pods	All	4	1.7×10^{-1}	7.4	2.0×10^{-2}	1.2
			Sand	1	5.0×10^{-2}			
			Loam	1	2.0×10^{-2}			
	Root crops	Roots	All	5	4.2×10^{-2}	1.2	3.6×10^{-2}	6.0×10^{-2}

For footnote see p. 62.

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Pm	Tubers	Tubers	All	3	1.0×10^{-2}	1.3	7.5×10^{-3}	1.2×10^{-2}
	Root crops	Leaves	All	5	1.9×10^{-1}	1.2	1.6×10^{-1}	2.5×10^{-1}
Po	Cereals	Grain	All	2	2.4×10^{-4}		2.2×10^{-4}	2.6×10^{-4}
	Maize	Grain	All	2	2.4×10^{-4}		1.8×10^{-5}	4.7×10^{-4}
	Leafy vegetables	Leaves	All	12	7.4×10^{-3}	6.9	2.5×10^{-4}	5.0×10^{-2}
	Non-leafy vegetables	Stems and shoots	All	2	1.9×10^{-4}		1.6×10^{-5}	3.7×10^{-4}
	Leguminous vegetables	Seeds and pods	All	4	2.7×10^{-4}	3.9	6.0×10^{-5}	1.0×10^{-3}
	Root crops	Roots	All	10	5.8×10^{-3}	4.3	2.4×10^{-4}	4.9×10^{-2}
		Stems and shoots	All	2	7.7×10^{-2}		5.8×10^{-2}	9.7×10^{-2}
	Tubers	Tubers	All	9	2.7×10^{-3}	5.8	1.4×10^{-4}	3.4×10^{-2}
	Pasture	Stems and shoots	All	10	1.2×10^{-1}	4.2	2.2×10^{-2}	1.0
	Leguminous fodder	Stems and shoots	All	2	1.1×10^{-2}		2.6×10^{-5}	2.2×10^{-4}
Pr	*Cereals*	*Grain*	*All*	*1*	2.0×10^{-2}			
	Leafy vegetables	*Leaves*	*All*	*1*	2.0×10^{-2}			
	Root crops	*Roots*	*All*	*1*	2.0×10^{-2}			
Pu	Cereals	Grain	All	105	9.5×10^{-6}	6.7	2.0×10^{-7}	1.1×10^{-3}
			Sand	76	3.3×10^{-5}	6.6×10^{-5}	5.0×10^{-7}	3.6×10^{-4}
			Loam	10	4.9×10^{-6}	11.0	3.5×10^{-7}	3.1×10^{-4}
			Clay	16	7.4×10^{-6}	14.9	2.0×10^{-7}	5.1×10^{-4}
			Organic	2	5.4×10^{-4}		2.3×10^{-6}	1.1×10^{-3}
		Stems and shoots	All	10	4.4×10^{-5}	16.4	4.4×10^{-7}	9.0×10^{-4}
			Sand	1	4.0×10^{-5}			
			Loam	5	4.5×10^{-4}	2.0	1.5×10^{-4}	9.0×10^{-4}
			Clay	4	2.4×10^{-6}	5.5	4.4×10^{-7}	2.0×10^{-5}
	Maize	Grain	All	1	3.0×10^{-6}			
		Stems and shoots	All	58	5.2×10^{-5}	2.7	2.0×10^{-6}	3.2×10^{-4}
			Sand	58	5.2×10^{-5}	2.7	2.0×10^{-6}	3.2×10^{-4}
	Leafy vegetables	Leaves	All	13	8.3×10^{-5}	2.7	1.0×10^{-5}	2.9×10^{-4}
			Sand	4	1.1×10^{-4}	2.7	2.9×10^{-5}	2.9×10^{-4}
			Loam	1	2.8×10^{-4}			
			Organic	1	2.7×10^{-5}			
	Non-leafy Vegetables	Fruits, heads, berries, buds	All	9	6.5×10^{-5}	2.7	6.0×10^{-6}	2.0×10^{-4}
			Loam	8	6.2×10^{-5}	2.7	6.0×10^{-6}	2.0×10^{-4}
	Leguminous vegetables	Seeds and pods	All	18	6.3×10^{-5}	1.4	3.7×10^{-5}	1.5×10^{-4}
			Sand	18	6.3×10^{-5}	1.4	3.7×10^{-5}	1.5×10^{-4}

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	*N*	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Pu	Root crops	Roots	All	5	3.9×10^{-4}	10.0	7.0×10^{-5}	5.8×10^{-3}
			Sand	4	5.5×10^{-4}	10.0	7.0×10^{-5}	5.8×10^{-3}
		Leaves	All	10	1.2×10^{-3}	2.5	2.5×10^{-4}	4.9×10^{-3}
			Sand	4	7.7×10^{-4}	1.9	3.4×10^{-4}	1.6×10^{-3}
			Loam	5	2.2×10^{-3}	1.8	1.1×10^{-3}	4.9×10^{-3}
			Organic	1	2.5×10^{-4}			
	Tubers	Tubers	All	87	1.1×10^{-4}	5.5	3.8×10^{-6}	5.0×10^{-3}
			Sand	72	1.0×10^{-4}	5.0	3.8×10^{-6}	2.0×10^{-3}
			Loam	9	1.5×10^{-4}	11.0	6.2×10^{-6}	5.0×10^{-3}
			Clay	3	3.6×10^{-4}	3.7	8.0×10^{-5}	9.4×10^{-4}
			Organic	2	4.1×10^{-4}		1.3×10^{-5}	8.0×10^{-4}
	Grasses	Stems and shoots	All	2	1.6×10^{-4}		5.0×10^{-5}	2.7×10^{-4}
	Leguminous fodder	Stems and shoots	All	74	4.9×10^{-4}	2.2	1.1×10^{-4}	2.9×10^{-3}
			Sand	33	4.8×10^{-4}	2.2	1.1×10^{-4}	2.0×10^{-3}
			Loam	25	5.8×10^{-4}	2.4	1.1×10^{-4}	2.9×10^{-3}
			Clay	16	4.1×10^{-4}	1.9	1.2×10^{-4}	1.1×10^{-3}
	Pasture	Stems and shoots	All	22	5.5×10^{-4}	3.0	6.3×10^{-5}	3.9×10^{-3}
			Sand	5	4.6×10^{-4}	1.8	2.1×10^{-4}	9.4×10^{-4}
			Loam	10	3.0×10^{-4}	3.0	6.3×10^{-5}	3.3×10^{-3}
			Clay	5	2.0×10^{-3}	1.5	1.2×10^{-3}	3.9×10^{-3}
			Organic	1	1.1×10^{-3}			
Ra	Cereals	Grain	All	24	1.7×10^{-2}	1.2×10^{1}	8.0×10^{-5}	6.7×10^{-1}
			Loam	7	2.9×10^{-2}	9.7	8.0×10^{-4}	6.7×10^{-1}
			Clay	10	3.9×10^{-2}	9.9	2.4×10^{-4}	5.0×10^{-1}
		Stems and shoots	All	20	3.6×10^{-2}	4.8	1.6×10^{-3}	4.3×10^{-1}
			Loam	10	5.2×10^{-2}	4.4	7.2×10^{-3}	4.3×10^{-1}
	Maize	Grain	All	28	2.4×10^{-3}	5.4	1.2×10^{-4}	1.1×10^{-1}
			Loam	4	1.7×10^{-3}	1.8	9.0×10^{-4}	3.0×10^{-3}
			Clay	16	1.4×10^{-3}	4.8	1.2×10^{-4}	1.1×10^{-1}
		Stems and shoots	All	6	1.8×10^{-2}	5.2	9.6×10^{-4}	8.5×10^{-2}
	Leafy vegetables	Leaves	All	77	9.1×10^{-2}	6.7	1.8×10^{-3}	1.3×10^{2}
			Loam	10	1.2×10^{-1}	2.5	1.6×10^{-2}	4.4×10^{-1}
			Clay	20	4.0×10^{-2}	4.5	1.8×10^{-3}	4.2×10^{-1}
			Organic	9	4.9×10^{-2}	2.1	2.0×10^{-2}	1.4×10^{-1}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	44	1.7×10^{-2}	8.4	2.4×10^{-4}	6.3
			Sand	3	2.2×10^{-3}	2.1	1.1×10^{-3}	5.0×10^{-3}
			Loam	4	4.8×10^{-2}	5.6	6.9×10^{-3}	3.4×10^{-1}
			Clay	17	2.2×10^{-2}	2.8	3.9×10^{-3}	2.1×10^{-1}
		Stems and shoots	All	13	6.1×10^{-2}	6.4	6.7×10^{-3}	1.8

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TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Ra	Leguminous vegetables	Seeds and pods	All	40	1.4×10^{-2}	8.2	3.2×10^{-4}	6.2
			Loam	12	9.8×10^{-3}	4.5	4.8×10^{-4}	8.7×10^{-2}
			Clay	15	9.3×10^{-3}	4.2	8×10^{-4}	1.1×10^{-1}
		Stems and shoots	All	18	2.8×10^{-2}	1.1×10^{1}	1.1×10^{-5}	1.5
			Loam	6	1.1×10^{-2}	3.2×10^{1}	1.1×10^{-5}	1.1×10^{-1}
	Root crops	Roots	All	60	7×10^{-2}	9.2	2.0×10^{-3}	5.6×10^{1}
			Sand	3	4.8×10^{-3}	2.3	2.0×10^{-3}	1.1×10^{-2}
			Loam	8	9.1×10^{-2}	1.9	2.9×10^{-2}	2.0×10^{-1}
			Clay	23	3.9×10^{-2}	2.9	3.2×10^{-3}	2.2×10^{-1}
		Stems and shoots	All	22	7.1×10^{-2}	4.6	2.5×10^{-3}	7.1×10^{-1}
			Loam	6	1.5×10^{-1}	5.6	9.6×10^{-3}	7.1×10^{-1}
	Tubers	Tubers	All	45	1.1×10^{-2}	6.8	2.4×10^{-4}	3.9
			Loam	8	1.2×10^{-2}	1.1×10^{1}	2.4×10^{-4}	6.2×10^{-1}
			Clay	24	5.4×10^{-3}	2.5	1.3×10^{-3}	8.0×10^{-2}
		Shoots	All	6	1.6×10^{-1}	2.2	4.3×10^{-2}	3.3×10^{-1}
	Herbs	Herbs	All	20	6.9×10^{-2}	4.5	5.3×10^{-3}	3.3
	Other	Sunflower	All	4	4.2×10^{-1}	3.0	8.5×10^{-2}	1.1
		Tea leaves	All	1	3.3×10^{-2}			
	Grasses	Stems and shoots	All	62	1.3×10^{-1}	4	3.6×10^{-3}	1.6
			Sand	24	1.4×10^{-1}	4.2	5.4×10^{-3}	1.6
			Loam	14	2.6×10^{-1}	2.00	9.6×10^{-2}	7.2×10^{-1}
			Clay	3	4.2×10^{-2}	1.5	2.7×10^{-2}	6.1×10^{-2}
	Pasture	Stems and shoots	All	42	7.1×10^{-2}	7.6	5.1×10^{-5}	1.6
			Sand	3	8.0×10^{-3}	3.8	1.8×10^{-3}	2.3×10^{-2}
			Loam	6	8.8×10^{-3}	1.9×10^{1}	5.1×10^{-5}	1.1×10^{-1}
	Leguminous fodder	Stems and shoots	All	16	1.7×10^{-1}	3.1	3.4×10^{-2}	1.5
			Sand	5	1.7×10^{-1}	2.5	8.0×10^{-2}	5.7×10^{-1}
			Loam	8	1.2×10^{-1}	3.9	3.4×10^{-2}	1.5
Rb	Cereals	Grain	All	1	9.0×10^{-1}			
	Leafy vegetables	Leaves	All	2	6.2×10^{-1}		3.4×10^{-1}	9.0×10^{-1}
	Root crops	Roots	All	1	9.0×10^{-1}			
Rh	*Not specified*		*All*	*1*	9.0×10^{-1}			
Ru	Cereals	Grain	All	12	3.0×10^{-3}	2.6	6.0×10^{-4}	1.0×10^{-2}
			Sand	2	6.5×10^{-3}		3.0×10^{-3}	1.0×10^{-2}
			Loam	6	3.4×10^{-3}	2.2	1.0×10^{-3}	8.0×10^{-3}
			Clay	3	1.3×10^{-3}	3.3	6.0×10^{-4}	5.0×10^{-3}
		Stems and shoots	All	19	1.6×10^{-1}	2.7	3.0×10^{-2}	1.0
			Sand	3	5.9×10^{-1}	1.9	3.0×10^{-1}	1.0
			Loam	10	2.0×10^{-1}	2.2	5.0×10^{-2}	6.5×10^{-1}
			Clay	5	6.2×10^{-2}	1.7	3.0×10^{-2}	9.5×10^{-2}

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Ru	Leafy vegetables	Leaves	All	3	9.0×10^{-2}	3.7	2.0×10^{-2}	2.3×10^{-1}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	1	2.0×10^{-2}			
	Leguminous vegetables	Seeds and pods	All	2	1.5×10^{-2}		1.0×10^{-2}	2.0×10^{-2}
	Root crops	Roots	All	1	1.0×10^{-2}			
	Tubers	Tubers	All	1	5.0×10^{-3}			
Sb	Cereals	Grain	All	24	1.8×10^{-3}	2.7	3.0×10^{-4}	9.0×10^{-3}
			Sand	4	1.2×10^{-3}	3.7	4.5×10^{-4}	7.8×10^{-3}
			Loam	19	2.0×10^{-3}	2.7	3.0×10^{-4}	9.0×10^{-3}
		Stems and shoots	All	7	2.5×10^{-2}	1.6	1.2×10^{-2}	5.3×10^{-2}
	Leafy vegetables	Leaves	All	5	9.4×10^{-5}	2.6	2.2×10^{-5}	2.3×10^{-4}
			Sand	2	2.2×10^{-4}		2.0×10^{-4}	2.3×10^{-4}
			Loam	3	5.5×10^{-5}	2.2	2.2×10^{-5}	1.0×10^{-4}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	5	1.3×10^{-4}	6.7	1.5×10^{-5}	1.6×10^{-3}
	Leguminous vegetables	Seeds and pods	All	1	7.0×10^{-3}			
	Root crops	Roots	All	5	6.2×10^{-4}	1.5	4.0×10^{-4}	1.1×10^{-3}
	Tubers	Tubers	All	1		2.0×10^{-3}		
Sr	Cereals	Grain	All	282	1.1×10^{-1}	2.7	3.6×10^{-3}	1.0
			Sand	123	1.4×10^{-1}	3.0	3.6×10^{-3}	1.0
			Loam	71	1.1×10^{-1}	2.4	1.6×10^{-2}	7.2×10^{-1}
			Clay	72	7.8×10^{-2}	2.4	5.3×10^{-3}	7.1×10^{-1}
			Organic	10	9.7×10^{-2}	4.1	1.2×10^{-2}	3.6×10^{-1}
		Stems and shoots	All	37	1.1	2.5	1.5×10^{-1}	9.8
			Sand	11	2.1	2.3	9.3×10^{-1}	9.8
			Loam	3	1.8	2.3	7.2×10^{-1}	3.6
			Clay	20	7.5×10^{-1}	2.4	1.5×10^{-1}	2.8
	Maize	Grain	All	39	3.2×10^{-1}	4.1	2.0×10^{-3}	2.6
			Sand	19	5.2×10^{-1}	3.3	4.0×10^{-2}	2.6
			Loam	13	3.6×10^{-1}	1.6	1.5×10^{-1}	8.6×10^{-1}
			Clay	7	6.9×10^{-2}	6.7	2.0×10^{-3}	3.9×10^{-1}
		Stems and shoots	All	36	7.3×10^{-1}	6.0	1.2×10^{-1}	3.0
			Sand	23	8.2×10^{-1}	2.6	1.2×10^{-1}	3.0
			Loam	7	7.0×10^{-1}	1.7	2.8×10^{-1}	1.4
			Clay	6	5.0×10^{-1}	1.9	1.8×10^{-1}	1.1

For footnote see p. 62.

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Sr	Leafy vegetables	Leaves	All	217	7.6×10^{-1}	6.0	3.9×10^{-3}	7.8
			Sand	72	1.7	4.1	6.4×10^{-2}	7.8
			Loam	84	1.2	4.1	4.1×10^{-2}	5.0
			Clay	54	1.5×10^{-1}	6.0	3.9×10^{-3}	2.2
			Organic	6	2.1×10^{-1}	1.4	1.5×10^{-1}	3.0×10^{-1}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	19	3.6×10^{-1}	5.5	7.1×10^{-3}	7.9
			Sand	5	8.7×10^{-1}	4.1	2.0×10^{-1}	7.9
			Loam	3	1.4	1.6	9.0×10^{-1}	2.3
			Clay	8	1.3×10^{-1}	6.0	7.1×10^{-3}	8.6×10^{-1}
			Organic	2	2.2×10^{-1}	4.2×10^{-2}	1.9×10^{-1}	2.5×10^{-1}
	Leguminous vegetables	Seeds and pods	All	148	1.4	2.3	1.3×10^{-1}	6.0
			Sand	55	2.2	2.1	3.0×10^{-1}	6.0
			Loam	68	1.3	1.9	1.7×10^{-1}	4.6
			Clay	25	6.2×10^{-1}	2.2	1.3×10^{-1}	2.6
	Root crops	Roots	All	56	7.2×10^{-1}	4.1	3.0×10^{-2}	4.8
			Sand	26	1.1	3.7	3.0×10^{-2}	4.8
			Loam	16	6.1×10^{-1}	4.5	4.4×10^{-2}	4.5
			Clay	13	4.1×10^{-1}	4.5	5.2×10^{-2}	3.9
	Tubers	Tubers	All	106	1.6×10^{-1}	3.0	7.4×10^{-3}	1.6
			Sand	39	2.2×10^{-1}	2.6	2.6×10^{-2}	1.6
			Loam	41	1.3×10^{-1}	3.0	7.4×10^{-3}	4.5×10^{-1}
			Clay	21	1.3×10^{-1}	2.3	2.6×10^{-2}	6.7×10^{-1}
			Organic	4	5.8×10^{-2}	4.5	8.0×10^{-3}	2.3×10^{-1}
	Grasses	Stems and shoots	All	50	9.1×10^{-1}	1.9	2.5×10^{-1}	2.8
			Sand	34	1.1	1.7	2.6×10^{-1}	2.8
			Loam	6	6.0×10^{-1}	2.5	2.9×10^{-1}	2.0
			Clay	7	7.9×10^{-1}	1.3	4.8×10^{-1}	9.7×10^{-1}
			Organic	3	2.6×10^{-1}	1.1	2.5×10^{-1}	2.8×10^{-1}
	Leguminous fodder	Stems and shoots	All	35	3.7	1.9	1.3	1.8×10^{1}
			Sand	14	4.9	2.0	1.3	1.8×10^{1}
			Loam	11	3.3	1.8	1.4	9.8
			Clay	10	2.8	1.7	1.3	5.8
			Organic	1	3.9×10^{1}			
	Pasture	Stems and shoots	All	172	1.3	2.2	5.6×10^{-2}	7.3
			Sand	87	1.7	5.5	9.8×10^{-2}	7.3
			Loam	58	1.1	1.6	3.7×10^{-1}	2.6
			Clay	22	8.0×10^{-1}	2.2	9.0×10^{-2}	2.8
			Organic	4	3.5×10^{-1}	3.7	5.6×10^{-2}	1.2
	Herbs	Stems and shoots	All	1	4.5			
	Other crops		All	9	8.8×10^{-1}	6.0	2.0×10^{-2}	8.2

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Te	Cereals	Grain	All	1	1.0×10^{-1}			
	Leafy vegetables	Leaves	All	1	3.0×10^{-1}			
	Non-leafy vegetables	Fruits, heads, berries, buds	All	1	3.0×10^{-1}			
	Root crops	Roots	All	1	3.0×10^{-1}			
	Tubers	Tubers	All	1	2.0×10^{-1}			
	Pasture	Stems and shoots	All	1	1.0			
Th	Cereals	Grain	All	36	2.1×10^{-3}	3.4	1.6×10^{-4}	2.2×10^{-2}
			Sand	4	4.4×10^{-3}	1.4	3.0×10^{-3}	6.0×10^{-3}
			Loam	18	2.7×10^{-3}	3.4	2.1×10^{-4}	2.2×10^{-2}
			Clay	9	1.2×10^{-3}	1.6	7.0×10^{-4}	2.6×10^{-3}
		Stems and shoots	All	28	6.1×10^{-3}	2.4	1.6×10^{-3}	3.7×10^{-2}
			Sand	4	1.4×10^{-2}	1.3	1.1×10^{-2}	1.8×10^{-2}
			Loam	11	6.6×10^{-3}	1.9	2.4×10^{-3}	1.3×10^{-2}
			Clay	8	3.6×10^{-3}	1.6	2.0×10^{-3}	6.0×10^{-3}
			Organic	3	2.0×10^{-3}	1.5	1.6×10^{-3}	3.2×10^{-3}
	Maize	Grain	All	18	6.4×10^{-5}	9.2	1.2×10^{-6}	1.1×10^{-2}
			Loam	10	2.0×10^{-4}	9.3	1.4×10^{-5}	1.1×10^{-2}
			Clay	7	1.5×10^{-5}	3.7	1.2×10^{-6}	5.4×10^{-5}
		Stems and shoots	All	2	1.8×10^{-3}		5.4×10^{-4}	3.0×10^{-3}
	Leafy vegetables	Leaves	All	24	1.2×10^{-3}	6.0	9.4×10^{-5}	2.1×10^{-1}
			Loam	13	8.6×10^{-4}	3.3	9.4×10^{-5}	5.8×10^{-3}
			Clay	7	4.9×10^{-4}	2.8	1.9×10^{-4}	4.1×10^{-3}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	17	7.8×10^{-4}	6.8	6.2×10^{-5}	1.6×10^{-2}
			Loam	10	2.0×10^{-4}	9.3	1.4×10^{-5}	1.1×10^{-2}
			Clay	7	1.5×10^{-5}	3.7	1.2×10^{-6}	5.4×10^{-5}
		Stems and shoots	All	6	2.2×10^{-3}	5.1	3.3×10^{-4}	2.4×10^{-2}
	Leguminous vegetables	Seeds and pods	All	22	5.3×10^{-4}	9.4	2.5×10^{-5}	4.8×10^{-1}
			Loam	14	1.8×10^{-3}	3.9	1.7×10^{-4}	2.4×10^{-2}
			Clay	10	4.1×10^{-4}	2.3×10^{1}	2.5×10^{-5}	4.8×10^{-1}
			Organic	4	4.5×10^{-4}	7.6	8.0×10^{-5}	4.0×10^{-3}
		Stems and shoots	All	7	4.3×10^{-3}	4.0	5.3×10^{-4}	2.4×10^{-2}
	Root crops	Roots	All	33	8.0×10^{-4}	1.3×10^{1}	8.2×10^{-6}	9.5×10^{-2}
			Loam	14	1.1×10^{-3}	1.6×10^{1}	8.2×10^{-6}	5.3×10^{-2}
			Clay	14	2.6×10^{-4}	5.4	4.5×10^{-5}	2.3×10^{-2}
		Stems and shoots	All	8	8.7×10^{-3}	4.4	2.1×10^{-3}	7.8×10^{-2}

For footnote see p. 62.

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	*N*	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Th	Tubers	Tubers	All	24	2×10^{-4}	9.9	1.3×10^{-5}	1.8×10^{-2}
			Loam	10	2.5×10^{-4}	6.4	1.3×10^{-5}	3.6×10^{-3}
			Clay	12	9.6×10^{-5}	1.1×10^{1}	1.3×10^{-5}	1.8×10^{-2}
		Stems and shoots	All	2	1.9×10^{-2}		4.8×10^{-3}	3.2×10^{-2}
	Other crops	Tea leaves		2	3.4×10^{-3}			
	Grasses	Stems and shoots	All	1	4.2×10^{-2}	3.1	7.4×10^{-4}	6.5×10^{-1}
	Pasture	Stems and shoots	All	64	9.9×10^{-2}	5.5	2.9×10^{-3}	2.7
	Leguminous fodder	Stems and shoots	All	36	2.6×10^{-3}	1.6	1.5×10^{-3}	4×10^{-3}
U	Cereals	Grain	All	59	6.2×10^{-3}	7.7	1.6×10^{-4}	8.2×10^{-1}
			Sand	6	8.9×10^{-3}	1.1×10^{1}	1.9×10^{-4}	6.2×10^{-2}
			Loam	20	7.7×10^{-3}	5.1	1.6×10^{-4}	6.2×10^{-2}
			Clay	11	3.8×10^{-3}	4.0	7.6×10^{-4}	5.0×10^{-2}
		Stems and shoots	All	55	2.7×10^{-2}	7.5	3.0×10^{-5}	3.5
			Sand	6	3.4×10^{-2}	6.0	2.1×10^{-3}	1.7×10^{-1}
			Loam	25	5.4×10^{-2}	6.30	7.4×10^{-4}	3.5
			Clay	8	1.0×10^{-2}	3.6	2.8×10^{-3}	9.8×10^{-2}
	Maize	Grain	All	9	1.5×10^{-2}	1.2×10^{1}	5.0×10^{-4}	7.1×10^{-1}
		Stems and shoots	All	11	7.8×10^{-3}	1.4×10^{1}	1.6×10^{-4}	9.6×10^{-1}
	Leafy vegetables	Leaves	All	108	2.0×10^{-2}	7.3	7.8×10^{-5}	8.8
			Sand	7	1.7×10^{-1}	1.5×10^{1}	1.5×10^{-3}	8.8
			Loam	14	4.3×10^{-2}	3.9	7.7×10^{-3}	2.7×10^{-1}
			Clay	9	3.6×10^{-3}	4.2	7.6×10^{-4}	4.3×10^{-2}
			Organic	6	1.8×10^{-1}	9.7	7.9×10^{-3}	8.0
	Non-leafy vegetables	Fruits, heads, berries, buds	All	38	1.5×10^{-2}	4.2	5.2×10^{-4}	2.0×10^{-1}
			Sand	7	1.9×10^{-2}	5.5	1.3×10^{-3}	1.6×10^{-1}
			Loam	4	2.3×10^{-2}	2.2	7.6×10^{-3}	4.7×10^{-2}
			Clay	7	1.8×10^{-2}	4.2	5.0×10^{-3}	2.0×10^{-1}
		Stems and shoots	All	6	5.3×10^{-2}	9.9	4.3×10^{-3}	7.1×10^{-1}
	Leguminous vegetables	Seeds and pods	All	19	2.2×10^{-3}	1.2×10^{1}	5.4×10^{-5}	1.5×10^{-1}
			Loam	4	3.0×10^{-3}	1.8×10^{1}	5.4×10^{-5}	4.7×10^{-2}
			Clay	7	5.5×10^{-4}	4.7	5.7×10^{-5}	5.0×10^{-3}
		Stems and shoots	All	21	6.4×10^{-2}	1.4×10^{1}	7.4×10^{-4}	8.7
			Sand	6	2.8×10^{-1}	2.0×10^{1}	5.3×10^{-3}	8.7
			Loam	6	1.2×10^{-2}	6.2	7.4×10^{-4}	1.4×10^{-1}

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
U	Root crops	Roots	All	46	8.4×10^{-3}	6.2	4.9×10^{-4}	2.6×10^{-1}
			Sand	9	7.8×10^{-3}	5.9	9.9×10^{-4}	2.3×10^{-1}
			Loam	10	2.5×10^{-2}	3.2	2.6×10^{-3}	1.2×10^{-1}
			Clay	5	6.8×10^{-3}	6.2	7.9×10^{-4}	9.2×10^{-2}
		Stems and shoots	All	37	2.8×10^{-2}	5.4	2.0×10^{-3}	7.0×10^{-1}
			Sand	9	2.5×10^{-2}	5.6	2.0×10^{-3}	2.4×10^{-1}
			Loam	11	5.0×10^{-2}	3.0	1.3×10^{-2}	3.2×10^{-1}
			Clay	5	1.1×10^{-2}	4.3	2.0×10^{-3}	5.8×10^{-2}
	Tubers	Tubers	All	28	5.0×10^{-3}	6.4	1.8×10^{-4}	8.0×10^{-2}
			Sand	4	1.9×10^{-2}	3.8	4.3×10^{-3}	7.8×10^{-2}
			Loam	3	2.8×10^{-2}	3.2	8.2×10^{-3}	8.0×10^{-2}
			Clay	6	9.2×10^{-4}	3.0	1.9×10^{-4}	4.8×10^{-3}
		Stems and shoots	All	1	1.9×10^{-1}			
	Herbs		All	9	3.6×10^{-2}	4.9	8.6×10^{-3}	4.1×10^{-1}
	Other crops	Sunflower (leaves)	All	39	7.1×10^{-2}	3.9	8.9×10^{-3}	7.8
			Sand	5	4.1×10^{-1}	5.3	1.6×10^{-1}	7.8
			Loam	22	7.1×10^{-2}	2.9	1.0×10^{-2}	6.4×10^{-1}
			Clay	11	2.7×10^{-2}	2.1	8.9×10^{-3}	1.0×10^{-1}
		Sunflower (grain)	All	2	1.5×10^{-2}		8.2×10^{-3}	2.9×10^{-2}
	Grasses	Stems and shoots	All	147	1.7×10^{-2}	9.4	2.0×10^{-4}	5.5
			Sand	19	1.6×10^{-2}	1.7×10^{1}	5.5×10^{-4}	1.8
			Loam	34	9.8×10^{-3}	8.4	3.1×10^{-4}	4.6×10^{-1}
	Pasture	Stems and shoots	All	53	4.6×10^{-2}	5.3	1.3×10^{-3}	1.4×10^{1}
			Sand	3	2.7×10^{-3}	1.8	1.3×10^{-3}	3.9×10^{-3}
			Loam	7	7.2×10^{-2}	3.3×10^{1}	1.8×10^{-3}	1.4×10^{1}
	Leguminous fodder	Stems and shoots	All	15	1.5×10^{-2}	4.2	2.0×10^{-3}	1.6
			Sand	12	1.0×10^{-2}	2.0	2.0×10^{-3}	2.1×10^{-2}
W	*Unspecified*		*All*	*1*	*1.0×10^{-1}*			
Y	Cereals	Grain	All	5	5.0×10^{-4}			
	Leafy vegetables	Leaves	All	1	2.0×10^{-3}			
	Non-leafy vegetables	Fruits, heads, berries, buds	All	1	2.0×10^{-3}			
	Root crops	Roots	All	1	2.0×10^{-3}			
	Tubers	Tubers	All	1	1.0×10^{-3}			
	Pasture	Stems and shoots	All	1	5.0×10^{-3}			

For footnote see p. 62.

TABLE 17. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Zn	Cereals	Grain	All	86	1.8	2.7	2.0×10^{-2}	1.4×10^{1}
			Sand	42	2.0	2.5	3.9×10^{-1}	1.4×10^{1}
			Loam	21	1.5	2.5	5.2×10^{-1}	7.0
			Clay	17	1.4	1.6	6.6×10^{-1}	3.6
			Organic	4	8.6×10^{-1}	1.7	4.7×10^{-1}	1.6
		Stems and shoots	All	28	5.3	1.7	2.0	1.5×10^{1}
			Sand	6	8.2	1.5	4.2	1.2×10^{1}
			Loam	14	4.4	1.5	2.5	9.5
			Clay	8	3.8	1.6	2.0	7.2
	Maize	Grain	All	17	5.8×10^{-1}	1.4	2.8×10^{-1}	9.1×10^{-1}
			Sand	7	5.6×10^{-1}	1.5	2.8×10^{-1}	8.8×10^{-1}
			Loam	7	5.8×10^{-1}	1.3	3.4×10^{-1}	8.0×10^{-1}
			Clay	3	6.6×10^{-1}	1.4	4.8×10^{-1}	9.1×10^{-1}
		Stems and shoots	All	2	5.8	1.8	4.5	7.0
	Leafy vegetables	Leaves	All	112	2.4	2.4	1.0×10^{-1}	1.7×10^{1}
			Sand	39	4.2	2.0	7.4×10^{-1}	1.7×10^{1}
			Loam	53	1.8	2.1	3.4×10^{-1}	9.3
			Clay	19	2.1	2.5	3.2×10^{-1}	8.6
	Non-leafy vegetables	Fruits, heads, berries, buds	All	3	4.2×10^{-1}	3.7	1.0×10^{-1}	9.5×10^{-1}
			Organic	2	8.6×10^{-1}		7.8×10^{-1}	9.5×10^{-1}
	Leguminous vegetables	Seeds and pods	All	86	9.1×10^{-1}	2.4	2.5×10^{-1}	1.3×10^{1}
			Sand	31	9.7×10^{-1}	1.8	2.7×10^{-1}	5.9
			Loam	14	3.9×10^{-1}	1.2	2.5×10^{-1}	4.7×10^{-1}
			Clay	13	1.6	2.5	2.5×10^{-1}	8.8
	Tubers	Tubers	All	20	3.0×10^{-1}	1.8	5.0×10^{-2}	6.3×10^{-1}
			Sand	6	3.5×10^{-1}	1.5	1.9×10^{-1}	6.3×10^{-1}
			Loam	10	3.0×10^{-1}	1.6	1.5×10^{-1}	5.8×10^{-1}
			Clay	3	3.7×10^{-1}	1.4	2.4×10^{-1}	4.6×10^{-1}
	Pasture	Stems and shoots	All	73	1.0	1.9	5.4×10^{-2}	3.2
			Sand	38	1.3	1.4	4.8×10^{-1}	2.5
			Loam	34	7.8×10^{-1}	2.1	5.4×10^{-2}	3.2
Zr	Cereals	Grain	All	1	1.0×10^{-3}			
	Leafy vegetables	Leaves	All	1	4.0×10^{-3}			
	Non-leafy Vegetables	Fruits, heads, berries, buds	All	1	4.0×10^{-3}			
	Root crops	Roots	All	1	4.0×10^{-3}			
	Tubers	Tubers	All	1	2.0×10^{-3}			
	Pasture	Stems and shoots	All	1	1.0×10^{-2}			

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[a] GSD/SD: Geometric standard deviation/standard deviation.

By definition, the soil to plant transfer factors concept implies equilibrium or quasi-equilibrium conditions in the soil–plant system. This precondition is met in most cases when flows of the radionuclide from soil to plants are negligible compared with the total amount of the radionuclide in soil. In selecting data for the current publication, special care was taken to avoid data obtained under non-equilibrium conditions due to interference by soil sorption/adsorption processes, and thus, indirectly, it was assumed that radionuclide flows from soils to plants were low compared with the available pool of the radionuclide in the soil.

However, this is not the case for very mobile radionuclides, such as chlorine and technetium, that have soil to plant transfer factor values of around 100 or even higher. Also, chlorine and technetium are very mobile in soil and may be subject to considerable migration to deeper soil layers, making the soil activities at the end of the vegetation growth period much lower than those at the beginning of the growth period. Such a decline was observed in the study by Kashparov et al. [97, 98], where the chlorine activity dropped by a factor of 10–100 due to heavy rainfall during the growth period.

However, the activity in plants is due to radionuclide uptake from soil during the whole vegetation growth period. Transfer factors derived from the radionuclide activity concentrations in the soil and plants are usually determined at the end of this period, which may lead to very high transfer factor values. Applying those transfer factor values to radionuclide activity concentrations in soil determined at the start of the vegetation growth period may lead to serious overestimations.

Therefore, for the present publication, average values for chlorine and technetium concentrations in soil were selected (Table 18). For some radionuclides (e.g. ^{3}H, ^{14}C, ^{36}Cl), transfer parameters and models are normally formulated in terms of specific activity. Data for these particular radionuclides are therefore treated separately here (see Section 10).

For five radionuclides (Cu, Nd, Pr, Rh, W), no additional information was obtained. Thus the database only contains F_v values from TRS-364 [3]; these are given in italics in Table 17. The reference values for these radionuclides are mainly a product of expert judgement and are based on a single reference (Ref. [80]). Therefore, results of radiological assessments based on these values should be interpreted with caution.

5.2.2. Radionuclide transfer to fruits

Data presented in this section relate to fruit plants grown in agricultural ecosystems in temperate regions. Data on fruits growing in tropical and subtropical environments are reported in Section 5.3. As information on the subject is scarce, all available information has been included here. Details on the

TABLE 18. TEMPERATE ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) FOR CHLORINE AND TECHNETIUM

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/SD[a]	Minimum	Maximum
Cl	Cereals	Grain	All	7	3.6×10^{1}	1.6	2.0×10^{1}	8.6×10^{1}
			Sand	2	2.5×10^{1}		2.0×10^{1}	2.9×10^{1}
			Loam	3	4.7×10^{1}	1.8	2.6×10^{1}	8.6×10^{1}
			Clay	2	3.7×10^{1}		2.8×10^{1}	4.5×10^{1}
		Stems and shoots	All	7	3.4×10^{2}	1.5	2.1×10^{2}	6.2×10^{2}
			Sand	2	3.0×10^{2}		2.1×10^{2}	3.9×10^{2}
			Loam	3	3.4×10^{2}	1.7	2.2×10^{2}	6.2×10^{2}
			Clay	2	4.0×10^{2}		3.4×10^{2}	4.5×10^{2}
	Leafy vegetables	Leaves	All	6	2.6×10^{1}	1.7	1.4×10^{1}	4.8×10^{1}
			Sand	1	1.6×10^{1}			
			Loam	4	2.5×10^{1}	1.7	1.4×10^{1}	4.8×10^{1}
			Clay	1	4.5×10^{1}			
	Leguminous vegetables	Seeds and pods	All	7	1.1×10^{1}	1.3	7.0	1.5×10^{1}
			Sand	2	1.3×10^{1}		1.1×10^{1}	1.5×10^{1}
			Clay	2	9.0		7.0	1.1×10^{1}
	Root crops	Roots	All	14	1.2×10^{1}	1.8	4.8	3.6×10^{1}
			Sand	4	1.2×10^{1}	1.4	8.6	1.7×10^{1}
			Loam	6	1.1×10^{1}	2.0	4.8	3.6×10^{1}
Tc	Cereal	Grain	All	2	1.3		1.8×10^{-1}	2.4
	Maize	Grain	All	8	3.8	8.2	5.0×10^{-1}	5.2×10^{1}
		Stems and shoots	All	20	6.4	3.3	8.4×10^{-1}	3.7×10^{1}
	Leafy vegetables	Leaves	All	10	1.8×10^{2}	13.5	4.5	3.4×10^{3}
			Sand	4	1.1×10^{2}	33.1	4.5	2.9×10^{3}
			Loam	6	2.5×10^{2}	8.2	2.5×10^{1}	3.4×10^{3}
	Leguminous vegetables	Seeds and pods	All	5	4.3	5.2	1.1	3.0×10^{1}
			Sand	3	1.3	1.1	1.1	1.4
			Loam	2	2.6×10^{1}		2.3×10^{1}	3.0×10^{1}
	Root crops	Roots	All	2	4.6×10^{1}		1.4×10^{1}	7.9×10^{1}
	Tubers	Tubers	All	8	2.3×10^{-1}	3.7	1.3×10^{-2}	6.5×10^{-1}
			Sand	6	3.9×10^{-1}	1.6	1.8×10^{-1}	6.5×10^{-1}
			Loam	2	9.4×10^{-2}		1.3×10^{-2}	1.8×10^{-1}
	Pasture	Stems and shoots	All	18	7.6×10^{1}	3.0	7.9	4.7×10^{2}

[a] GSD/SD: Geometric standard deviation/standard deviation.

information sources and processes governing radionuclide transfer to fruits are reported elsewhere [5, 99–102].

Data on root uptake are reported as F_v values related to fresh weight, because consumption data for fruits are usually given in fresh weight (converted from dry weight where necessary; see Appendix I, Table 83):

$$F_v = \frac{\text{Bq fresh fruit weight}}{\text{Bq dry soil weight}}$$

In the absence of this information, an average water content of 80% has been assumed, as proposed in Ref. [102].

Fruits are derived from plants having widely varying growth features and morphological and physiological traits. The data have therefore been divided into three groups: woody trees, shrubs and herbaceous plants. The ‘woody trees’ group includes apple, pear, peach, apricot, olive, orange and grapevine. The ‘shrubs’ group includes gooseberry, blackcurrant, red raspberry and red currant. The ‘herbaceous plants’ group includes strawberry, melon, watermelon and rhubarb [5]. This subdivision is more extensive than that of the plant classification scheme used elsewhere in this handbook.

The variability of the transfer factors for fruits is attributable primarily to the different properties of soils. For example, the highest transfer factors for caesium are specific to peat or light sandy soils. The lowest transfer factors for strontium are specific to organic soils, such as peat, and to soils with high calcium content. The transfer of both plutonium and americium is lower in loam, organic and calcareous soils [99–101].

The type of plant makes a smaller contribution to the variability of transfer factors. Given the paucity of data, it is difficult to determine which species generally has the highest soil to fruit transfer of radionuclides [100]. Contamination of fruits borne by woody trees in the years following an initial deposition can occur by remobilization of radionuclides from the storage organs of the tree. However, the relative importance of the processes of transfer from soil to plant and re-translocation from storage organs has not yet been well determined [99, 100].

Generally, the activity concentrations in fruits in the years following a deposition show a decrease of several orders of magnitude, depending not only on the kind of radionuclide and the species of plant but presumably also on different human interventions in the soil–plant system [100].

Radionuclide activity concentrations in fruit depend on the yield. Low yield correlates with high concentrations of radionuclides [99]. The radionuclide concentration in fruit also varies with time to ripening. It may increase because of leaf to fruit translocation or soil to fruit transfer, decrease because of growth dilution, and then increase again closer to ripening because of water loss due to ageing [100].

Transfer factors for fruits, evaluated on the basis of information presented in the accompanying TECDOC [5], are given in Table 19.

TABLE 19. TEMPERATE ENVIRONMENT: SOIL TO FRUIT TRANSFER FACTORS (F_v)

Element	Plant group	Soil group	N	Mean/ value	GDS/ SD[a]	Minimum	Maximum
Am	Woody trees	All	6	3.1×10^{-5}	2.4	1.3×10^{-6}	6.2×10^{-4}
		Loam	1	8.0×10^{-6}			
		Sand	1	1.5×10^{-5}			
		Organic	1	1.3×10^{-6}			
		Unspecified	3	1.8×10^{-4}	1.8×10^{0}	2.2×10^{-5}	6.2×10^{-4}
	Shrubs	Unspecified	2	1.5×10^{-4}		6.5×10^{-5}	2.3×10^{-4}
	Herbaceous plants	All	8	1.1×10^{-4}	1.0×10^{0}	4.1×10^{-5}	7.2×10^{-4}
		Loam	1	7.3×10^{-5}			
		Sand	1	1.7×10^{-4}			
		Organic	1	6.8×10^{-5}			
		Unspecified	5	2.3×10^{-4}	2.9×10^{-4}	4.1×10^{-5}	7.2×10^{-4}
Ce	Woody trees	Unspecified	2	5.3×10^{-4}		4.4×10^{-4}	6.2×10^{-4}
	Herbaceous plants	Unspecified	1	3.0×10^{-4}			
Cm	Woody trees	Unspecified	2	5.3×10^{-4}	1.3×10^{-4}	4.4×10^{-4}	6.2×10^{-4}
	Herbaceous plants	Unspecified	1	3.0×10^{-4}			
Co	Woody tree	Loam	1	4.8×10^{-3}			
Cs	Woody trees	All	15	5.8×10^{-3}	1.5×10^{0}	8.6×10^{-4}	8.0×10^{-2}
		Clay	2	1.1×10^{-3}		8.8×10^{-4}	1.4×10^{-3}
		Loam	5	3.5×10^{-3}	8.8×10^{-1}	9.4×10^{-4}	9.2×10^{-3}
		Sand	4	1.5×10^{-2}	1.6×10^{0}	1.9×10^{-3}	8.0×10^{-2}
		Organic	1	3.7×10^{-2}			
		Unspecified	3	6.0×10^{-3}	1.7×10^{0}	8.6×10^{-4}	1.9×10^{-2}
	Shrubs	All	6	2.1×10^{-3}	8.1×10^{-1}	6.9×10^{-4}	5.7×10^{-3}
		Clay	2	2.2×10^{-3}		9.8×10^{-4}	3.3×10^{-3}
		Loam	2	3.8×10^{-3}		1.8×10^{-3}	5.7×10^{-3}
		Unspecified	2	2.0×10^{-3}		6.9×10^{-4}	3.3×10^{-3}
	Herbaceous plants	All	8	2.9×10^{-3}	3.3×10^{-3}	4.1×10^{-4}	8.9×10^{-3}
		Loam	1	9.0×10^{-4}			
		Sand	1	4.2×10^{-3}			
		Organic	1	6.4×10^{-3}			
		Unspecified	5	1.0×10^{-3}	1.3×10^{0}	4.1×10^{-4}	8.9×10^{-3}

TABLE 19. TEMPERATE ENVIRONMENT: SOIL TO FRUIT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Soil group	N	Mean/ value	GDS/ SD[a]	Minimum	Maximum
Cu	Herbaceous plants	Unspecified	1	6.6×10^{-5}			
I	Woody trees	Unspecified	5	6.3×10^{-3}	1.6×10^{0}	4.1×10^{-4}	3.1×10^{-2}
	Herbaceous plants	Unspecified	1	1.5×10^{-2}			
Mn	Fruit	Unspecified	1	3.9×10^{0}			
Na	Woody trees	Loam	1	2.4×10^{-2}			
Pu	Woody trees	All	10	1.4×10^{-4}	2.9×10^{0}	1.3×10^{-6}	2.1×10^{-2}
		Loam	1	8.0×10^{-6}			
		Sand	1	2.0×10^{-5}			
		Organic	1	1.0×10^{-6}			
		Unspecified	7	5.5×10^{-4}	2.2×10^{0}	2.8×10^{-5}	2.1×10^{-2}
	Shrubs	Unspecified	2	1.7×10^{-4}		6.4×10^{-5}	2.7×10^{-4}
	Herbaceous plants	All	9	1.2×10^{-4}	1.2×10^{0}	2.7×10^{-5}	8.3×10^{-4}
		Loam	1	8.8×10^{-5}			
		Sand	1	1.6×10^{-4}			
		Organic	1	7.3×10^{-5}			
		Unspecified	6	1.3×10^{-4}	1.5×10^{0}	2.7×10^{-5}	8.3×10^{-4}
Ru	Woody trees	Unspecified	2	1.3×10^{-3}		1.1×10^{-3}	1.6×10^{-3}
	Herbaceous plants	Unspecified	1	7.4×10^{-4}			
Sr	Woody trees	All	18	1.7×10^{-2}	9.7×10^{-1}	1.2×10^{-3}	7.0×10^{-2}
		Loam	4	3.9×10^{-2}	8.2×10^{-1}	1.2×10^{-2}	7.0×10^{-2}
		Sand	1	2.5×10^{-2}			
		Organic	1	1.2×10^{-3}			
		Unspecified	12	1.6×10^{-2}	6.1×10^{-1}	4.3×10^{-3}	3.4×10^{-2}
	Shrubs	All	9	4.4×10^{-2}	7.6×10^{-1}	1.4×10^{-2}	1.1×10^{-1}
		Clay	2	5.4×10^{-2}		2.6×10^{-2}	8.1×10^{-2}
		Loam	2	3.6×10^{-2}		1.7×10^{-2}	5.5×10^{-2}
		Unspecified	5	5.0×10^{-2}	8.5×10^{-1}	1.4×10^{-2}	1.1×10^{-1}
	Herbaceous plants	All	8	3.3×10^{-2}	1.0	1.2×10^{-2}	2.1×10^{-1}
		Loam	1	1.0×10^{-1}			
		Sand	1	2.1×10^{-1}			
		Organic	1	1.2×10^{-2}			
		Unspecified	5	2.2×10^{-2}	3.7×10^{-1}	1.5×10^{-2}	4.0×10^{-2}

[a] GSD/SD: Geometric standard deviation/standard deviation.

5.3. TROPICAL AND SUBTROPICAL ENVIRONMENTS

To a large extent, the climate and parent rock material determine the characteristics of soil development. In tropical areas, several soil types occur in which radionuclide uptake by crops consistently deviates from that characteristic of temperate environments. In a typical tropical environment, almost all organic materials that reach the soil surface decompose rapidly, and the surface accumulation of organic matter in soil is minimal. Consequently, there is rapid recycling of nutrients and contaminants into the vegetation. In temperate zones, the decomposition of organic debris is usually slower, and the accumulation of soil organic matter is greater than the rate of decomposition, resulting in highly organic surface soil [5, 103–106]. In the tropics, due to high mineral weathering rates, clays having low exchange activity, such as kaolinite, are more common than in the temperate zone. This leads to soils with a low exchange capacity despite their high clay content [103].

From new data it appears that, although the direct influence of climatic conditions on radioecological transfer parameters seems to be minimal, the indirect effects of climatic conditions, through changes of soil and crop properties, can be significant [103–105]. Transfer factor values for tropical and subtropical environments are given in Tables 20 and 21, respectively.

TABLE 20. TROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Am	Fruits	Fruits	Other[b]	2	3.7×10^{-5}		2.6×10^{-5}	4.8×10^{-5}
		Coconut milk[c]	Other	1	3.7×10^{-5}			
	Non-leafy vegetables	Fruits	Other	1	1.1×10^{-5}			
Co	Leguminous vegetables	Seeds and pods	All	19	6.6×10^{-1}	2.3	2.0×10^{-3}	3.6
			Clay	18	6.5×10^{-1}	2.3	2.0×10^{-1}	3.6
	Leafy vegetables	Leaves	All	41	9.2×10^{-2}	1.9	3.2×10^{-2}	2.8×10^{-1}
			Clay	39	9.1×10^{-2}	2	3.2×10^{-2}	2.8×10^{-1}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	28	3.1×10^{-1}	1.7	1.4×10^{-1}	6.9×10^{-1}
			Clay	26	3.1×10^{-1}	1.7	1.4×10^{-1}	6.9×10^{-1}
	Root crops	Roots	All	7	1.2×10^{-1}	1.7	6.3×10^{-2}	2.1×10^{-1}
			Clay	5	1.2×10^{-1}	1.7	6.3×10^{-2}	2.1×10^{-1}
	Tubers	Tubers	All	4	3.7×10^{-1}	1.0	3.6×10^{-1}	3.9×10^{-1}
			Clay	3	3.7×10^{-1}	1.2	3.6×10^{-1}	3.9×10^{-1}

Text cont. on p. 80.

TABLE 20. TROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
K	Fruits	Fruits	Organic	2	5.5×10^{1}		4.0×10^{1}	7.0×10^{1}
		Leaves[c]	All	2	3.2×10^{1}		9.0×10^{-1}	6.2×10^{1}
			Loam	1	9.0×10^{-1}			
			Organic	1	6.2×10^{1}			
	Grasses	Stems and shoots	Loam	1	8.7×10^{-1}			
	Other crops	Leaves	Loam	13	1.4	2.0	4.9×10^{-1}	5.6
		Stems and shoots	Loam	5	1.7	1.3	1.2	2.3
	Tubers	Tubers	Loam	1	2.7			
Cs	Cereals	Grain	All	4	2.3×10^{-1}	3.4	6.0×10^{-2}	1.0
			Sand	1	1.3×10^{-1}			
			Loam	1	3.3×10^{-1}			
	Fruits	Fruits	All	13	4.8×10^{-1}	5.7	5.0×10^{-2}	8.7
			Sand	1	3.6×10^{-1}			
			Unspecified	5	2.6	3.6	3.6×10^{-1}	8.7
		Coconut milk[c]	Unspecified	2	4.3		3.2×10^{-1}	8.2
		Leaves	Unspecified	1	5.8			
	Grasses	Grain	All	34	1.4×10^{-2}	2.9×10^{1}	1.5×10^{-4}	1.3×10^{1}
			Sand	24	6.6×10^{-3}	2.8×10^{1}	1.5×10^{-4}	8.6
			Unspecified	2	1.2×10^{1}		1.0×10^{1}	1.3×10^{1}
		Stems and shoots	Sand	24	1.1×10^{-2}	2.5×10^{1}	4.2×10^{-4}	9.60
	Herbs	Leaves	All	3	5.3×10^{-1}	1.4×10^{1}	$2.\times10^{-2}$	3.20
			Other	1	1.9			
	Leguminous vegetables	Grain	All	7	1.1	4.5	1.9×10^{-1}	4.1
			Sand	6	1.4	4.1	2.2×10^{-1}	4.1
			Loam	1	1.9×10^{-1}			
		Stems and shoots	Sand	4	7.3	1.3	5.4	9.6
		Leaves	All	61	1.1×10^{-1}	3.9	1.0×10^{-2}	3.9
			Sand	1	4.4×10^{-1}			
			Clay	53	1.0×10^{-1}	3.7	1.0×10^{-2}	7.7×10^{-1}
			Unspecified	1	3.9			
	Other crops	Leaves	All	19	5.9×10^{-1}	7.2	4.0×10^{-2}	2.1×10^{1}
			Unspecified	6	5.6	2.7	1.1	2.1×10^{1}
		Fruits	Unspecified	2	6.6		4.2	9.0
		Stems and shoots	Loam	4	7.0×10^{-2}	1.1	6.0×10^{-2}	8.0×10^{-2}

For footnotes see p. 73.

TABLE 20. TROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Cs	Non-leafy vegetables	Fruits, heads, berries, buds	All	38	7.0×10^{-1}	3.3	5.0×10^{-2}	1.1×10^{1}
			Clay	26	9.3×10^{-1}	1.7	3.6×10^{-1}	2.3
			Sand	4	5.6×10^{-2}	1.1	5.0×10^{-2}	6.3×10^{-2}
			Unspecified	2	7.3		3.6	1.1×10^{1}
	Root crops	Roots	All	9	4.3×10^{-1}	2	1.3×10^{-1}	8.1×10^{-1}
			Clay	5	6×10^{-1}	1.3	4.5×10^{-1}	8.1×10^{-1}
	Tubers	Tubers	All	8	4.3×10^{-1}	3.4	6.0×10^{-2}	3.0
			Sand	1	2.0×10^{-1}			
			Clay	4	3.7×10^{-1}	3.5	6.0×10^{-2}	10×10^{-1}
			Unspecified	1	3.0			
	Leafy vegetables	Leaves	All	49	9.8×10^{-1}	2.3	1.1×10^{-1}	2.9
			Clay	39	1.3	1.5	3.6×10^{-1}	2.9
			Unspecified	1	4.1×10^{-1}			
	Maize	Grain	Unspecified	2	2.0		1.4	2.5
Pu	Fruits	Fruits	Unspecified	2	2.3×10^{-5}		1.6×10^{-5}	2.9×10^{-5}
		Coconut milk[c]	Unspecified	1	3.2×10^{-5}			
	Other crops	Unspecified	Unspecified	1	6.7×10^{-5}			
	Non-leafy vegetables	Fruits, heads, berries, buds	Unspecified	1	1.7×10^{-5}			
Pb	Cereals	Grain	Sand	1	2.5×10^{-3}			
	Grasses	Leaves	Sand	9	2.1×10^{-1}	2.2	5.9×10^{-2}	1.00
	Herbs	Leaves	Sand	2	3.7×10^{-1}		2.0×10^{-2}	7.1×10^{-1}
	Leguminous vegetables	Grain	All	9	3.3×10^{-3}	2.4	6.5×10^{-4}	8.9×10^{-3}
			Sand	3	3.4×10^{-3}	1.3	2.8×10^{-3}	4.4×10^{-3}
			Loam	6	3.2×10^{-3}	3.0	6.5×10^{-4}	8.9×10^{-3}
	Other crops		Sand	18	2.3×10^{-1}	2.7	1.4×10^{-2}	1.0
	Non-leafy vegetables		All	2	7.0×10^{-3}		7.0×10^{-3}	7.0×10^{-3}
	Pasture	Stems and shoots	Unspecified	1	3.0×10^{-1}			
	Root crops	Roots	Loam	3	2.4×10^{-3}	1.5	1.8×10^{-3}	4.0×10^{-3}
	Tubers	Tubers	All	16	5.7×10^{-4}	2.4	1.5×10^{-4}	2.3×10^{-3}
			Sand	1	1.6×10^{-3}			
			Loam	15	5.3×10^{-4}	2.4	1.5×10^{-4}	2.3×10^{-3}
	Maize	Grain	All	6	8.5×10^{-4}	2.1	5.2×10^{-4}	3.8×10^{-3}
			Sand	1	5.2×10^{-4}			
			Loam	5	9.3×10^{-4}	2.2	5.9×10^{-4}	3.8×10^{-3}
Ra	Cereals		All	3	3.5×10^{-3}	2.5	1.7×10^{-3}	1.0×10^{-2}
			Sand	2	2.1×10^{-3}		1.7×10^{-3}	2.0×10^{-3}
	Fruits	Leaves	Loam	1	1.0×10^{-1}			
	Grasses	Stems and shoots	All	33	1.7	4.3	1.8×10^{-2}	5.8×10^{1}
			Loam	1	1.9×10^{-1}			

TABLE 20. TROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Ra	Herbs	Stems and shoots	Unspecified	4	7.5×10^{-2}	1.4×10^{1}	1.0×10^{-2}	3.0
		Leaves	Unspecified	11	1.1×10^{-1}	4.8	1.1×10^{-2}	1.0
	Leguminous vegetables	Grain	All	31	2.1×10^{-2}	4.3	7.6×10^{-4}	2.7×10^{-1}
			Sand	5	3.6×10^{-2}	3.0	5.7×10^{-3}	8.7×10^{-2}
			Loam	26	1.9×10^{-2}	4.5	7.6×10^{-4}	2.7×10^{-1}
	Other crops	Leaves	All	12	1.1×10^{-1}	2.1	3.7×10^{-2}	3.7×10^{-1}
			Loam	11	1.2×10^{-1}	2,0	4.0×10^{-2}	3.7×10^{-1}
		Roots	All	3	9.8×10^{-2}	5.8	1.3×10^{-2}	2.7×10^{-1}
		Stems and shoots	All	6	1.2×10^{-1}	2.5	2.0×10^{-2}	2.7×10^{-1}
			Loam	5	1.6×10^{-1}	1.4	1.0×10^{-1}	2.7×10^{-1}
			All	57	2.6	5.5	5.7×10^{-2}	1.3×10^{2}
			Loam	1	8.0×10^{-2}			
	Non-leafy vegetables	Fruits, heads, berries, buds	All	9	3.2×10^{-3}	5.6	5.2×10^{-4}	7.0×10^{-2}
			Loam	6	1.4×10^{-3}	3.4	5.2×10^{-4}	1.4×10^{-2}
	Pasture	Stems and shoots	Unspecified	1	7.0×10^{-2}			
			Loam	22	1.1×10^{-2}	4.9	1.2×10^{-3}	2.2×10^{-1}
	Tubers	Tubers	All	42	1.9×10^{-3}	3.8	2.6×10^{-4}	1.9×10^{-1}
			Sand	1	1.6×10^{-3}			
			Loam	41	2.0×10^{-3}	3.9	2.6×10^{-4}	1.9×10^{-1}
	Leafy vegetables		Loam	22	2.7×10^{-2}	4.5	3.0×10^{-3}	4.3×10^{-1}
	Maize	Grain	All	18	1.1×10^{-3}	2.4	1.9×10^{-4}	8.3×10^{-3}
			Sand	3	3.8×10^{-3}	2.0	2.0×10^{-3}	8.3×10^{-3}
			Loam	15	8.7×10^{-4}	2.0	1.9×10^{-4}	3.8×10^{-3}
Sr	Cereals	Grain	All	2	6.0×10^{-1}		4.4×10^{-1}	7.6×10^{-1}
			Sand	1	4.4×10^{-1}			
			Loam	1	7.6×10^{-1}			
	Fruits	Fruits	Others	3	1.7×10^{-2}	6.2	3.7×10^{-3}	1.3×10^{-1}
	Grasses	Grain	Sand	24	1.9×10^{-1}	7.9	1.4×10^{-2}	6.8
		Leaves	Sand	24	3.0×10^{-1}	7.6	2.8×10^{-2}	9.7
	Herbs	Leaves	All	1	3.6			
	Leguminous vegetables	Grain	All	6	3.7	1.9	1.8	8.2
			Sand	5	3.9	2.0	1.8	8.2
			Loam	1	2.7			
		Leaves	All	2	5.0×10^{1}		3.7×10^{1}	6.3×10^{1}
			Sand	1	3.7×10^{1}			
			Loam	1	6.3×10^{1}			
		Stems and shoots	Sand	4	7.5	1.3	6.0	9.5
			Clay	17	1.2	6.2	7.9×10^{-2}	5.9
	Other crops		Others	1	4.8×10^{-1}			

For footnotes see p. 73.

TABLE 20. TROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
Sr	Non-leafy vegetables	Fruits, heads, berries, buds	All	16	1.2	2.6	2.6×10^{-1}	4.2
			Clay	13	1.2	2.6	3.9×10^{-1}	4.2
			Others	1	2.6×10^{-1}			
	Root crops	Roots	All	4	1.8	1.6	1.2	2.8
			Clay	2	2.0		1.2	2.8
	Tubers	Tubers	All	2	6.8×10^{-1}		6.6×10^{-1}	7.0×10^{-1}
			Clay	1	6.6×10^{-1}			
	Leafy vegetables	Leaves	All	34	3.6	1.9	1.4	1.2×10^{1}
			Clay	32	3.6	1.9	1.4	1.2×10^{1}
Th	Herbs	Leaves	Unspecified	3	5.8×10^{-2}	1.1×10^{1}	1.2×10^{-2}	9.2×10^{-1}
		Stems and shoots	Unspecified	9	1.8×10^{-1}	5.5	1.8×10^{-2}	1.2
	Leguminous vegetables	Grain	Loam	4	6.3×10^{-5}	2.5	2.6×10^{-5}	2.1×10^{-4}
	Non-leafy vegetables	Fruits, heads, berries, buds	Loam	2	5.3×10^{-6}		3.3×10^{-6}	7.3×10^{-6}
	Other crops	Leaves	Unspecified	3	5.8×10^{-2}	2.3	3.5×10^{-2}	1.5×10^{-1}
		Stems and shoots	Unspecified	3	2.6×10^{-1}	1.1×10^{1}	5.3×10^{-2}	3.9
		Unspecified	Unspecified	4	8.2×10^{-3}	1.6	5.0×10^{-3}	1.5×10^{-2}
	Root crops	Roots	Loam	5	1.9×10^{-5}	1.7	9.0×10^{-6}	3.9×10^{-5}
	Tubers	Tubers	Loam	13	8.9×10^{-6}	2.6	2.9×10^{-6}	3.5×10^{-5}
	Leafy vegetables	Leaves	Loam	6	3.4×10^{-5}	1.9	1.8×10^{-5}	7.6×10^{-5}
	Maize	Grain	Loam	6	1.2×10^{-5}	3.5	1.9×10^{-6}	5.0×10^{-5}
U	Cereals	Grain	All	3	1.8×10^{-2}	3.8×10^{1}	6.0×10^{-4}	8.2×10^{-1}
			Sand	1	6.0×10^{-4}			
		All plant	Unspecified	1	4.6×10^{-1}			
	Fruits	Fruits	Unspecified	3	4.4×10^{-2}	3.9	1.1×10^{-2}	1.6×10^{-1}
		All plant	Unspecified	1	6.2×10^{-1}			
	Grasses	Stems and shoots	Unspecified	10	6.4×10^{-1}	1.5	2.5×10^{-1}	8.8×10^{-1}
	Herbs	Leaves	Unspecified	5	7.8×10^{-3}	1.4	5.0×10^{-3}	1.2×10^{-2}
		Fruits	Unspecified	1	3.7×10^{-1}			
			Unspecified	3	4.9×10^{-2}	1.9	2.8×10^{-2}	9.8×10^{-2}
	Leguminous vegetables	Grain	All	7	3.8×10^{-2}	1.1×10^{1}	2.3×10^{-3}	9.2×10^{-1}
			Sand	2	3.4×10^{-3}		2.3×10^{-3}	4.4×10^{-3}
			Loam	1	3.2×10^{-3}			
		All plant	Unspecified	2	8.5×10^{-1}		8.5×10^{-1}	8.6×10^{-1}
	Other crops	Leaves	Unspecified	8	4.9×10^{-3}	1.5	3.3×10^{-3}	8.4×10^{-3}
		Roots	Unspecified	10	2.5×10^{-2}	1.9	1.1×10^{-2}	5.5×10^{-2}
		Tubers	Unspecified	7	8.9×10^{-3}	2.0	2.9×10^{-3}	2.6×10^{-2}
		All plant	Unspecified	27	2.2×10^{-1}	6.1	8.0×10^{-4}	9.4×10^{-1}

TABLE 20. TROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/ SD[a]	Minimum	Maximum
U	Non-leafy vegetables	Fruits	Unspecified	14	2.6×10^{-2}	2.8	4.3×10^{-3}	1.8×10^{-1}
		All plant	Unspecified	2	7.0×10^{-1}		7.0×10^{-1}	7.1×10^{-1}
	Roots	Leaves	Unspecified	1	2.5×10^{-1}			
		Roots	Unspecified	6	4.7×10^{-2}	5.1	8.3×10^{-3}	2.6×10^{-1}
		Stems and shoots	Unspecified	1	1.7×10^{-1}			
	Tubers	Tubers	Unspecified	4	2.0×10^{-2}	2.3	7.3×10^{-3}	4.3×10^{-2}
	Leafy vegetables	Leaves	Unspecified	19	4.8×10^{-2}	3.2	4.4×10^{-3}	4.1×10^{-1}
		All plant	Unspecified	1	6.8×10^{-1}			
	Maize	Grain	All	2	8.7×10^{-2}		1.5×10^{-3}	1.7×10^{-1}
			Sand	1	1.5×10^{-3}			
		All plant	Unspecified	1	9.6×10^{-1}			
Zn	Cereals	Grain	All	2	2.2×10^{1}		1.8×10^{1}	2.6×10^{1}
			Loam	1	2.6×10^{1}			
	Grasses	Grain	Sand	12	2.2×10^{-1}	1.8	1.1×10^{-1}	7.0×10^{-1}
		Stems and shoots	Sand	12	2.0×10^{-1}	1.9	9.5×10^{-2}	5.7×10^{-1}
	Leguminous vegetables	Grain	All	2	1.8×10^{1}		1.5×10^{1}	2.0×10^{1}
			Sand	1	1.5×10^{1}			
			Loam	1	2.0×10^{1}			
		Leaves	All	2	1.9×10^{1}	5.0	1.5×10^{1}	2.2×10^{1}
			Sand	1	1.5×10^{1}			
			Loam	1	2.2×10^{1}			
			Clay	18	1.5	1.4	9.3×10^{-1}	2.5
	Non-leafy vegetables	Fruits	All	28	1.7	1.6	5.8×10^{-1}	3.4
			Clay	26	1.7	1.6	5.8×10^{-1}	3.4
	Root crops	Roots	All	7	1.2	1.8	5.6×10^{-1}	2.2
			Clay	5	1.3	1.8	5.6×10^{-1}	2.2
	Tubers	Tubers	All	4	1.1	1.2	9.2×10^{-1}	1.5
			Clay	3	1.1	1.3	9.2×10^{-1}	1.5
	Leafy vegetables	Leaves	All	41	1.7	1.4	7.3×10^{-1}	4.8
			Clay	39	1.7	1.4	7.3×10^{-1}	4.8

[a] GSD/SD: Geometric standard deviation/standard deviation.

[b] 'Other' refers to soils that are outside the classification scheme used here, such as Marshall Island soils, classified by the authors as coral sand soil.

[c] This plant compartment is outside the classification scheme used here.

TABLE 21. SUBTROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/SD[a]	Minimum	Maximum
Ag	Herbs	Grain	Sand	2	1.1×10^{-2}		1.1×10^{-2}	1.1×10^{-2}
	Leguminous vegetables	Grain	Sand	2	8.0×10^{-3}		8.0×10^{-3}	8.0×10^{-3}
	Non-leafy vegetables	Stems, shoots	Sand	1	3.0×10^{-3}			
		Fruits	Sand	1	1.0×10^{-2}			
		Tubers	Sand	2	1.2×10^{-2}		9.0×10^{-3}	1.5×10^{-2}
			Sand	4	8.0×10^{-3}	2.0	3.0×10^{-3}	1.5×10^{-2}
	Root crops	Roots	Sand	2	2.3×10^{-2}		2.3×10^{-2}	2.3×10^{-2}
	Leafy vegetables	Leaves	Sand	8	2.1×10^{-2}	5.8	2.0×10^{-3}	1.2×10^{-1}
Co	Grasses		Sand	19	2.6×10^{-1}	2.5	4.0×10^{-2}	9.2×10^{-1}
	Leguminous vegetables	Grain	Loam	3	1.1×10^{-1}	1.5	8.0×10^{-2}	1.8×10^{-1}
			Unspecified	1	5.5×10^{-2}			
	Other crops		Loam	3	6.7×10^{-1}	1.2	6.0×10^{-1}	7.8×10^{-1}
	Non-leafy vegetables	Fruits	Loam	3	7.9×10^{-1}	1.1	7.3×10^{-1}	8.8×10^{-1}
	Pasture	Stems, shoots	Loam	2	2.8×10^{-1}		2.7×10^{-1}	2.8×10^{-1}
	Root crops	Leaves	Unspecified	10	1.3×10^{-3}	3.8	1.9×10^{-4}	8.4×10^{-3}
		Roots	Unspecified	11	1.3×10^{-3}	4.8	1.7×10^{-4}	3.3×10^{-2}
	Leafy vegetables	Leaves	All	19	1.1×10^{-1}	5.8	4.8×10^{-3}	1.5
			Loam	7	5.1×10^{-1}	2.0	2.0×10^{-1}	1.2
		Roots	Loam	2	4.7×10^{-2}		1.1×10^{-2}	8.3×10^{-2}
		Stems, shoots	Loam	2	1.1×10^{-2}		1.0×10^{-2}	1.2×10^{-2}
Cs	Cereals	Grain	All	23	3.1×10^{-3}	2.4	1.0×10^{-3}	2.6×10^{-2}
			Loam	15	2.5×10^{-3}	2.4	1.0×10^{-3}	2.6×10^{-2}
		Stems, shoots	Loam	11	1.0×10^{-2}	1.9	3.4×10^{-3}	2.0×10^{-2}
	Fruits	Fruits	All	20	2.0×10^{-2}	4.3	2.8×10^{-3}	6.6×10^{-1}
			Loam	12	2.1×10^{-2}	6.3	2.8×10^{-3}	6.6×10^{-1}
			Clay	8	1.7×10^{-2}	2.0	6.0×10^{-3}	3.5×10^{-2}
	Grasses	Grain	Loam	9	2.7×10^{-3}	1.3	1.9×10^{-3}	4.0×10^{-3}
		Stems, shoots	All	51	2.5×10^{-1}	6.3	6.0×10^{-3}	3.7
			Loam	21	2.7×10^{-1}	1.6×10^{1}	6.0×10^{-3}	3.7
	Herbs	Leaves	All	18	1.1×10^{-1}	3.9	5.4×10^{-3}	8.9×10^{-1}
			Loam	8	9.6×10^{-2}	1.7	4.6×10^{-2}	1.9×10^{-1}
			Clay	8	2.4×10^{-1}	2.9	5.1×10^{-2}	8.9×10^{-1}
		Fruit	Clay	1	7.0×10^{-4}			
		Stems, shoots	Unspecified	1	6.8×10^{-3}			
	Leguminous vegetables	Grain	All	31	1.6×10^{-2}	4.1	2.0×10^{-3}	3.1×10^{-1}
			Loam	28	1.5×10^{-2}	4.1	2.0×10^{-3}	3.1×10^{-1}
			Clay	2	5.9×10^{-2}		8.0×10^{-3}	1.1×10^{-1}

TABLE 21. SUBTROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/SD[a]	Minimum	Maximum
Cs	Other crops	Grain	Clay	1	3.0×10^{-4}			
		Leaves	All	10	1.3×10^{-1}	1.1×10^{1}	3.7×10^{-3}	1.9
			Sand	4	8.9×10^{-3}	2.4	3.7×10^{-3}	2.9×10^{-2}
		Roots	All	2	6.2×10^{-2}		4.0×10^{-2}	8.3×10^{-2}
			Sand	1	8.3×10^{-2}			
			Loam	1	4.0×10^{-2}			
		Stem, shoots	Unspecified	9	5.5×10^{-1}	2.4	2.1×10^{-1}	1.5
			All	18	6.9×10^{-1}	9.6	3.0×10^{-3}	1.0×10^{1}
			Loam	6	2.4×10^{-1}	4.6	2.6×10^{-2}	8.9×10^{-1}
			Clay	2	5.7×10^{-2}		3.0×10^{-3}	1.1×10^{-1}
			Other[b]	3	7.3	1.8	3.8	1.0×10^{1}
	Non-leafy vegetables	Fruits, heads, berries, buds	All	13	1.9×10^{-2}	6.5	2.3×10^{-3}	3.0×10^{-1}
			Loam	10	2.5×10^{-2}	7.8	2.3×10^{-3}	3.0×10^{-1}
			Clay	3	7.3×10^{-3}	1.8	4.0×10^{-3}	1.2×10^{-2}
		Leaves	Loam	6	2.6×10^{-2}	2.1	1.0×10^{-2}	8.0×10^{-2}
		Roots	Loam	6	5.3×10^{-3}	3.3	1.0×10^{-3}	2.3×10^{-2}
			All	6	3.2×10^{-2}	4.1	2.0×10^{-3}	1.1×10^{-1}
			Loam	2	5.0×10^{-2}		5.0×10^{-2}	5.0×10^{-2}
			Clay	2	1.7×10^{-2}		2.0×10^{-3}	3.1×10^{-2}
	Pasture	Stems, shoots	All	34	1.9×10^{-1}	2.5	2.0×10^{-2}	6.3×10^{-1}
			Loam	6	7.5×10^{-2}	2.8	2.0×10^{-2}	2.2×10^{-1}
	Root crops	Leaves	Unspecified	10	3.5×10^{-2}	4.5	3.9×10^{-3}	3.5×10^{-1}
		Roots	All	15	1.5×10^{-2}	4.4	1.4×10^{-3}	2.3×10^{-1}
			Loam	2	2.6×10^{-2}		2.1×10^{-2}	3.0×10^{-2}
	Tubers	Tubers	All	34	6.5×10^{-2}	2.4	9.0×10^{-3}	4.1×10^{-1}
			Sand	8	1.5×10^{-1}	2.3	4.8×10^{-2}	4.1×10^{-1}
			Loam	8	4.2×10^{-2}	2.0	9.0×10^{-3}	8.0×10^{-2}
			Clay	4	4.7×10^{-2}	1.6	3.0×10^{-2}	8.0×10^{-2}
	Leafy vegetables	Leaves	All	35	3.8×10^{-2}	6.2	1.1×10^{-3}	1.4
			Sand	6	1.0×10^{-2}	5.49	1.1×10^{-3}	8.9×10^{-2}
			Loam	22	4.1×10^{-2}	6.0	6.0×10^{-3}	8.9×10^{-1}
			Clay	1	8.0×10^{-3}			
	Maize	Grain	Clay	2	5.0×10^{-3}		2.0×10^{-3}	8.0×10^{-3}
I	Cereals	Grain	Unspecified	1	1.5×10^{-4}			
		Leaves	Unspecified	1	2.0×10^{-2}			
		Stems, shoots	Unspecified	3	1.0×10^{-2}	4.5	4.1×10^{-3}	5.8×10^{-2}
	Herbs	Leaves	Unspecified	1	2.4×10^{-1}			
	Leguminous vegetables	Grain	Unspecified	1	3.0×10^{-3}			
	Non-leafy vegetables	Fruits	Unspecified	3	1.2×10^{-3}	2.1	6.5×10^{-4}	2.7×10^{-3}
		Leaves	Unspecified	1	4.5×10^{-2}			
		Roots	Unspecified	1	1.1×10^{-2}			

For footnotes see p. 77.

TABLE 21. SUBTROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	*N*	Mean/ value	GSD/SD[a]	Minimum	Maximum
I	Root crops	Leaves	Unspecified	1	1.2×10^{-1}			
		Roots	Unspecified	2	5.6×10^{-2}		5.1×10^{-2}	6.1×10^{-2}
	Leafy vegetables	Leaves	All	8	3.0×10^{-2}	2.4	6.7×10^{-3}	8.0×10^{-2}
			Sand	5	3.5×10^{-2}	2.0	1.2×10^{-2}	6.3×10^{-2}
		Roots	Unspecified	1	1.3×10^{-1}			
		Stems, shoots	Unspecified	1	3.0×10^{-3}			
K	Grasses	Stems, shoots		33	1.5	1.5	6.7×10^{-1}	2.8
	Other crops		Other	3	2.8	2.3	1.6	7.2
	Tubers	Tubers	All	18	2.4×10^{-1}	1.5	1.0×10^{-1}	4.1×10^{-1}
			Sand	6	1.8×10^{-1}	1.5	1.0×10^{-1}	2.7×10^{-1}
			Loam	8	2.9×10^{-1}	1.3	1.8×10^{-1}	4.1×10^{-1}
			Clay	4	2.4×10^{-1}	1.4	1.5×10^{-1}	3.0×10^{-1}
Mn	Grasses	Stems, shoots	Unspecified	6	1.04	2.4	4.0×10^{-1}	3.3
	Leguminous vegetables	Grain	Unspecified	1	1.0×10^{-1}			
	Root crops	Leaves	Unspecified	10	3.7×10^{-2}	4.8	2.9×10^{-3}	2.9×10^{-1}
		Roots	Unspecified	11	6.0×10^{-3}	9.7	4.7×10^{-4}	1.5
	Leafy vegetables	Leaves	Unspecified	4	1.0	6.4	2.3×10^{-1}	1.3×10^{1}
		Roots	Unspecified	2	3.9×10^{-1}		1.5×10^{-1}	6.2×10^{-1}
		Stems, shoots	Unspecified	2	1.6×10^{-1}		9.0×10^{-2}	2.2×10^{-1}
Pu	Non-leafy vegetables	Fruits	Unspecified	2	8.2×10^{-4}		4.3×10^{-4}	1.2×10^{-3}
	Root crops	Roots	Unspecified	2	4.6×10^{-3}		5.3×10^{-4}	8.6×10^{-3}
	Tubers	Tubers	Unspecified	6	1.5×10^{-3}	2.4	6.2×10^{-4}	4.8×10^{-3}
	Leafy vegetables	Leaves	Unspecified	2	1.1×10^{-3}		1.9×10^{-4}	2.0×10^{-3}
Sr	Cereals	Grain	Loam	8	5.1×10^{-2}	1.3	3.6×10^{-2}	6.5×10^{-2}
		Stems, shoots	Loam	7	1.5×10^{-1}	2.5	4.2×10^{-2}	4.2×10^{-1}
	Fruits	Fruits	All	16	1.0×10^{-1}	3.7	1.1×10^{-2}	8.8×10^{-1}
			Loam	10	1.5×10^{-1}	3.7	2.9×10^{-2}	8.8×10^{-1}
			Clay	6	5.2×10^{-2}	3.0	1.1×10^{-2}	1.9×10^{-1}
	Grasses	Grain	Loam	9	3.4×10^{-2}	2.3	1.7×10^{-2}	2.5×10^{-1}
		Stems, shoots	Loam	9	5.2×10^{-1}	1.4	2.9×10^{-1}	8.0×10^{-1}
	Herbs	Fruits	Clay	2	2.0×10^{-2}		7.1×10^{-3}	3.3×10^{-2}
	Leguminous vegetables	Grain	Loam	26	2.8×10^{-1}	3.0	2.0×10^{-2}	2.5
	Other crops		Loam	4	2.1×10^{-1}	1.2	1.8×10^{-1}	2.4×10^{-1}
	Non-leafy vegetables	Fruits	All	15	1.1×10^{-1}	3.7	1.9×10^{-2}	6.5×10^{-1}
			Loam	10	2.1×10^{-1}	2.8	4.8×10^{-2}	6.5×10^{-1}
			Clay	5	3.2×10^{-2}	2.2	1.9×10^{-2}	1.3×10^{-1}
		Grain	Loam	3	1.1×10^{-1}	1.4	8.2×10^{-2}	1.5×10^{-1}
		Leaves	Loam	3	1.7	1.5	1.2	2.5
		Roots	Loam	3	9.7×10^{-1}	1.1	8.5×10^{-2}	1.1

TABLE 21. SUBTROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean/ value	GSD/SD[a]	Minimum	Maximum
Sr	Pasture	Stems, shoots	All	5	7.8×10^{-1}	1.1	6.9×10^{-1}	9.1×10^{-1}
			Sand	1	7.2×10^{-1}			
			Loam	4	8.0×10^{-1}	1.1	6.9×10^{-1}	9.1×10^{-1}
	Root crops	Leaves	Unspecified	10	1.4×10^{-1}	5.4	1.3×10^{-2}	9.4×10^{-1}
		Roots	All	12	4.1×10^{-2}	5.4	3.2×10^{-3}	8.7×10^{-1}
			Clay	1	5.4×10^{-2}			
	Tubers	Tubers	All	29	4.5×10^{-1}	3.0	5.3×10^{-2}	3.6
			Sand	6	8.2×10^{-1}	1.9	3.5×10^{-1}	1.9
			Loam	8	3.6×10^{-1}	2.50	9.0×10^{-2}	1.1
			Clay	7	4.0×10^{-1}	5.73	5.3×10^{-2}	3.6
	Leafy vegetables	Leaves	All	36	9.8×10^{-1}	3.5	5.2×10^{-2}	5.0
			Loam	22	1.8	1.9	6.6×10^{-1}	5.0
			Clay	2	8.6×10^{-2}		5.2×10^{-2}	1.2×10^{-1}
	Maize	Grain	Clay	2	3.4×10^{-2}		2.2×10^{-2}	4.5×10^{-2}
Tc	Cereals	Grain	Unspecified	1	3.0×10^{-2}			
	Leguminous vegetables	Grain	Unspecified	2	5.0×10^{-1}		2.0×10^{-1}	8.0×10^{-1}
	Non-leafy vegetables	Fruits	Unspecified	2	3.0×10^{-1}		3.0×10^{-1}	3.0×10^{-1}
		All plant	Unspecified	2	3.0×10^{-1}		1.0×10^{-1}	5.0×10^{-1}
	Root crops	Roots	Unspecified	1	1.9			
	Tubers	Tubers	Unspecified	3	5.0×10^{-1}	7.2	8.0×10^{-2}	4.0
	Leafy vegetables	Leaves	Unspecified	6	7.2×10^{-1}	2.1	1.7×10^{-1}	1.3
Zn	Leguminous vegetables	Grain, seeds, pods	All	4	6.3×10^{-1}	2.0	2.2×10^{-1}	1.0
			Loam	3	8.9×10^{-1}	1.13	8.0×10^{-1}	1.0
	Other crop		Loam	3	1.1	1.1	9.8×10^{-1}	1.3
	Non-leafy vegetables	Fruits, heads, berries, buds	Loam	3	1.3	1.1	1.2	1.5
	Pasture	Stems, shoots	Loam	3	1.8	1.1	1.7	1.9
	Root crops	Leaves	Unspecified	10	1.1×10^{-1}	3.5	2.2×10^{-2}	8.7×10^{-1}
		Roots	Unspecified	11	1.1×10^{-1}	3.2	2.4×10^{-2}	1.4
	Leafy vegetables	Leaves	All	18	8.9×10^{-1}	3.8	1.1×10^{-1}	1.4×10^{1}
			Loam	6	1.5	2.1	7.1×10^{-1}	3.1
		Roots	Unspecified	2	3.3×10^{-1}		2.5×10^{-1}	4.1×10^{-1}
		Stems, shoots	Unspecified	2	2.2×10^{-1}		1.5×10^{-1}	2.9×10^{-1}

[a] GSD/SD: Geometric standard deviation/standard deviation.

[b] ‘Other’ refers to sawdust as a substrate where this plant group was grown.

Between 30% (tropical) and 50% (subtropical) of the data lacked information about soil classification or textural composition. Moreover, about 20% of the data are related to plants that are outside the classification scheme used here for temperate ecosystems. This emphasizes the need for alternative guidance on soil and plant classifications for tropical plants.

5.4. RADIONUCLIDE TRANSFER TO RICE

One of the critical foods with respect to intake of radionuclides by humans is rice (*Oryza sativa* L.), which is the dominant staple food crop in humid tropical countries around the globe [5]. Although rice is also grown in temperate environments, the primary source is tropical and subtropical environments.

Most rice is produced under flooded conditions, in fields covered by a 5–15 cm layer of water. Cultivation methods have important effects on plant uptake of radionuclides from soil. Under flooded conditions, oxygen is depleted quickly by the respiration of soil microorganisms and plant roots [107–109]. After the disappearance of oxygen, various degrees of anaerobiosis occur and chemical reduction of mineral nutrients takes place. In addition, the pH increases with soil reduction [107–109]. This farming practice is significantly different from the cultivation of cereals in unflooded fields. Therefore, there is a need to consider the soil to rice transfer factors separately from the transfer factors of other crops [105].

Transfer factor values for rice were evaluated on the basis of the information presented in the accompanying TECDOC [5]. The values derived from radionuclide studies are given in Table 22; the values derived from stable element data are presented in Table 23. Transfer factor values for both brown and white rice are reported separately in Ref. [5]. It should be mentioned that, compared with other crops, the difference in transfer factor values between brown and white rice is generally rather small for the majority of elements; therefore, the values reported here combine information for both types of rice.

5.5. TIME DEPENDENCE OF RADIONUCLIDE TRANSFER TO PLANTS

This section primarily describes radionuclide transfer from soil to plants in equilibrium conditions, that is, at a time long enough after deposition for equilibrium conditions to be approached. However, radionuclides can also be transferred to plants from soil in the year of deposition. Such a situation can be of importance, particularly in the case of acute deposition during the plant growth period. Many models allow the contamination of plants to be calculated for this

TABLE 22. TRANSFER FACTORS (F_v) FROM SOIL TO RICE

Element	Soil type	*N*	Mean/value	GSD/SD[a]	Minimum	Maximum
Co	All	5	5.1×10^{-3}	1.7	2.2×10^{-3}	1.0×10^{-2}
Cs	All	466	8.3×10^{-3}	6.2	1.3×10^{-4}	6.1×10^{-1}
	Sand	7	5.9×10^{-2}	3.5	7.1×10^{-3}	1.7×10^{-1}
	Loam	24	7.5×10^{-3}	4.1	1.1×10^{-3}	2.8×10^{-1}
	Clay	23	2.2×10^{-2}	5.7	1.1×10^{-3}	1.5×10^{-1}
I	All	8	3.8×10^{-3}	2.1	1.1×10^{-3}	7.6×10^{-3}
Mn	All	5	2.6×10^{-1}	1.7	1.2×10^{-1}	5.2×10^{-1}
	Sand	1	2.3×10^{-1}			
	Loam	4	2.6×10^{-1}	1.9	1.2×10^{-1}	5.2×10^{-1}
Pb	All	2	8.4×10^{-3}		4.7×10^{-3}	1.2×10^{-2}
Po	All	2	1.3×10^{-2}		9.4×10^{-3}	1.7×10^{-2}
Ra	All	40	8.7×10^{-4}	3.1	2.2×10^{-4}	2.8×10^{-2}
	Loam	14	7.8×10^{-4}	2.4	2.7×10^{-4}	8.8×10^{-3}
	Clay	18	5.7×10^{-4}	1.7	2.5×10^{-4}	2.9×10^{-3}
Sr	All	71	2.3×10^{-2}	4.7	2.1×10^{-3}	6.0×10^{0}
	Sand	6	6.0×10^{-2}	2.6	1.2×10^{-2}	2.2×10^{-1}
	Loam	4	9.5×10^{-2}	8.1	5.5×10^{-3}	8.3×10^{-1}
	Clay	14	3.2×10^{-2}	3.0	2.1×10^{-3}	1.1×10^{-1}
Tc	All	2	$<2\times10^{-4}$			
Th	All	57	1.6×10^{-4}	3.3	2.2×10^{-5}	3.0×10^{-2}
	Loam	22	1.5×10^{-4}	3.1	2.2×10^{-5}	4.0×10^{-3}
	Clay	31	1.4×10^{-4}	2.5	2.6×10^{-5}	8.3×10^{-4}
	Organic	1	3.0×10^{-2}			
U	All	65	2.43×10^{-4}	5.98	8.56×10^{-6}	9.00×10^{-2}
	Sand	3	5.38×10^{-3}	2.58	1.93×10^{-3}	1.26×10^{-2}
	Loam	23	2.07×10^{-4}	6.73	8.56×10^{-6}	2.42×10^{-2}
	Clay	29	1.79×10^{-4}	3.57	2.31×10^{-5}	1.80×10^{-3}
	Organic	1	9.00×10^{-2}			
Zn	All	5	1.5×10^{0}	1.96	5.80×10^{-1}	2.70×10^{0}
	Sand	1	2.3×10^{0}			
	Loam	3	1.5×10^{0}	2.28	5.80×10^{-1}	2.70×10^{0}

[a] GSD/SD: Geometric standard deviation/standard deviation.

TABLE 23. TRANSFER FACTORS (F_v) OF STABLE ELEMENT TRANSFER FROM SOIL TO RICE

Element	Soil type	*N*	Mean/value	GSD[a]	Minimum	Maximum
Ba	All	87	9.4×10^{-4}	2.8	8.5×10^{-5}	7.8×10^{-3}
Ca	All	87	6.4×10^{-3}	2.2	1.3×10^{-3}	4.6×10^{-2}
Cd	All	87	9.3×10^{-2}	3.2	9.0×10^{-3}	1.2×10^{0}
Ce	All	60	3.3×10^{-5}	2.7	1.9×10^{-5}	5.7×10^{-4}
Co	All	86	6.8×10^{-4}	2.1	1.3×10^{-4}	6.4×10^{-3}
Cr	All	87	1.8×10^{-3}	3.5	1.1×10^{-4}	1.9×10^{-2}
Cs	All	83	7.3×10^{-4}	2.7	1.1×10^{-4}	1.6×10^{-2}
	Loam	26	1.0×10^{-3}	3.7	1.1×10^{-4}	1.6×10^{-2}
	Clay	36	6.7×10^{-4}	2.2	1.4×10^{-4}	3.4×10^{-3}
Fe	All	87	1.8×10^{-4}	2.2	3.8×10^{-5}	1.3×10^{-3}
I	All	40	2.7×10^{-3}	3.2	1.3×10^{-4}	2.0×10^{-2}
K	All	87	1.3×10^{-1}	2.3	1.8×10^{-2}	7.8×10^{-1}
La	All	79	4.2×10^{-5}	2.2	4.6×10^{-6}	1.4×10^{-3}
Mn	All	87	2.9×10^{-2}	2.1	5.4×10^{-3}	1.2×10^{-1}
Na	All	87	8.4×10^{-4}	2.0	2.0×10^{-4}	6.9×10^{-3}
Ni	All	87	1.4×10^{-2}	2.2	3.0×10^{-3}	8.7×10^{-2}
P	All	50	2.4×10^{0}	1.8	3.7×10^{-1}	9.4×10^{0}
Pb	All	63	2.9×10^{-4}	2.6	3.6×10^{-5}	5.9×10^{-3}
	Loam	26	2.4×10^{-4}	2.1	7.2×10^{-5}	1.1×10^{-3}
	Clay	35	3.0×10^{-4}	2.6	3.6×10^{-5}	3.5×10^{-3}
Rb	All	87	8.6×10^{-2}	3.1	7.3×10^{-3}	2.2×10^{0}
Se	All	67	6.1×10^{-2}	1.9	9.0×10^{-3}	2.9×10^{-1}
Sr	All	63	1.9×10^{-3}	2.2	3.8×10^{-4}	8.2×10^{-3}
	Loam	26	1.6×10^{-3}	2.1	4.1×10^{-4}	6.4×10^{-3}
	Clay	34	2.1×10^{-3}	2.3	3.8×10^{-4}	8.2×10^{-3}
Zn	All	87	2.2×10^{-1}	1.6	6.1×10^{-2}	6.8×10^{-1}

[a] GSD: Geometric standard deviation.

scenario with some uncertainty. Radionuclides acutely deposited during the plant growth period are localized within the soil surface until harvest, because farmland is not ploughed during this period. In such cases the use of F_v values is inappropriate, and it is necessary to use aggregated transfer factors (T_{ag}) specified for the time from deposition until harvest [110–113]. The T_{ag} values for such time dependent scenarios for selected radionuclides (T, Co, Mn, Sr, Cs) are given in the accompanying TECDOC [5].

The rate of decrease of radionuclide uptake by plants is irregular by nature, and several time periods should be considered when applying a half-life approach for data evaluation. In the first years after deposition, the bioavailability of some radionuclides in soil reaches its maximum, resulting in the maximum radionuclide transfer rate to plants. From the data it can be concluded that the ecological half-live of ^{137}Cs in plants is in the range of 1–2 years in the first years after deposition, increasing to 12–20 years in the long term. The ecological half-live of ^{90}Sr tends to be slightly longer, at an estimated 20–30 years. Unfortunately, data are rather scarce in the literature, even for ^{90}Sr and ^{137}Cs, and any such estimates should be interpreted with caution.

Evaluation of radionuclide transfer in the environment implies consideration of the decrease of radionuclide activity concentrations in plants over time after a single release of radionuclides to the environment. This decrease occurs because radionuclides transferred to the environment are gradually fixed by natural sorbents (soils, bottom sediments in water ecosystems, etc.) and are lixiviated to lower soil layers, becoming less biologically available for inclusion in food chains.

Time dependent behaviour of radionuclides is often quantified by reference to the ecological half-life, which is an integral parameter relating to the reduction of activity or activity concentration in a specific medium. According to the definition given in Section 2, the ecological half-life is equal to the period of time over which the concentration of a radionuclide, in a given component of a trophic chain, is decreased by a factor of two, excluding the effects of radioactive decay. Although field data on variations in radionuclide transfer factors over time after clearly defined depositions are rather scarce, there are three prime sources of information on radionuclide half-lives in plants: global fallout, and the Kyshtym and Chernobyl accidents [87, 89, 91, 94, 95, 114–116].

5.6. APPLICATION OF DATA

Assessment of F_v values based on sources in the literature is always associated with various constraints, and often considerable judgement must be exercised in evaluating the available data. First, some data are based on studies that were not originally intended for transfer factor assessments. Second, the experimental design of the research may deviate from the design required by the transfer factor definition. For example, vertical distribution of radionuclides in soil profiles can depart from the uniform distribution assumed by the transfer factor definition. Radionuclide transfer to plants depends on numerous factors including the physical and chemical forms of the radionuclide in the soil, soil properties, plant species, plant compartments and farming practices. Such factors result in high variability, and the individual F_v values themselves can vary by over five orders of magnitude [5].

To decrease the uncertainty associated with soil and/or plant factors, several classifications were developed, and soil to plant transfer factors were reviewed and grouped according to the selected plant and soil categories. These data, providing information for specific plant and soil groups, allow more precise radiological assessments in different areas around the world. However, even for temperate environments, clear gaps in transfer factor values remain for a substantial number of radionuclides, plants and soil groups.

Far fewer data are available for tropical and subtropical ecosystems than for temperate environments. Additional uncertainty in the application of the tropical and subtropical data provided in this handbook can be assigned with the use of different climate classification schemes. F_v values are highly variable, which constitutes a strong limitation for their application. The concentration of a radionuclide in a soil is not the only factor influencing its uptake by plants. Mean values reported in this section should be used only as an indication of the tendency of the radionuclide transfer from soil to plants.

Soil and plant classifications facilitate application of the recommended F_v values for radiological assessments and increase the robustness of such estimates. However, site specific information on soils, plants and climatic conditions should be considered when using the F_v values from the tables given in this section.

Transfer factors are not appropriate for natural and semi-natural ecosystems because of the layered structure of those soils and the highly inhomogeneous distribution of root systems. Therefore, as an alternative, aggregated transfer factors (T_{ag}) are used to quantify radionuclide availability to various types of natural or semi-natural vegetation and animal products. T_{ag} is defined as the ratio of the radionuclide activity concentration in the plant (Bq kg^{-1} fresh weight or Bq kg^{-1} dry weight) or any other food product, divided by the total deposition on the soil (Bq m^{-2}). The concept of T_{ag} is adopted as a reasonable empirical measure to normalize radionuclide accumulation in semi-natural products, regardless of variations in the vertical radionuclide distribution and availability in the soil profile, which greatly depend on the site.

6. AGRICULTURAL ECOSYSTEMS: TRANSFER TO ANIMALS

Animals can be contaminated by radionuclides via three different routes: through the skin, by inhalation and by ingestion. The most important transfer pathway to animals is ingestion of contaminated feed and soil. Radionuclide intake via soil can be significant, but the availability for absorption of soil associated radionuclides may be low. Hence, it is the ingestion of contaminated feed and processes influencing absorption and retention that determine the radionuclide content in animals.

The most commonly applied transfer parameter for agricultural animal products is the transfer coefficient, which incorporates all the processes from ingestion of a radionuclide in herbage or soil to its incorporation into a specific tissue. Values for gastrointestinal fractional absorption are also given, owing to the importance of this process in determining the extent of radionuclide contamination of tissues and its application in a number of models.

6.1. GASTROINTESTINAL FRACTIONAL ABSORPTION

The degree of fractional absorption from the gastrointestinal tract is a key factor in determining the extent of radionuclide contamination of animal tissues and milk. Where possible, absorption is reported as the true absorption coefficient, A_t [117]. When A_t values are not available, the apparent absorption coefficient, A_a, is used (where A_a, is generally defined as the difference in dietary intake and faecal output, expressed as a proportion of dietary intake). However, this approach is too insensitive to measure absorption from sources with a low availability, and negative values of absorption can be derived. Furthermore, A_a does not take into account endogenous secretion of absorbed radioactivity from the body to faeces, which may be important for some radionuclides.

6.1.1. Absorption in ruminants

The gastrointestinal fractional absorption values for ruminants given in Table 24 were derived either from a database compiled for this purpose or from authoritative animal nutrition reviews [118, 119]. Agricultural review sources were used for those radionuclides that are isotopes of essential nutrient elements. The data source is specified for each element included in the tables [5].

The values given in Table 24 were derived from data for ruminants older than 100 d, because there is some evidence of enhanced absorption in young animals [120]. The table excludes data where: (a) there may have been effects on absorption of high stable element intakes (e.g. cadmium); (b) reduced absorption occurs for radiocaesium sources of low bioavailability; and (c) absorption may be underestimated due to unquantified losses in excreta and milk. Detailed discussion of the derivation of these values and of the literature used can be found in Ref. [121].

Fractional absorption of the three major dose forming radionuclides — iodine, strontium and caesium — is complete for radioiodine, and higher for radiocaesium than for radiostrontium. Fractional absorption of radiocaesium

TABLE 24. GASTROINTESTINAL FRACTIONAL ABSORPTION VALUES[a] FOR ADULT RUMINANTS
(taken from the database and agricultural reviews)

Element	*N*	Mean	GSD[b]	Minimum	Maximum
Ag	1	5.6×10^{-2}			
Am	2	1.4×10^{-4}		1.4×10^{-4}	1.4×10^{-4}
Ba	2	5.5×10^{-2}		5.0×10^{-2}	6.0×10^{-2}
Ca		3.0×10^{-1}		8.0×10^{-2}	4.2×10^{-1}
Cd	1	1.2×10^{-3}			
Ce	5	6.1×10^{-4}	2.9	1.9×10^{-4}	3.0×10^{-3}
Cl		9.0×10^{-1}		7.1×10^{-1}	1.0
Co	9	4.7×10^{-2}	2.9	1.5×10^{-2}	1.1×10^{-1}
Cs	14	8.0×10^{-1}	1.1	6.7×10^{-1}	9.3×10^{-1}
Fe		1.0×10^{-1}		2.0×10^{-2}	2.0×10^{-1}
I	13	9.8×10^{-1}	1.4	7.0×10^{-1}	1.1
Mn		7.5×10^{-3}		5.0×10^{-3}	4.0×10^{-2}
Na		9.0×10^{-1}		7.4×10^{-1}	1.0
Nb	1	$>1.4\times10^{-3}$			
P		6.7×10^{-1}		5.8×10^{-1}	1.0
Pb	9	4.0×10^{-2}	2.2	1.0×10^{-2}	1.1×10^{-1}
Pm	1	$>5.2\times10^{-4}$			
Pu	3	8.5×10^{-5}	1.4	6.5×10^{-5}	1.2×10^{-4}
Ru	6	5.8×10^{-3}	4.9	1.4×10^{-3}	7.1×10^{-2}
Se		5.2×10^{-1}		4.0×10^{-1}	6.5×10^{-1}
Sr	21	1.1×10^{-1}	2.0	5.5×10^{-2}	2.7×10^{-1}
Te	1	$>1.6\times10^{-1}$			
Y	2	1.2×10^{-3}		5.0×10^{-4}	1.9×10^{-3}
U	2	1.1×10^{-2}		1.0×10^{-2}	1.2×10^{-2}
Zn		1.5×10^{-1}		5.3×10^{-2}	3.1×10^{-1}
Zr	1	6.8×10^{-3}			

[a] Some values are apparent absorption coefficients; see Ref. [121].
[b] GSD: Geometric standard deviation.

varies with the chemical form, ranging from <0.10 to >0.80. The extent of calcium absorption in the ruminant gastrointestinal tract is governed by the animal's calcium requirement, which depends on factors such as age, growth rate and milk yield [118, 119, 122].

The absorption of essential elements is relatively high compared with that of other elements. In contrast, elements with high atomic weights, which are not essential elements or analogues of essential elements, are poorly absorbed. For example, the absorption of transuranic elements, such as plutonium, is low compared with that of many other elements.

6.1.2. Absorption in monogastrics

Gastrointestinal fractional absorption values for use in assessments of radionuclide transfer to humans have been reported by the International Commission on Radiological Protection (ICRP) [123]; these values are relevant for monogastric animals. The ICRP values for selected radionuclides are shown in Table 25. For most radionuclides, the ICRP reference values recommended for humans are similar to those given in Table 24 for ruminants. However, direct comparisons with the values given in Table 24 are difficult because: (a) the ICRP reference values are sometimes based on data for both ruminants and non-ruminants; and (b) the procedures for deriving the values differ.

Recently, data for the fractional absorption of a small number of radionuclides in pigs and hens have become available from Russian language publications [120]. These data are generally in agreement with the ICRP values, with the exception of a strontium fractional absorption value in laying hens of 0.6 (probably as the consequence of a high requirement for calcium).

6.2. TRANSFER TO ANIMAL PRODUCTS

Two alternative methods of quantifying transfer to animal products are given below. The transfer coefficient has been the main approach in use since the 1960s. The concentration ratio approach is an alternative that has potential advantages, but for which there are currently fewer relevant data.

TABLE 25. RECOMMENDED GASTROINTESTINAL FRACTIONAL ABSORPTION VALUES FOR ADULT HUMANS [123]

Element	Fractional absorption
H, C, Cs, S, Mo, I	1
Se	0.8
Zn, Tc, Po	0.5
Te, Sr, Ca	0.3
Ba, Ra, Pb	0.2
Co, Fe, Sb	0.1
Ru, Ni, Ag	0.05
U	0.02
Zr, Nb	0.01
Ce, Th, Np, Pu, Am, Cm	0.0005

6.2.1. Transfer coefficients

The transfer coefficient has been widely adopted for quantifying radionuclide transfer to both milk ($F_{m,}$ d L^{-1} or d kg^{-1}) and meat ($F_{f,}$ d kg^{-1}) as the equilibrium ratio of the radionuclide activity concentration in milk/meat to the daily dietary radionuclide intake [124, 125].

Ward et al. [126] reported that this parameter exhibited less variability between individual animals within the experimental herd than when transfer was expressed as the total amount of caesium excreted in milk as a percentage of intake. They also defined the meat transfer coefficient as the ratio of the ^{137}Cs activity concentration in boneless meat to the dietary daily ^{137}Cs intake [127].

To estimate transfer coefficients, the composition of the animal's diet must be quantified. For agricultural animals, this varies according to feeding strategies (including whether the animals graze or are kept indoors), maintenance requirements, agricultural practices, and diet composition and characteristics such as dry matter digestibility. The typical diet of agricultural animals varies between and within countries, and with the season.

The relative proportion of grass, grain and other dietary constituents is important in determining radionuclide intake by agricultural animals, since grassy vegetation tends to be more highly contaminated. It is therefore most appropriate to consult data from animal nutrition reviews relevant to the region and farming system being considered, to derive dietary intake information.

Details of how the transfer coefficient values provided here were derived can be found in the accompanying TECDOC [5].

6.2.1.1. Factors affecting transfer values: Duration of intake

Confidence in estimates of the feed intake of experimental animals is clearly greater in experimental studies under controlled conditions than in most field studies, where intake often is not measured. In the latter, different approaches are used for estimating mass intake — some based on agricultural production criteria but others using 'expert' judgement — which can lead to variability in reported F_f and F_m values.

By definition, a transfer coefficient needs to be in equilibrium with the dietary intake of the radionuclide. There can be considerable temporal variation in an animal's intake of radionuclides, and hence tissue concentrations may be constantly changing. In the case of milk an approximate equilibrium is reached rapidly for many radionuclides.

However, experimental observations, from which transfer coefficients are derived, often are not conducted long enough for equilibrium to have been reached in tissues or milk. The requirement of equilibrium conditions often is not met for radionuclides with short physical half-lives or for those radionuclides with long radioactive and biological half-lives in tissues (e.g. plutonium), so that activity concentrations in tissues will not have equilibrated with the diet by the time of slaughter.

For this reason, dynamic models describing the behaviour of radionuclides within animal tissues have been developed. These models can be used to predict radionuclide activity concentrations in different tissues following continuous, single or varying intakes [128–132].

6.2.1.2. Other factors affecting transfer values

A number of authors have reported variations in transfer coefficients for some radionuclides. The best documented example is for radiocaesium, where transfer coefficients vary with chemical form and metabolic factors including dietary intake rates [133].

Transfer coefficients of radionuclides are generally higher for animals with lower body mass and dietary intake rates; thus the transfer coefficients for lambs, for instance, will generally be larger than those for ewes.

Stable element status can affect the behaviour of a radionuclide analogue. For example, the transfer coefficient for radiostrontium transfer to milk declines as calcium intake increases [134–138].

The physical and chemical form of ingested radionuclides can affect the extent of gastrointestinal absorption and subsequent transfer to animal products. This is most clearly shown for radiocaesium [120, 139, 140].

There are relatively few estimates of the bioavailability of particle associated radionuclides in animals, and transfer is likely to be highly dependent on the type of particle and its origin. Therefore, estimates of absorption and transfer coefficients for one source are not necessarily likely to be relevant to another source. This also applies to different soil types, which may bind radionuclides to different extents and may be ingested by grazing animals.

6.2.2. Concentration ratios

Transfer coefficients for smaller animals are higher than those for larger animals, and those for adults are lower than those for (smaller) young livestock. It is likely that much of this difference is because transfer coefficients incorporate dry matter intake, which increases with animal size [141].

An alternative method for quantifying transfer from herbage to animal products is the concentration ratio, *CR*, which is the equilibrium ratio of the radionuclide activity concentration in the food product (fresh weight) divided by the radionuclide concentration in the feed (dry matter). Transfer coefficient values can be derived by dividing a *CR* value by the daily dietary intake (in kg d^{-1}), and *CR* values can be derived by multiplying the transfer coefficient value by the daily dietary intake (in kg d^{-1}). It has been suggested that, unlike transfer coefficients, the *CR* for a given element may be generally consistent across species [141].

The *CR* has the advantage in field studies that dietary dry matter intake does not need to be calculated or, as is more often the case, have a value assumed for it. However, when the diet consists of a number of foodstuffs, the relative proportions of all dietary components will be required to be known in order to apply *CR* values in assessments.

6.2.3. Transfer values

6.2.3.1. Transfer to milk

Tables 26–28 provide F_m values for cow's, sheep's and goat's milk, respectively. All data for the F_m values given in the tables are in units of d L^{-1}. More detailed information on derivation of the values is available in Refs [5, 133].

In addition to experimentally derived values, the agricultural/animal nutrition literature contains a wealth of data on many stable elements in milk and herbage that can be used to derive transfer parameters. Where appropriate, a number of key reviews [118, 119, 122, 142–147] have been used to identify typical concentrations of elements in milk and herbage. In turn, these concentrations have been used to derive transfer coefficients for milk by assuming dry matter intake rates of 16 kg of dry matter per day for lactating cows and 1.5 kg of dry matter per day for sheep and goats.

This may potentially overestimate transfer, as for some nutrient elements a considerable proportion of the dietary nutrients may be supplied in feed supplements within developed farming systems (i.e. the nutrient intake rate may have been underestimated). There is obviously variation in dry matter intake, but this is unlikely to influence the derived F_m values by more than a factor of 2–3.

Many of the stable elements considered will be under homeostatic control, and the transfer will therefore not be linear with the intake rate. However, given the large databases on which these values have been based, they are likely to be representative of 'typical values', taking into account the provisos above. Where this method has been used to select the recommended F_m value, that fact is indicated in the tables included here.

For cow's milk there were adequate data in the database to derive values for most of the elements, whereas for sheep's and goat's milk the stable element compilation was used more often. Where reference values are derived from the

TABLE 26. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO COW'S MILK (d L^{-1})

Element	*N*	Mean	GSD[a]	Minimum	Maximum
Am	1	4.2×10^{-7}			
Ba	15	1.6×10^{-4}	2.7	3.8×10^{-5}	7.3×10^{-4}
Be	1	8.3×10^{-7}			
Ca	15	1.0×10^{-2}	1.7	4.0×10^{-3}	2.5×10^{-2}
Cd	8	1.9×10^{-4}	15	1.8×10^{-6}	8.4×10^{-3}
Ce	6	2.0×10^{-5}	5.8	2.0×10^{-6}	1.3×10^{-4}
Co	4	1.1×10^{-4}	2.0	6.0×10^{-5}	3.0×10^{-4}
Cr	3	4.3×10^{-4}	26	1.0×10^{-5}	4.3×10^{-3}
Cs	288	4.6×10^{-3}	2.0	6.0×10^{-4}	6.8×10^{-2}
Fe	7	3.5×10^{-5}	2.0	1.0×10^{-5}	9.7×10^{-5}
I	104	5.4×10^{-3}	2.4	4.0×10^{-4}	2.5×10^{-2}
Mn	4	4.1×10^{-5}	4.9	7.0×10^{-6}	3.3×10^{-4}
Mo	7	1.1×10^{-3}	2.3	4.3×10^{-4}	5.2×10^{-3}
Na	7	1.3×10^{-2}	2.0	5.0×10^{-3}	5.0×10^{-2}
Nb	1	4.1×10^{-7}			
Ni	2	9.5×10^{-4}		6.5×10^{-4}	1.3×10^{-3}
P		2.0×10^{-2}			
Pb[b]	15	1.9×10^{-4}	1.0	7.3×10^{-6}	1.2×10^{-3}
Po	4	2.1×10^{-4}	1.8	8.9×10^{-5}	3.0×10^{-4}
Pu[c]		1.0×10^{-5}			
Ra	11	3.8×10^{-4}	2.3	9.0×10^{-5}	1.4×10^{-3}
Ru	6	9.4×10^{-6}	8.5	6.7×10^{-7}	1.4×10^{-4}
S	1	7.9×10^{-3}			
Sb	3	3.8×10^{-5}	2.5	2.0×10^{-5}	1.1×10^{-4}
Se	12	4.0×10^{-3}	2.1	1.5×10^{-3}	1.6×10^{-2}
Sr	154	1.3×10^{-3}	1.7	3.4×10^{-4}	4.3×10^{-3}
Te	11	3.4×10^{-4}	2.4	7.8×10^{-5}	1.0×10^{-3}
U	3	1.8×10^{-3}	3.5	5.0×10^{-4}	6.1×10^{-3}
W	7	1.9×10^{-4}	3.1	3.4×10^{-5}	6.8×10^{-4}
Zn	8	2.7×10^{-3}	3.9	1.3×10^{-4}	9.0×10^{-3}
Zr	6	3.6×10^{-6}	4.3	5.5×10^{-7}	1.7×10^{-5}

[a] GSD: Geometric standard deviation.

[b] Value taken from the animal nutrition literature.

[c] Value taken from a recent review paper [148].

TABLE 27. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO GOAT'S MILK (d L^{-1})

Element	*N*	Mean	GSD[a]	Minimum	Maximum
Am	2	6.9×10^{-6}		3.7×10^{-6}	1.0×10^{-5}
Ba	3	1.1×10^{-2}	9.9	2.1×10^{-3}	1.5×10^{-1}
Ca	12	7.3×10^{-2}	1.9	1.2×10^{-2}	1.4×10^{-1}
Cd	1	1.6×10^{-2}			
Ce	1	4.0×10^{-5}			
Co	1	5.0×10^{-3}			
Cr	2	1.5×10^{-2}		2.9×10^{-3}	2.8×10^{-2}
Cs	28	1.1×10^{-1}	2.2	7.0×10^{-3}	3.3×10^{-1}
Fe[b]		5.2×10^{-2}			
I	24	2.2×10^{-1}	2.9	2.7×10^{-2}	7.7×10^{-1}
Mn[b]		1.0×10^{-3}			
Mo	4	8.2×10^{-3}	1.4	5.0×10^{-3}	1.1×10^{-2}
Na[b]		1.2×10^{-1}			
Nb	1	6.4×10^{-6}			
Ni	2	8.3×10^{-2}		3.2×10^{-3}	1.6×10^{-1}
Np	1	5.3×10^{-5}			
P[b]		2.9×10^{-1}			
Pb	1	6.0×10^{-3}			
Pm	1	2.7×10^{-5}			
Po	2	2.3×10^{-3}		1.8×10^{-3}	2.7×10^{-3}
S	12	3.8×10^{-2}	1.7	1.6×10^{-2}	6.8×10^{-2}
Se	2	6.9×10^{-2}		5.9×10^{-2}	7.9×10^{-2}
Sr	21	1.6×10^{-2}	2.0	5.8×10^{-3}	8.1×10^{-2}
Te	1	4.4×10^{-3}			
U	1	1.4×10^{-3}			
Y	1	2.0×10^{-5}			
Zn[b]		6.4×10^{-2}			
Zr	1	5.5×10^{-6}			

[a] GSD: Geometric standard deviation.

[b] Value taken from the animal nutrition literature.

database, summary statistics are provided in the tables; if the values were derived from stable element review data, only a best estimate is given as the reference value.

CR values for the milk of cows, sheep and goats have been derived from the database compiled to derive F_m values. If data were not available in the database, the stable element review values were used, from which it was also possible to estimate *CR* values for horse milk. Table 29 compares the *CR* values for the four animal species; as has been suggested [140], the *CR* values for a given element are broadly similar across the species.

TABLE 28. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO SHEEP'S MILK (d L^{-1})

Element	N	Mean	GSD[a]	Minimum	Maximum
Ba	1	4.1×10^{-2}			
Ca[b]		2.3×10^{-1}			
Cd	1	4.9×10^{-2}			
Co	2	2.7×10^{-3}		1.2×10^{-3}	4.1×10^{-3}
Cr	1	2.0×10^{-2}			
Cs	28	5.8×10^{-2}	2.3	6.0×10^{-3}	3.2×10^{-1}
Fe[b]		7.9×10^{-2}			
I	7	2.3×10^{-1}	3.3	3.0×10^{-2}	9.4×10^{-1}
Mn	1	2.4×10^{-3}			
Na	1	1.0×10^{-1}			
Ni	1	2.8×10^{-1}			
P[b]		3.1×10^{-1}			
Pb[b]		3.5×10^{-2}			
Pu	1	1.0×10^{-4}			
S[b]		1.5×10^{-1}			
Sr	4	2.7×10^{-2}	1.2	1.3×10^{-2}	4.0×10^{-2}
Te	1	2.9×10^{-3}			
Zn[b]		8.1×10^{-2}			

[a] GSD: Geometric standard deviation.
[b] Value taken from the animal nutrition literature.

6.2.3.2. *Transfer to meat and eggs*

Approaches to deriving F_f values for meat were as described above for the compilation of F_m values. Exceptions were that: (a) no additional stable element review of the animal nutrition literature was conducted, although the database includes some stable element values; and (b) single (acute) administration studies were not used unless sufficient time series data were available.

In summarizing F_f values, only results reported for pigs, sheep and goats aged six months or older (where this information was given) were used; for cattle, only data from animals aged 1 year or older were included; and for poultry, only data for animals older than 40 d were used. However, if no data for animals meeting these age criteria were available for an element, data for younger animals were used (on only two occasions).

Data from experiments of less than 20 days' duration were not used for sheep, goats, pigs or poultry; for cattle, experiments of less than 60 days' duration were not used. Few single administration data were used; among the experiments that were included are those reported by Beresford et al. [149, 150], where

TABLE 29. CONCENTRATION RATIOS (*CR*) FOR THE MILK OF DIFFERENT ANIMALS (kg L^{-1})

Element	Cow					Goat					Sheep					Horse	Mean	Ratio
	CR	SD	Minimum	Maximum	*N*	*CR*	SD	Minimum	Maximum	*N*	*CR*	SD	Minimum	Maximum	*N*	*CR*	All species	Min/Max
Ba	1.3×10^{-2}	1.6×10^{-3}	1.2×10^{-2}	1.5×10^{-2}	3	1.2×10^{-1}		1.4×10^{-2}	2.3×10^{-1}	2	6.1×10^{-2}				1	3.5×10^{-3}	5.0×10^{-2}	2.9×10^{-2}
Ca	2.5×10^{-1}					2.0×10^{-1}	8.3×10^{-2}	1.3×10^{-1}	2.9×10^{-1}	4	3.4×10^{-1}					1.5×10^{-1}	2.4×10^{-1}	4.4×10^{-1}
Cd	4.3×10^{-2}	7.4×10^{-2}	2.7×10^{-5}	1.3×10^{-1}	3	2.4×10^{-2}				1	7.4×10^{-2}				1		4.7×10^{-2}	3.3×10^{-1}
Cl	6.9×10^{-2}				1												6.9×10^{-2}	
Ce	3.2×10^{-3}				1												3.2×10^{-3}	
Co	2.5×10^{-3}				1	7.6×10^{-3}				1	6.2×10^{-3}				1		5.4×10^{-3}	3.3×10^{-1}
Cr	4.0×10^{-2}		3.7×10^{-2}	4.3×10^{-2}	2	4.1×10^{-2}				1	3.0×10^{-2}				1		3.7×10^{-2}	7.2×10^{-1}
Cs	1.1×10^{-1}	1.2×10^{-1}	3.6×10^{-3}	6.9×10^{-1}	119	1.8×10^{-1}	6.5×10^{-2}	6.3×10^{-2}	3.0×10^{-1}	12	1.7×10^{-1}	1.3×10^{-1}	2.0×10^{-2}	5.8×10^{-1}	17		1.5×10^{-1}	6.4×10^{-1}
Fe	1.2×10^{-3}	2.4×10^{-4}	1.0×10^{-3}	1.5×10^{-3}	3	3.4×10^{-2}				1	5.2×10^{-2}				1	9.3×10^{-3}	2.4×10^{-2}	2.4×10^{-2}
I	3.0×10^{-1}	2.8×10^{-1}	3.0×10^{-3}	7.9×10^{-1}	44	5.0×10^{-1}	5.8×10^{-1}	8.4×10^{-2}	1.2	3	5.8×10^{-1}	2.5×10^{-1}	2.5×10^{-1}	8.8×10^{-1}	5		4.6×10^{-1}	5.2×10^{-1}
Mn	4.5×10^{-3}		8.6×10^{-4}	8.2×10^{-3}	2	1.5×10^{-3}				1	3.6×10^{-3}				1	1.6×10^{-3}	2.8×10^{-3}	3.2×10^{-1}
Mo	2.8×10^{-2}	1.3×10^{-2}	1.9×10^{-2}	4.3×10^{-2}	3	2.7×10^{-2}				1						2.1×10^{-2}	2.5×10^{-2}	7.5×10^{-1}
Na	3.7×10^{-1}		2.3×10^{-1}	5.0×10^{-1}	2	1.8×10^{-1}					1.6×10^{-1}					6.0×10^{-2}	1.9×10^{-1}	1.6×10^{-1}
Nb	1.0×10^{-5}				1	1.9×10^{-5}				1							1.5×10^{-5}	5.3×10^{-1}
Ni	8.2×10^{-2}					2.5×10^{-1}				1	4.2×10^{-1}				1		2.5×10^{-1}	1.9×10^{-1}
P	3.1×10^{-1}					4.3×10^{-1}					4.7×10^{-1}					1.8×10^{-1}	3.5×10^{-1}	3.8×10^{-1}
Pb	2.4×10^{-3}	1.3×10^{-3}	9.9×10^{-4}	4.3×10^{-3}	7	9.0×10^{-3}				1	3.0×10^{-2}				1		1.4×10^{-2}	7.9×10^{-2}
Po	2.4×10^{-3}				1												2.4×10^{-3}	
S	1.4×10^{-1}				1	6.1×10^{-2}	3.0×10^{-2}	3.5×10^{-2}	1.0×10^{-1}	4	2.3×10^{-1}						1.4×10^{-1}	2.7×10^{-1}
Sb	2.7×10^{-3}				1												2.7×10^{-3}	
Se	5.7×10^{-2}	4.5×10^{-2}	2.6×10^{-2}	1.5×10^{-1}	7	3.5×10^{-2}											4.6×10^{-2}	6.2×10^{-1}
Sr	2.3×10^{-2}	2.2×10^{-2}	5.0×10^{-3}	1.4×10^{-1}	43	4.4×10^{-2}	4.4×10^{-2}	1.6×10^{-2}	1.2×10^{-1}	5						4.4×10^{-2}	3.7×10^{-2}	5.2×10^{-1}
Te	8.0×10^{-3}		4.8×10^{-3}	1.1×10^{-2}	2	1.2×10^{-2}				1							1.0×10^{-2}	6.7×10^{-1}
U	5.0×10^{-3}																5.0×10^{-3}	
Zn	7.5×10^{-2}	1.6×10^{-2}	5.5×10^{-2}	9.5×10^{-2}	6	9.6×10^{-2}					1.2×10^{-1}					5.5×10^{-2}	8.7×10^{-2}	4.6×10^{-1}
Zr	1.4×10^{-5}				1	1.7×10^{-5}				1							1.5×10^{-5}	8.3×10^{-1}

Note: Shading denotes values estimated from the stable element review.

models were fitted to data for consecutive slaughter dates over approximately one year after a single administration. Subsequent predictions of F_f were made for different periods of continuous administration; values incorporated into the database were equilibrium or 1000 d predictions. In some cases, data are available for a series of different sample times after continuous feeding (see Ref. [151]). In this case, transfer values derived for the shorter time periods have been excluded from the database.

Transfer coefficients for the meat of a range of domestic animals are given in Tables 30–34. All data for F_f values are in units of d kg^{-1} fresh weight. If it was necessary to convert reported dry weight values to fresh weight, it was assumed

TABLE 30. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO BEEF (d kg^{-1})

Element	*N*	Mean	GSD[a]	Minimum	Maximum
Am	1	5.0×10^{-4}			
Ba	2	1.4×10^{-4}		5.0×10^{-5}	2.3×10^{-4}
Ca	3	1.3×10^{-2}	30.0	1.0×10^{-3}	6.1×10^{-1}
Cd	8	5.8×10^{-3}	7.8	1.5×10^{-4}	6.0×10^{-2}
Cl	1	1.7×10^{-2}			
Co	4	4.3×10^{-4}	2.3	1.3×10^{-4}	8.4×10^{-4}
Cs	58	2.2×10^{-2}	2.4	4.7×10^{-3}	9.6×10^{-2}
Fe	4	1.4×10^{-2}	1.5	9.0×10^{-3}	2.5×10^{-2}
I	5	6.7×10^{-3}	3.2	2.0×10^{-3}	3.8×10^{-2}
La	3	1.3×10^{-4}	1.2	1.1×10^{-4}	1.5×10^{-4}
Mn	2	6.0×10^{-4}		6.0×10^{-4}	6.0×10^{-4}
Mo	1	1.0×10^{-3}			
Na	2	1.5×10^{-2}		1.0×10^{-2}	2.0×10^{-2}
Nb	1	2.6×10^{-7}			
P	1	5.5×10^{-2}			
Pb	5	7.0×10^{-4}	2.5	2.0×10^{-4}	1.6×10^{-3}
Pu	5	1.1×10^{-6}	24.8	8.8×10^{-8}	3.0×10^{-4}
Ra	1	1.7×10^{-3}			
Ru	3	3.3×10^{-3}	1.8	2.2×10^{-3}	6.4×10^{-3}
Sb[b]	2	1.2×10^{-3}		1.1×10^{-3}	1.3×10^{-3}
Sr	35	1.3×10^{-3}	2.9	2.0×10^{-4}	9.2×10^{-3}
Te	1	7.0×10^{-3}			
Th	6	2.3×10^{-4}	2.9	4.0×10^{-5}	9.6×10^{-4}
U	3	3.9×10^{-4}	1.6	2.5×10^{-4}	6.3×10^{-4}
Zn	6	1.6×10^{-1}	3.2	4.0×10^{-2}	6.3×10^{-1}
Zr	1	1.2×10^{-6}			

[a] GSD: Geometric standard deviation.

[b] Young animals (5–6 months old).

that the dry matter content of meat for all animal types was 25%. Data for poultry meat are largely for chickens but also include some data for duck. More detailed information is available in the accompanying TECDOC [5].

The F_f values for egg contents, that is, excluding the shell, are presented in Table 35 (data are largely for chickens, but some values for duck are included). Data for most radionuclides are relatively scarce. The values in Table 35 are generally similar to those proposed in TRS-364 [3], because many of the TRS-364 values were based on Ref. [152], which continues to be a major source of data.

TABLE 31. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO MUTTON (d kg^{-1})

Element	*N*	Mean/value	GSD[a]	Minimum	Maximum
Ag	1	4.8×10^{-4}			
Am	1	1.1×10^{-4}			
Cd	1	1.2×10^{-3}			
Ce	1	2.5×10^{-4}			
Co	2	1.2×10^{-2}		8.0×10^{-3}	1.6×10^{-2}
Cs	41	1.9×10^{-1}	2.2	5.3×10^{-2}	1.3
I	1	3.0×10^{-2}			
Mn	1	9.0×10^{-3}			
Na	1	1.1×10^{-1}			
Pb	2	7.1×10^{-3}		4.0×10^{-3}	1.0×10^{-2}
Pu	2	5.3×10^{-5}		2.0×10^{-5}	8.5×10^{-5}
Ru	2	2.1×10^{-3}		6.3×10^{-4}	3.6×10^{-3}
S	3	1.7	1.3	1.2	2.1
Sr	25	1.5×10^{-3}	1.7	3.0×10^{-4}	4.0×10^{-3}
Zn	6	4.5×10^{-2}	2.2	2.0×10^{-2}	1.4×10^{-1}

[a] GSD: Geometric standard deviation.

TABLE 32. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO GOAT MEAT (d kg^{-1})

Element	*N*	Mean	GSD[a]	Minimum	Maximum
Ba	1	1.3×10^{-5}			
Cs	11	3.2×10^{-1}	2.5	1.2×10^{-1}	1.9
Nb	1	6.0×10^{-5}			
Sr	8	2.9×10^{-3}	1.2	2.0×10^{-3}	3.7×10^{-3}
Te	1	2.4×10^{-3}			
Y	1	5.4×10^{-2}			
Zr	1	2.0×10^{-5}			

[a] GSD: Geometric standard deviation.

TABLE 33. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO PORK (d kg^{-1})

Element	*N*	Mean	GSD[a]	Minimum	Maximum
Ca	1	2.0×10^{-3}			
Cs	22	2.0×10^{-1}	1.5	1.2×10^{-1}	4.0×10^{-1}
Fe[b]	1	3.0×10^{-3}			
I	2	4.1×10^{-2}		1.5×10^{-2}	6.6×10^{-2}
Mn	1	5.3×10^{-3}			
P	1	2.7×10^{-2}			
Ru	1	3.0×10^{-3}			
Se	1	3.2×10^{-1}			
Sr	12	2.5×10^{-3}	2.7	5.0×10^{-4}	8.0×10^{-3}
U	2	4.4×10^{-2}		2.6×10^{-2}	6.2×10^{-2}
Zn	2	1.7×10^{-1}		1.3×10^{-1}	2.0×10^{-1}

[a] GSD: Geometric standard deviation.
[b] Young animals (2 months old).

TABLE 34. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO POULTRY MEAT (d kg^{-1})

Element	*N*	Mean	GSD[a]	Minimum	Maximum
Ba	2	1.9×10^{-2}		9.2×10^{-3}	2.9×10^{-2}
Ca	2	4.4×10^{-2}		4.4×10^{-2}	4.4×10^{-2}
Cd[b]	2	1.7		1.7	1.8
Co[b]	2	9.7×10^{-1}		3.0×10^{-2}	1.9
Cs[b]	13	2.7	1.6	1.2	5.6
I	3	8.7×10^{-3}	2.0	4.0×10^{-3}	1.5×10^{-2}
Mn	2	1.9×10^{-3}		1.0×10^{-3}	2.8×10^{-3}
Mo	1	1.8×10^{-1}			
Na[b]	1	7.0			
Nb	1	3.0×10^{-4}			
Po	1	2.4			
Se	4	9.7	2.3	4.1	2.8×10^{1}
Sr[b]	7	2.0×10^{-2}	1.8	7.0×10^{-3}	4.1×10^{-2}
Te	1	6.0×10^{-1}			
U	2	7.5×10^{-1}		3.0×10^{-1}	1.2
Zn	3	4.7×10^{-1}	1.2	3.8×10^{-1}	5.3×10^{-1}
Zr	1	6.0×10^{-5}			

[a] GSD: Geometric standard deviation.
[b] Includes values for duck.

TABLE 35. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO EGG CONTENTS (d kg^{-1})

Element	*N*	Mean	GSD[a]	Minimum	Maximum
Am	1	3.0×10^{-3}			
Ba	1	8.7×10^{-1}			
Ca	1	4.4×10^{-1}			
Ce	1	3.1×10^{-3}			
Co[b]	2	3.3×10^{-2}		2.6×10^{-2}	4.0×10^{-2}
Cs[b]	11	4.0×10^{-1}	1.5	1.6×10^{-1}	7.1×10^{-1}
Fe	2	1.8		8.5×10^{-1}	2.8
I	4	2.4	1.3	1.9	3.2
Mn	3	4.2×10^{-2}	1.4	3.2×10^{-2}	6.2×10^{-2}
Mo	3	6.4×10^{-1}	1.3	5.2×10^{-1}	8.7×10^{-1}
Na[b]	2	4.0		1.9	6.0
Nb	1	1.0×10^{-3}			
P	1	6.4×10^{-1}			
Po	1	3.1			
Pu	2	1.2×10^{-3}		9.9×10^{-6}	2.3×10^{-3}
Ru	1	4.0×10^{-3}			
Se	4	1.6×10^{1}	1.9	8.8	2.8×10^{1}
Sr[b]	9	3.5×10^{-1}	1.4	2.5×10^{-1}	6.4×10^{-1}
Te	1	5.1			
U	2	1.1		9.2×10^{-1}	1.2
Zn	4	1.4	1.2	1.2	1.9
Zr	1	2.0×10^{-4}			

[a] GSD: Geometric standard deviation.
[b] Includes values for duck eggs, which, with the exception of Sr, included the shell.

CR values for the meat of a number of species are given in Table 36. The data are only extensive for cow meat, and therefore comparisons across species for the elements are fewer but still encouraging. In addition to the data given, values for horse meat of 3.8×10^{-1} for iron and 5.3×10^{-1} for zinc can be derived using stable data from the agricultural nutrition review sources described above. These values are in reasonable agreement with the values for other species given in Table 36.

6.3. APPLICATION OF DATA

The data compilation for gastrointestinal absorption in ruminants can be used as an additional data source or as an alternative to the ICRP data. Additional analysis is required of the underlying data of both sources to critically evaluate whether current differences are significant.

TABLE 36. CONCENTRATION RATIOS (*CR*) FOR THE MEAT OF DIFFERENT ANIMALS[a]

Element	Beef					Sheep					Pork					Generic	Ratio
	CR	SD	Minimum	Maximum	*N*	*CR*	SD	Minimum	Maximum	*N*	*CR*	SD	Minimum	Maximum	*N*		Min/ Max
Ag						4.3×10^{-4}				1						4.3×10^{-4}	
Am						1.1×10^{-4}				1						1.1×10^{-4}	
Ca	2.3×10^{-2}		2.1×10^{-2}	2.6×10^{-2}	2	1.4×10^{-2}										1.9×10^{-2}	6.0×10^{-1}
Cd	1.7×10^{-1}	1.5×10^{-1}	2.3×10^{-3}	3.5×10^{-1}	7	1.2×10^{-2}		1.3×10^{-3}	2.3×10^{-2}	2	1.3×10^{-1}				1	9.2×10^{-2}	6.9×10^{-2}
Ce						2.2×10^{-4}				1						2.2×10^{-4}	
Cl	2.4×10^{-1}		4.8×10^{-2}	4.3×10^{-1}	2											2.4×10^{-1}	
Co	3.9×10^{-1}		7.2×10^{-3}	7.8×10^{-1}	2	2.3×10^{-1}										3.1×10^{-1}	5.9×10^{-1}
Cs	2.3×10^{-1}	1.7×10^{-1}	2.2×10^{-2}	7.3×10^{-1}	17	6.4×10^{-1}	1.0	5.3×10^{-2}	7.5	51	9.2×10^{-2}	1.0×10^{-1}	8.3×10^{-3}	2.4×10^{-1}	4	3.9×10^{-1}	1.4×10^{-1}
Fe	2.2×10^{-1}	2.5×10^{-1}	6.0×10^{-2}	7.2×10^{-1}	6	2.7×10^{-1}				1						2.5×10^{-1}	8.2×10^{-1}
I	9.5×10^{-2}	8.2×10^{-2}	3.2×10^{-2}	1.9×10^{-1}	3					1	9.3×10^{-2}		3.5×10^{-2}	1.5×10^{-1}	2	9.4×10^{-2}	9.8×10^{-1}
La	1.6×10^{-3}	2.4×10^{-4}	1.3×10^{-3}	1.8×10^{-3}	3											1.6×10^{-3}	
Mg	1.4×10^{-1}		9.4×10^{-2}	1.9×10^{-1}	2											1.4×10^{-1}	
Mn	8.0×10^{-3}		4.6×10^{-3}	1.1×10^{-2}	2											8.0×10^{-3}	
Mo	9.6×10^{-2}		2.5×10^{-2}	1.7×10^{-1}	2											9.6×10^{-2}	
Na	9.7×10^{-1}				1											9.7×10^{-1}	
Nb	6.5×10^{-6}				1											6.5×10^{-6}	
Ni	8.0×10^{-2}				1											8.0×10^{-2}	
P	1.3^{2}															1.3	
Pb	7.7×10^{-2}	1.8×10^{-1}	1.0×10^{-3}	6.2×10^{-1}	11	1.2×10^{-2}	4.0×10^{-3}	9.2×10^{-3}	1.6×10^{-2}	3	6.6×10^{-1}		2.3×10^{-1}	1.1	2	2.5×10^{-1}	1.8×10^{-2}
Po	1.4×10^{-1}	1.3×10^{-1}	3.7×10^{-2}	4.1×10^{-1}	7											1.4×10^{-1}	
Pu						3.9×10^{-5}	2.4×10^{-5}	1.5×10^{-5}	6.3×10^{-5}	3						3.9×10^{-5}	
Ra	1.8×10^{-1}	3.8×10^{-1}	1.3×10^{-3}	1.3	11											1.8×10^{-1}	
Rb	3.0×10^{-1}				1											3.0×10^{-1}	
Ru						5.7×10^{-4}				1						5.7×10^{-4}	

TABLE 36. CONCENTRATION RATIOS (*CR*) FOR THE MEAT OF DIFFERENT ANIMALS[a] (cont.)

Element	Beef					Sheep					Pork					Generic	Ratio
	CR	SD	Minimum	Maximum	*N*	*CR*	SD	Minimum	Maximum	*N*	*CR*	SD	Minimum	Maximum	*N*		Min/ Max
S						5.0×10^{-1}										5.0×10^{-1}	
Sb	2.7×10^{-1}				1											2.7×10^{-1}	
Se											1.1				1	1.1	
Te	1.8×10^{-1}				1											1.8×10^{-1}	
Th	6.2×10^{-3}	5.0×10^{-3}	1.7×10^{-3}	1.2×10^{-2}	3											6.2×10^{-3}	
U	3.3×10^{-1}	6.1×10^{-1}	3.0×10^{-3}	1.7	8											3.3×10^{-1}	
Zn	1.7	1.1	4.7×10^{-1}	3.2	9	2.1		1.3	2.9	2						1.9	8.2×10^{-1}

Note: Shading denotes values estimated from the stable element review.

[a] For goats, the value of 6.2×10^{-1} for caesium ($N = 4$) is included in the generic value.

It is proposed here that the concentration ratio would be a more robust and generic parameter than the transfer coefficient. For most radionuclides, the concentration ratio data compiled vary little between the species considered (sheep, goats, cattle and horses). Therefore, concentration ratios derived for one species could be applied to another. Unfortunately, however, many authors who report transfer coefficients do not provide the information required to estimate concentration ratios.

7. RADIONUCLIDE TRANSFER IN FORESTS

7.1. RADIONUCLIDE TRANSFER TO TREES

7.1.1. Interception of radionuclides in tree canopies

Forests are managed as timber crops, with rotation periods of 50–100 years between planting and harvesting. Alternatively, they can be managed for wildlife conservation with no major removal of trees. Both types of forest, however, are long term features of the environment that, once contaminated with radionuclides, represent long term sources of radiation exposure to forest workers and to the general public. Forests are used as sources of natural foodstuffs, particularly wild fungi, fruits (berries) and game, which, since the Chernobyl accident, have all tended to have relatively high levels of radiocaesium contamination in comparison with agricultural food products.

During deposition of atmospheric radioactive fallout onto forests, the tree canopy is contaminated directly by dry or wet interception of aerosol-derived radionuclides (Table 37). This is followed by translocation from foliar surfaces to the trunk, branches and roots of the tree. Decontamination of the exterior surfaces of the tree canopy occurs with time as a result of weathering of intercepted radioactive materials by wind and rain, and the natural loss of leaf litter. These canopy processes are followed, or accompanied, by root uptake, which is the predominant route of tree contamination over the longer term. Two stages of the contamination of the forest system can be distinguished:

(1) The ‘early’ phase, lasting 4–5 years and characterized by a rapid redistribution of the initial deposits between trees and soil;
(2) The ‘steady state’ phase, characterized by slow changes in biological availability, with root uptake determining the degree of contamination of the trees.

TABLE 37. CANOPY INTERCEPTION FRACTIONS FOR DIFFERENT TYPES OF FOREST [153]

Forest type	Deposition type	Interception (%)
Pine forest, 6–10 years of age	Artificial injection of ^{89}Sr in a water soluble form into the crowns of trees	90–100
Pine forest, 60 years of age	Deposition of radioactive particles less than 50 μm in size	80–100
Pine forest, 25 years of age	Deposition of radioactive particles less than 100 μm in size	70–90
Pine forest, 30 years of age	Deposition of resuspended radioactive particles	40–60
Birch forest, 40 years of age, winter period	Deposition of resuspended radioactive particles	20–25
Birch forest, 35–40 years of age, summer period	Global fallout	20–60
Pine forest, 50–60 years of age	Global fallout	50–90
Tropical rain forest	Global fallout	100

Over the first few days of radioactive discharges from the accident at the Chernobyl nuclear power plant, about 70–80% of all the radioactive fallout was retained by the above ground parts of trees. Over this period, coniferous trees trapped radioactivity 2–3 times as effectively as did deciduous forests and 7–10 times more effectively than other types of natural or semi-natural ecosystems (meadow, mire) [154].

Over the course of the active growth of trees, ecological half-lives vary from 3–4 weeks to 3 months, depending on the type and age of the trees. In phases of physiological dormancy (autumn and winter), the half-lives are in the range of 4–6 months [154].

7.1.2. Aggregated transfer factors for soil–tree transfer

The relationship between radionuclide activity concentrations in forest soils and in trees is influenced by many factors, and thus T_{ag} values are highly variable [155, 156]. The most realistic use of T_{ag} values is for forest systems where radionuclide fluxes have stabilized (i.e. in the medium to long term after depositions), and in such cases T_{ag} values remain a satisfactory tool for simple screening models.

The aggregated transfer coefficient, T_{ag}, is expressed according to the following relationship:

$$T_{ag} = \frac{\text{activity concentration in tree compartments or forest products}}{\text{total deposition to forest floor}} \left(\frac{\text{Bq kg}^{-1}}{\text{Bq m}^{-2}} \right) \tag{31}$$

Tables 38 and 39 provide available data on the T_{ag} values for radiocaesium and radiostrontium in foliage and wood as recorded under different ecological conditions with varying ages and species of trees. More details, including the related information sources, are given in the accompanying TECDOC [5].

TABLE 38. RADIOCAESIUM TRANSFER FACTORS (T_{ag}, m^2 kg^{-1}, dry weight) TO FOREST TREES

(Measured under apparent steady state conditions)

Species	Wood		Needles/leaves		N
	Geometric mean	Range	Geometric mean	Range	
Spruce	1.5×10^{-3}	2.8×10^{-4}–3.9×10^{-3}	8.6×10^{-3}	5.7×10^{-4}–5.2×10^{-2}	7
Fir tree	1.2×10^{-4}	—	—	—	1
Pine	1.7×10^{-3}	1.1×10^{-4}–2.1×10^{-2}	1.0×10^{-2}	2.4×10^{-4}–9.2×10^{-2}	22
Oak	8.6×10^{-4}	1.1×10^{-4}–3.8×10^{-3}	1.2×10^{-2}	1.1×10^{-2}–1.2×10^{-2}	3
Beech	7.2×10^{-4}	1.8×10^{-4}–1.6×10^{-3}	2.5×10^{-3}	2.3×10^{-3}–2.7×10^{-3}	3
Birch	9.4×10^{-4}	2.4×10^{-4}–3.8×10^{-3}	8.7×10^{-3}	2.8×10^{-3}–3.0×10^{-2}	3
Willow	2.5×10^{-5}	1.0×10^{-5}–6.8×10^{-5}	2×10^{-2}	—	4

TABLE 39. RADIOSTRONTIUM TRANSFER FACTORS (T_{ag}, m^2 kg^{-1}, dry weight) TO FOREST TREES

(*measured following the Chernobyl (1991–1992) and Kyshtym (1966–1972) accidents; main reference: [157]*)

Species	Wood		Needles/leaves		N
	Geometric mean	Range	Geometric mean	Range	
Alder	9.5×10^{-4}	—	5.7×10^{-3}	—	1
Fir tree	4.4×10^{-3}	—	1.3×10^{-2}	—	1
Pine	1.6×10^{-3}	5.7×10^{-4}–1.0×10^{-2}	4.9×10^{-3}	1.5×10^{-3}–3.0×10^{-2}	5
Oak	1.3×10^{-3}	4.7×10^{-4}–2.8×10^{-3}	4.2×10^{-3}	1.9×10^{-3}–1.0×10^{-2}	3
Aspen	2.1×10^{-3}	—	1.7×10^{-2}	—	1
Birch	2.4×10^{-3}	5.8×10^{-4}–6.2×10^{-3}	1.8×10^{-2}	4.3×10^{-3}–7.8×10^{-2}	5

7.2. RADIONUCLIDE TRANSFER TO MUSHROOMS

Uptake of radionuclides by mushrooms is also commonly quantified using the aggregated transfer coefficient, T_{ag}, because of the difficulty of knowing the exact location within the soil, both vertically and horizontally, of the radionuclides being absorbed. The transfer coefficients to mushrooms are highly variable (3–4 orders of magnitude). This variability arises for several reasons:

(a) The intensity of caesium transfer is highly dependent on the species.
(b) The mycelium depth determines the contamination chronology.
(c) The type of mushroom can affect the degree of caesium transfer.

Saprophytic mushrooms develop on decomposing materials in the surface layers of a soil, and thus these kinds of mushroom will be contaminated immediately following the deposition. Transfer coefficients will subsequently decrease as the deposit migrates deeper into the soil. *Symbiotic* or *mycorrhizal* mushrooms live in a mutually beneficial association with trees. Most of the edible mushrooms are symbiotic and can be at their most contaminated in the medium and long terms after deposition. *Parasitic* mushrooms develop at the expense of the host trees. Very few are edible, and their radionuclide concentration is dependent on the degree of host tree contamination. Parasitic mushrooms tend to be characterized by low transfer coefficients.

The majority of the information available addresses ^{137}Cs (Table 40); however, such data are also available for some other long lived radionuclides, although to a lesser extent (Tables 41, 42). In Tables 40–42, it is assumed that the average dry matter content of mushrooms is equal to 10%. More accurately, the dry matter content of mushrooms varies from around 5 to 15%, depending on the species and weather conditions [160].

Aggregated transfer factors are presented here for edible species of mushrooms that contribute directly to human radiation doses. Data for 'non-edible' mushroom species, details of the relevant studies and the full set of references containing the data presented here are given in the accompanying TECDOC [5].

Some authors have used the conventional soil to plant transfer factor to quantify radionuclide absorption by mushrooms, especially for natural radionuclides. These data are presented in the accompanying TECDOC [5].

Changes in the contamination of mushrooms over time reflect the bioavailability of radionuclides in the various relevant nutrient sources used by different species. Figure 1 indicates the tendency of a slow decrease of ^{137}Cs in mushroom contamination during the 1990s.

TABLE 40. AGGREGATED TRANSFER FACTORS FOR ^{137}Cs IN EDIBLE MUSHROOMS (m^{2} kg^{-1}, dry weight)

Mushroom species	Type of mushroom	Transfer coefficient (m^{2} kg^{-1}, dry weight)		
		GM[a]	Range	*N*
Agaricus (*arvensis, campestris, silvatica*)	Humus saprophytic	0.005	5×10^{-4}–0.01	3
Agrocybe (*aegerita*)	Saprophytic	0.1	—	1
Amanita (*rubescens*)	Symbiotic	0.2	0.03–4	4
Armillaria (*mellea*)	Parasitic/xylophyte saprophytic	0.04	1×10^{-4}–1×10^{-1}	4
Boletus (*aestivalis, appendiculatus, edulis*)	Symbiotic	0.08	4×10^{-3}–1.4	10
Cantharellus (*cibarius, lutescens, pallens, tubaeformis*)	Symbiotic	0.3	0.015–1.5	10
Clitocybe (*gibba* or *infundibuliformis*)	Litter saprophytic	0.6	—	1
Coprinus (*comatus*)	Saprophytic	0.005	4×10^{-4}–0.015	1
Cortinarius (*praestans*)	Symbiotic	0.02	—	1
Craterellus (*cornucopioides*)	Symbiotic	0.03	—	1
Hydnum (*repandum*)	Symbiotic	0.4	—	1
Hygrophorus (sp.)	Symbiotic	2	—	1
Kuehneromyces (*mutabilis*)	Saprophytic	0.3	—	1
Laccaria (*amethystea*, *laccata, proxima*)	Symbiotic/humus saprophytic	5	2.0–8.1	5
Lactarius (*deliciosus, deterrimus, lignyotus, necator* or *turpis, porninsis, torminosus*)	Symbiotic	0.7	8×10^{-4}–6.0	7
Leccinum (sp., *aurantiacum, rotundifoliae, scabrum, versipelle*)	Symbiotic	0.2	8×10^{-4}–1.1	11
Leucoagaricus (*leucothites*) or *Lepiota* (*naucina*)	Humus saprophytic	0.1	—	1
Macrolepiota procera	Humus saprophytic	0.006	7×10^{-5}–4×10^{-2}	3
Lepista (*nuda, saeva*)	Litter saprophytic	0.01	2.5×10^{-4}–0.1	3
Lycoperdon (*perlatum*)	Humus saprophytic	0.04	0.003–0.07	2
Oudemansiella (sp.)	—	0.1	—	1
Rozites (*caperatus*)	Symbiotic	2.3	0.4–8	7
Russula (sp., *erythropoda*)	Symbiotic	0.5	0.03–4.2	6
Sarcodon (*imbricatum*)	Symbiotic	0.03	—	1
Suillus (*elegans* or *grevillei, luteus, variegates*)	Symbiotic	0.7	0.07–3.0	7
Xerocomus (*badius, chrysenteron, subtomentosus*)	Symbiotic	1.2	2×10^{-3}–7.0	13

[a] GM: Geometric mean.

TABLE 41. MEAN AGGREGATED TRANSFER FACTORS FOR ^{90}Sr IN MUSHROOMS (m^{2} kg^{-1}, dry weight) [158]

Mushroom species	Type of mushroom	^{90}Sr transfer coefficient [158]
Boletus edulis	Symbiotic	6×10^{-3}
Boletus appendiculatus	Symbiotic	5×10^{-3}
Cantharellus cibarius	Symbiotic	6×10^{-3}

TABLE 42. AGGREGATED TRANSFER FACTORS FOR Pu IN MUSHROOMS (m^2 kg^{-1}, dry weight) [159]

Mushroom species	Type of mushroom	*N*	Mean	Range
Armillaria mellea	Parasitic/xylophyte saprophytic	1	9×10^{-5}	—
Boletus edulis	Symbiotic	4	3×10^{-4}	1.4×10^{-4}–4.5×10^{-4}
Cantharellus cibarius	Symbiotic	1	2×10^{-2}	—
Macrolepiota procera	Humus saprophytic	2	4×10^{-4}	3.2×10^{-4}–5.7×10^{-4}
Suillus luteus	Symbiotic	1	9×10^{-4}	—
Xerocomus badius	Symbiotic	6	1×10^{-3}	8×10^{-5}–0.038

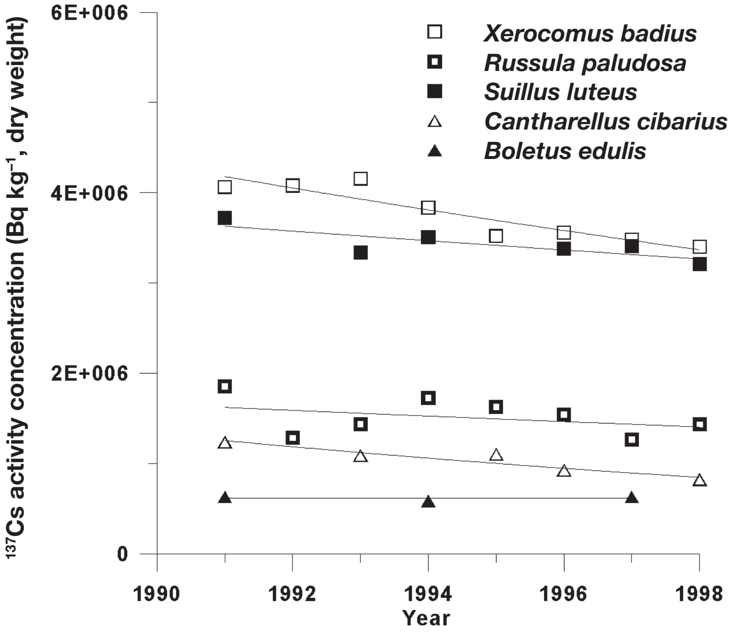

FIG. 1. Cs-137 activity concentrations (Bq kg^{-1}, dry weight) in selected mushroom species. Cs-137 soil deposition at the site in 1986 was around 555 kBq m^{-2} [161].

7.3. RADIONUCLIDE TRANSFER TO BERRIES

Uptake of radiocaesium by forest berries is high in comparison with uptake by foodstuffs grown in agricultural systems. Aggregated transfer factor values for radiocaesium in different berry species are given in Table 43.

TABLE 43. AGGREGATED TRANSFER FACTORS FOR RADIOCAESIUM IN BERRIES ($m^2 kg^{-1}$, dry weight) [162]

Berry species	*N*	Arithmetic mean	Range
Bilberry (*Vaccinium myrtillus*)	952	0.05	0.002–0.3
Cowberry (*Vaccinium vitis-idaea*)	170	0.03	0.005–0.1
Cranberry (*Vaccinium oxycoccus*)	65	0.12	0.003–0.2
Cloudberry (*Rubus chamaemorus*)	45	0.1	0.008–0.15
Raspberry (*Rubus idaeus*)	241	0.03	0.005–0.1
Blackberry (*Rubus fruticosus*)	686	0.02	0.005–0.07
Wild strawberry (*Fragaria vesca*)	466	0.004	0.002–0.007

Data on ^{90}Sr transfer to berries in areas affected by the Chernobyl accident are more limited than those for ^{137}Cs. The only available information was for 1992–1993 and 1999, with reported T_{ag} values of $(7.1 \pm 4.1) \times 10^{-3}$ $m^2 kg^{-1}$ and $(9.2 \pm 3.0) \times 10^{-2}$ $m^2 kg^{-1}$ to bilberry and wild strawberry, respectively [163].

After the Chernobyl accident, the evolution of the ^{137}Cs content in all plant organs of all berry species shows a clear decreasing trend. The mean effective half-life (T^{eff}) for ^{137}Cs in berries calculated for the period from 1991 to 2006 is close to 10 years for most of the berry species [164].

7.4. RADIONUCLIDE TRANSFER TO GAME

7.4.1. Factors affecting transfer values

Radionuclide activity concentrations in meat depend strongly on the feeding habits of the animal. Variability in contamination of game arises due to:

(a) Heterogeneous deposition of radionuclides onto forests and associated terrain.
(b) Different dietary composition and feeding behaviour of game species. For example, some species can utilize produce from neighbouring cultivated areas or can be reared with additional feed (e.g. brown hare, moose, pheasant).
(c) Seasonal variations in diet and/or feeding behaviour (e.g. roe deer, wild boar, reindeer, moose).

This variability means that the use of a single aggregated transfer coefficient may substantially underestimate or overestimate radionuclide activity concentrations in the muscles of game. To address such variability, more emphasis has been given in this section to the changes in transfer with habitat and over time.

Annual game bags are often reported as numbers of animals. For regional assessments of human ingestion dose via game meat, the edible fraction of carcass weight is needed (see Appendix I).

7.4.2. Aggregated transfer coefficient and half-life values in game and reindeer

Consumption of game meat from natural and semi-natural areas by the general population is low, but groups such as hunters may consume relatively large quantities, which can add up to critical dose levels. Early reports described relationships between radionuclide concentrations or amounts in precipitation, soil and animals, and their intake by humans [165, 166]. A review of studies conducted before and after the Chernobyl accident on the transfer of radiocaesium to ruminants provides an overview of such information for that radionuclide [167]. A general review of the parameter values for radionuclide transfers from soil to game provided for TRS-364 is given in Ref. [3]. The updated aggregated transfer factors in game are presented in Table 44. The range of the mean values of T_{ag} (3×10^{-4} – 0.10 $m^2\ kg^{-1}$, fresh weight) represents typical game animals hunted for food for humans and the variability in the composition of feed. Data for game species, details of the relevant studies and the full set of references containing the data presented here are given in the accompanying TECDOC [5].

Roe deer (*Capreolus capreolus*) consume a wide variety of herbs and grasses, as well as fungi when they are available. Radiocaesium levels in roe deer peak in August and September when fungi are abundant, causing a seasonal contamination pattern. Geometric mean values of T_{ag} for roe deer from Austria, the Czech Republic and Germany are given in Table 44. Radiocaesium activity concentrations in roe deer respond quickly to changes in the ingestion rate of radiocaesium, because the biological half-life in muscle is generally less than one month (reported values vary between 10 and 35 days [5]). All mammals exhibit fast and slow components of retention. A typical value for the fast component is 1 day for all mammalian species, although this typically relates to only about 10% of the retained activity. It was found that the interspecies variation in the half-life of the long term component of retention is determined by body mass, as discussed, for example, in Ref. [168]. Ecological half-lives of roe deer meat vary between 6 and 13 years. Soil properties have a significant influence (e.g. organic matter fraction in peat or spruce forest).

Red deer (*Cervus elaphus*) in Central Europe are for the most part managed game and live in deciduous or mixed forests. Few data exist concerning the time

TABLE 44. AGGREGATED TRANSFER COEFFICIENT ($m^2\ kg^{-1}$, fresh weight) FOR ^{137}Cs FROM ACCUMULATED DEPOSITION IN GAME MEAT AND MEAT OF SEMI-DOMESTICATED REINDEER

(based on post-Chernobyl data, representing typical game meat consumed over the hunting season)

Species or group of game animals	Range of geometric mean values		Number of references
Roe deer (*Capreolus capreolus*)	5×10^{-3}–5×10^{-2}		8
Red deer (*Cervus elaphus*)	1×10^{-2}–5×10^{-2}		4
Wild boar (*Sus scrofa*)	5×10^{-4}–2×10^{-1}		3
	Range of arithmetic mean values		
Reindeer (*Rangifer tarandus)*, Aug.–Sept.	0.04–0.35		2
Reindeer (*Rangifer tarandus*), winter	0.06–0.84		7
Moose (*Alces alces*), adult	0.010–0.016		6
Moose (*Alces alces*), calf	0.013–0.02		6
	GM[a]	GSD[b]	
White-tailed deer (*Odocoileus virginianus*)	0.03	1.5	1
Arctic hare (*Lepus timidus*)	0.03	2.2	1
Brown hare (*Lepus europaeus*)	0.009	1.6	1
Pheasant (*Phasianus colchicus*)	3×10^{-4}	1.3	1
Forest birds	0.014	2.0	1
Waterfowl (freshwater)			1
1986	0.013	3.8	
1988	0.005	5	
1989	0.002	3	

[a] GM: Geometric mean.
[b] GSD: Geometric standard deviation.

dependence of the aggregated transfer coefficient value with respect to ^{137}Cs in red deer (Table 44). Ecological half-lives of ^{137}Cs in red deer range from 5 to 18 years; for ^{90}Sr in antlers, values of about 22 years are reported. Geometric mean values of T_{ag} for red deer from Austria, the Czech Republic and Germany are given in Table 44.

Chamois (*Rupicapra rupicapra*) feed on grass and shrubs in summer and on buds and lichen in winter. T_{ag} values for chamois are not reported in the literature; however, ecological half-lives in the range of 8–26 years are mentioned.

Wild boar (*Sus scrofa*) feeds over a very large area. Omnivorous, the wild boar changes its diet with the seasons. It is nearly totally herbivorous in spring and summer, but behaves mainly as a burrower when grass is scarce in winter, feeding on roots, tubers, larvae and earthworms, from which the transfers of caesium are higher than from green plants. Hence, increased levels of contamination (of the order of 50%) are usually observed from October to March (see Table 44). Decades after a contamination event with radiocaesium, the activity concentration in wild boar can be very high, and it can even show no decline over time because of the special feeding habits of wild boar. Geometric mean values of T_{ag} for wild boar from Austria, the Czech Republic and Germany are given in Table 44; minimum values are valid for birch forests, maximum values for spruce forests.

Moose (*Alces alces*) is mostly hunted in boreal forests, and winter conditions inevitably change its diet and metabolism. The pastures of moose in summer and autumn largely determine the intake of ^{137}Cs in the months preceding hunting. Regional soil types are reflected in the T_{ag} values, and the post-Chernobyl decrease in these values has been almost negligible in Northern areas (Table 44), while a small decreasing trend has been observed in part of Central Europe. Overall, the bioavailability of radiocaesium in ecosystems grazed by moose seems to be rather constant, with no obvious reduction in radiocaesium activity over time other than that due to the caesium's physical half-life, which therefore determines the effective half-life [167, 168]. However, data for moose, or elk, from Poland show a gradual decline in ^{137}Cs activity concentrations during 1986–1991, thus implying the existence of processes that reduce the bioavailability of ^{137}Cs in soil in regions south of the boreal forest zone [5].

Among the species or groups of small game, the T_{ag} values for ^{137}Cs were highest for Arctic hare (*Lepus timidus*), which is also hunted in winter, when bark and branches of trees are its main source of food. Brown hare (*Lepus europaeus*) and particularly pheasant (*Phasianus colchicus*) feed off cultivated land, reflected by the low T_{ag} values. The group of forest birds characterized by consistent long term T_{ag} values comprises a mixture of species. For the group of waterfowl from freshwater ecosystems, the T_{ag} values for ^{137}Cs decrease exponentially over time, corresponding to an ecological half-life of 1.1 year during the first few years after the contaminating deposition. The 10–11 day biological half-life of ^{137}Cs in red grouse (*Lagopus lagopus*) was obtained for captive birds.

The seasonal composition of reindeer feed explains why the ^{137}Cs concentration in reindeer meat during summer and early autumn is only 10–20% (or less) of the winter concentration. Since the Chernobyl accident, the ecological half-life of ^{137}Cs in reindeer meat has ranged from 3 to 17 years; where fast and slow components have been estimated, the ranges were 1–3 years and 16–18 years, respectively. Estimates of ecological half-lives reveal a significant dependence on the type and condition of pastures, as well as a need to consider seasons, with their specific T_{ag} values. Values for the biological half-life of radiocaesium in reindeer are given as a fast component (1 day), and a season dependent slow component (ranging from 18 to 33 days).

7.5. APPLICATION OF DATA

The transfer of radionuclides to game and the rate of activity reduction, given as the ecological half-life, reflect the soil and pasture conditions. Forests in temperate and boreal regions differ by soil type and vegetation, and a faster decline of activity concentration in muscle often occurs in deer in temperate zones.

The parameter most widely used to quantify radionuclide transfers to wild foodstuffs in forests is the aggregated transfer coefficient. This simplified approach is adopted because of the complexity of transfer pathways in forests. Unlike domestic animals, game animals have diets that are difficult to identify because they vary between locations and between seasons. Edible fungi are an ecologically complex group of organisms that obtain their nutrition in widely different locations. Similarly, understorey plants producing edible berries can have complex root distributions, making it difficult to understand exactly where they absorb radionuclides in the soil profile.

The simplicity of the T_{ag} approach may lead to inappropriate application of T_{ag} values in dose assessment calculations. T_{ag} values should only be used in calculations for forest systems in which radionuclide fluxes have stabilized, that is, in the medium or long term after depositions. Where effective or ecological half-life data are available, T_{ag} values should not be considered to be constant over time. Finally, in all cases, T_{ag} values should be considered as a means of carrying out screening calculations, rather than as providing a definitive method for calculating transfers in forests under all conditions. Detailed, site specific dose assessments will require more careful consideration of local transfer processes, pathways and rates than T_{ag} values can provide.

8. ARCTIC AND ALPINE ECOSYSTEMS

8.1. DEFINITIONS AND PROCESSES

Arctic (or polar) and alpine (upland) areas typically are extensive, and include forests, upland areas, polar regions and unimproved pastures (e.g. semi-arid steppe). Due to the poor nutrient status of the soils, there is little agriculture involving crop production other than of herbage for animals. The main foodstuffs from these areas are wild products collected by humans, such as mushrooms and berries, a variety of game, and semi-domesticated animals including reindeer and other ruminants [5, 169, 170].

8.1.1. Polar regions

Owing to their specific environmental conditions, Arctic ecosystems are extremely vulnerable to radioactive contamination. Local dietary habits and the high utilization of semi-natural ecosystems for local production of foodstuffs may lead to high doses to the local population due to radiocaesium, strontium and polonium contamination, with significant contributions persisting long after the initial environmental contamination [171]. These areas are characterized by a pronounced diversity of environmental conditions, types of land use and dietary habits, which lead to high variability both of contamination levels in products and of transfer parameters.

As in other semi-natural environments, the transfer of radiocaesium to food products is higher in polar regions than in intensively cultivated land and persists long after deposition. This is because, owing to the low temperatures, soil building processes and litter decomposition in Arctic ecosystems are slower, leading to low pH values and nutrient deficient soils. In general, biogeochemical processes are slower, and contaminants remain available for biota longer than in temperate environments [5, 169–171].

The *lichen–reindeer–human* food chain has been the main object of study in terrestrial Arctic radioecological research. The high interception by lichen of radionuclides, particularly radiocaesium and polonium, is one of the key factors contributing to the high vulnerability of the Arctic food pathway. Lichen represents the main accessible reservoir of radionuclides in the Arctic environment, and 65% of the overall radionuclide burden is accumulated in the top 3 cm of lichen, which is consumed by reindeer [172].

8.1.2. Upland regions

In upland ecosystems, radiocaesium is efficiently stored in superficial soil layers and in plant litter; its storage in some areas is caused by the presence of high amounts of fungal biomass (in acid soils) [5, 173]. Deposited radiocaesium remains available for root uptake by meadow vegetation and can enter the grass–ruminant–human food chain. Upland regions can have a high socioeconomic value and serve as the basis for extensive agriculture. In summer, upland grass pastures are used as free range areas for cows, sheep and goats (milk and meat production) and, to a limited extent, for the production of winter feed for animals [5]. In this section, data from alpine areas are taken to represent the main features and parameters of radionuclide transfer in upland areas.

8.1.3. Application of transfer factors and ecological half-lives

T_{ag} values are highly variable between seasons and years. Similarly, using a single T_{ag} value for lamb neglects the seasonal pattern of sheep grazing in Norway (in the winter, sheep are stabled and fed stored feed) and assumes the exclusive consumption of locally produced feed. However, the slaughter of reindeer and sheep typically occurs during the autumn and/or winter of a given year. These temporal variations make it difficult to compare T_{ag} values between sites for different years [174, 175]. To predict changes over time, T_{ag} values need to be combined with effective ecological half-lives. When using T_{ag} values, major sources of variability must be taken into account, in particular [5]:

(a) Variation over time;
(b) Seasonal variability;
(c) Spatial variability and dietary variability of grazing animals.

The reduction of the concentration of radionuclides in both Arctic and alpine ecosystems is commonly described as an exponential decay with an effective half-life (see Section 2). For the transfer of radionuclides from feed to milk or the muscles of animals, the parameters F_m (d L^{-1}) and F_f were used, which are the *equilibrium* ratio of the activity concentration in milk or muscles to the daily dietary radionuclide intake (see also Section 6).

8.2. RADIONUCLIDE TRANSFER IN POLAR REGIONS

8.2.1. Transfer to lichens

Lichens are a major component of the diet of reindeer. They do not have a rooting system and take up nutrients and associated pollutants from the air and from precipitation. The deposited radionuclides are retained by the lichen, and the contamination level is thereafter reduced through dilution by fresh lichen growth, removal by grazing and/or leaching. Depending on their physical and chemical properties, radionuclides may also be translocated to fresh growth. Strontium-90 is more mobile than ^{137}Cs in lichens, and is washed out from lichens more rapidly than is ^{137}Cs [5]. Table 45 gives examples of mass interception fractions (f_l) estimated for lichens on the Kola Peninsula for 1961–1999 [176].

In a situation with deposition onto snow (in winter), lichen will only become contaminated during snowmelt, with some of the deposited radioactivity being lost via runoff, effectively decreasing the lichen interception fraction. In contrast, if radionuclide deposition occurs as a single-pulse dry deposition, the

TABLE 45. ^{137}Cs AND ^{90}Sr LICHEN MASS INTERCEPTION FRACTIONS (f_l, dry weight) ON THE KOLA PENINSULA AND ECOLOGICAL HALF-LIVES (T_1^{eco}, T_2^{eco}) IN LICHENS

Radionuclide	f_l (m^2 kg^{-1})	a_1^a	T_1^{eco} (year)	T_2^{eco} (year)
^{137}Cs	1.4	0.80	2.0	20
^{90}Sr	0.7	0.72	1.0	20

[a] a_1: The fraction of the initial concentration in lichen declining with the fast loss component.

interception fraction may exceed the annual values. If the season when deposition occurs and the type of deposition (dry or wet) are not considered, significant underestimation and overestimation, respectively, can influence radiological assessments. Post-Chernobyl studies of radiocaesium in lichens indicate effective half-lives of 3–6 years [5].

8.2.2. Transfer to reindeer

The diet of reindeer changes from a summer diet of a wide range of plants to a lichen based diet during winter. The autumn change towards a more highly contaminated lichen diet deficient in mineral elements like potassium is accompanied by a two- to threefold increase in the biological half-life of radiocaesium from about 7 to about 20 d [177, 178]. All three factors contribute significantly to the increased winter radiocaesium activity concentrations in reindeer. However, the seasonal variability also depends on the variable deposition levels in the grazing areas of these nomadic animals. Furthermore, in autumn, reindeer can eat large quantities of mushrooms and attain radiocaesium levels comparable with those of winter [179, 180]. A review of radionuclide contamination levels in reindeer and caribou due to fallout from nuclear weapons testing is presented in the accompanying TECDOC [5]. Some representative values from Golikov et al. [176], who analysed ^{137}Cs transfer to reindeer during winter on the Kola Peninsula (Russian Federation) and in northern Norway in the 1960s, are given in Table 46.

Observed ^{137}Cs concentrations in reindeer in central Sweden and Norway also indicate that concentrations declined faster during the initial period after the Chernobyl fallout than later [5], as suggested by a double exponential model. As an alternative approach, Åhman [177] divided the time period after the accident into the first 10 years (years 0–10) and the second 10 years (years 10–20). Analysis of data from all herds combined showed that the effective half-life during the first period was considerably shorter than that during the latter period (Table 47).

TABLE 46. INITIAL ^{137}Cs AGGREGATED TRANSFER FACTORS FOR REINDEER MEAT ($T_{ag}(0)$ m^2 kg^{-1}, fresh weight), AND ECOLOGICAL (T_1^{eco}, T_2^{eco}, years) AND EFFECTIVE (T_1^{eff}, T_2^{eff}) HALF-LIVES IN REINDEER MUSCLE [176]

Area	$T_{ag}(0)$	a_1^{a}	T_1^{eco}	T_2^{eco}	T_1^{eff}	T_2^{eff}
Kola Peninsula	1.7	0.82	2.0	18	1.9	11.3
Nenets Aut. Okrug	1.2	0.81	1.8	15.6	1.5	10.3
Kautokeino (Norway)	1.8	0.89	1.2	18	1.2	11.3

[a] a_1: The fraction of the initial concentration in lichen declining with the fast loss component.

TABLE 47. ^{137}Cs AGGREGATED TRANSFER FACTORS FOR REINDEER MEAT IN THE FIRST YEAR AFTER FALLOUT (T_{ag}, m^2 kg^{-1}, fresh weight) AND EFFECTIVE HALF-LIVES (T^{eff}, years) FOR DIFFERENT PERIODS AFTER THE CHERNOBYL ACCIDENT

(after Åhman [177] and Skuterud et al. [179])

Country and herd	Season	T_{ag}, 1986–1987	T^{eff}, years 1–10	T^{eff}, years 10–20	T^{eff}, years 1–20
Sweden:	September	0.11–0.24[a]	2.5–3.1	7.6–no decline	4.5–6.7
Vilhelmina norra,	October	0.27–0.39	2.1–2.5	11.4–20.6	5.8–7.9
Ubmeje, Ran	Nov.–Dec.	0.47–0.81	2.8–4.8	4.9–6.9	5.0–6.6
	Jan.–Apr.	0.92–1.21	4.5–7.0	7.5–10.4	5.1–6.8
Norway:	September		4.1–4.9	No decline	9.2–12.4
Østre Namdal, Vågå	Nov.–Jan.		3.9–4.1	6.6[b]	4.8–5.0

[a] Ranges are given for the individual herds.

[b] The estimate is 6.6 years for both sites, with standard errors of 0.8 and 1.5 years.

More detailed data on aggregated transfer factors and ecological half-lives of ^{137}Cs and ^{90}Sr in reindeer are given in the accompanying TECDOC [5], which also includes references to studies of ^{210}Po, ^{210}Pb and ^{226}Ra in reindeer and caribou in Alaska.

8.2.3. Transfer to ruminants

For animal products in the Arctic other than reindeer meat, radiocaesium activity concentrations decrease rapidly in the first year after deposition and then decrease more slowly. Seasonal variations occur, with higher ^{137}Cs and ^{90}Sr activity concentrations in summer, when cows are put out to pasture or are fed fresh grass. Tables 48 and 49 provide the available data on T_{ag} values for cow's milk (for early and late periods after deposition) as well as appropriate information on the variability of the effective ecological half-lives in milk. A compilation of T_{ag} values for lamb meat is given in Table 50.

TABLE 48. SUMMARY OF T_{ag} VALUES FOR COW’S MILK (m^2 kg^{-1}, fresh weight) [5]

Phase	Region	Year(s)	T_{ag}
Early period (T_{ag} (0)) after deposition	Fennoscandia and northwest Russian Federation		1.0×10^{-2}
	Arctic regions (esp. Norway)		1.0×10^{-2}
	Finnmark (Norway)		2.0×10^{-2}
	Troms (Norway)		9.0×10^{-3}
	Nordland (Norway)		1.4×10^{-2}
	Iceland	1965	7.6×10^{-3}
Late period after deposition	Lovozero (Russian Federation)	1998–1999	0.24×10^{-3}
	Kola region (Russian Federation)	1998–1999	0.15×10^{-3}
	Kola region (Russian Federation)	1974–1978	0.14×10^{-3}
	Nenets AO (Russian Federation)	1974–1978	0.12×10^{-3}
	Kola region (Russian Federation)	1978–1985	0.082×10^{-3}
	Nenets AO (Russian Federation)	1978–1985	0.062×10^{-3}
	Iceland	2001–2004	1.1×10^{-3}

TABLE 49. EFFECTIVE HALF-LIVE VALUES (years) FOR ^{137}Cs AND ^{90}Sr ACTIVITY CONCENTRATIONS IN MILK FROM VARIOUS ARCTIC AREAS [5, 170, 181]

Area	^{137}Cs — Global fallout	^{137}Cs — Chernobyl fallout		^{90}Sr — Chernobyl fallout	
	T^{eff}	T_1^{eff}	T_2^{eff}	T_1^{eff}	T_2^{eff}
Faroe Islands	1.0–1.8	1.3–1.8	6.5–8.8	1.0–1.4	5.2–5.5
Finland	1.0	0.7–3.4	4.5	1.3	8.4
Norway	1.1–1.9	—	4.5–6.1	1.5–1.8	4.0–4.6
Sweden	1.4–1.8	—	6.2–9.1	1.4–3.0	8.5–9.0

8.3. RADIONUCLIDE TRANSFER IN ALPINE ECOSYSTEMS

8.3.1. Soil to plant transfer in alpine ecosystems

As with other semi-natural systems, the use of aggregated transfer factors is quite effective for assessments of radionuclide transfer in alpine ecosystems. This is because the variability of conventional transfer factors is extremely high [182]. Factors influencing this variability include the high variability of microclimatic conditions, the small scale variability of soil properties and the changing hydrological conditions [182, 183]. The available peer reviewed data for alpine ecosystems are given in Table 51.

TABLE 50.SUMMARY OF INITIAL AND LATE PHASE T_{ag} VALUES FOR LAMB (SHEEP) MEAT ($m^2\ kg^{-1}$, fresh weight)

Phase	Region	Years	T_{ag}
Early period after deposition ($T_{ag}(0)$)	Fennoscandia and northwest Russian Federation		3.8×10^{-1}
	Arctic regions (esp. Norway)		1.5×10^{-1}
	Finnmark (Norway)		1.6×10^{-1}
	Troms (Norway)		6.3×10^{-1}
	Nordland (Norway)		1.4×10^{-1}
Late period after deposition	Northern Sweden	1990–1997	4.7×10^{-2}
	Faroe Islands	1990–1997	$(5.5–2.5)\times10^{-3}$
	Finland	1990–1993	0.83×10^{-3}
	Iceland	1990–1993	1.5×10^{-2}
	Norway	1990–1993	3.9×10^{-2}

8.3.2. Transfer to ruminants in alpine ecosystems

Table 52 gives the feed transfer coefficients that were determined for milk from alpine regions with calcareous and silicate bedrock [182–184], along with those from a lowland region with intensive production for comparison [183].

The feed transfer coefficients for ^{137}Cs in the lowland region are significantly lower than those for alpine production sites; however, no difference was found in the feed transfer coeffients for ^{90}Sr. Moreover, no significant differences were found between milk feed transfer factors on silicate and calcareous bedrock for either radionuclide.

Considerably longer ecological (or effective) half-lives have been observed in cow’s milk from alpine pastures than in cow’s milk from lowland production sites. For the period 1988–2006, Lettner et al. [185] derived ecological half-lives of 0.7–1.4 years for the fast loss component and of 9.3–12.7 years for the slow loss component of ^{137}Cs concentrations in cow’s milk. Allowing for the difference between ecological and effective half-lives, these values are similar to those for Arctic environments, discussed below.

8.4. APPLICATION OF DATA

Both the transfer of radiocaesium to game and the ecological half-lives reflect the soil and pasture conditions in semi-natural environments. The data for both parameters show considerable variability resulting from seasonality effects,

TABLE 51. AGGREGATED TRANSFER FACTORS (T_{ag}, m^2 kg^{-1}, fresh weight) FOR ^{137}Cs AND ^{90}Sr FROM SOIL TO GRASSLAND VEGETATION IN ALPINE ECOSYSTEMS

Soil type	*N*	GM[a]	GSD[b]	AM[c]	SD[d]	Minimum	Maximum
			^{137}Cs				
Sand	8	0.014	3.1	0.021	0.015	0.002	0.043
Loam	4	0.003	2.9	0.004	0.006	0.001	0.013
Unspecified	1	0.006					
All soils	13	0.008	3.7	0.015	0.015	0.001	0.043
			^{90}Sr				
All soils	3	0.026	2.1	0.030	0.018	0.011	0.047

[a] GM: Geometric mean.
[b] GSD: Geometric standard deviation.
[c] AM: Arithmetic mean.
[d] SD: Standard deviation.

TABLE 52. TRANSFER COEFFICIENTS TO COW'S MILK (F_m, d L^{-1}) FOR ^{137}Cs AND ^{90}Sr IN UPLAND ALPINE AREAS

Site	Arithmetic mean	Standard deviation	Minimum	Maximum
		^{137}Cs		
Lowland	0.0009	0.0008	—	—
Silicate bedrock	0.0071	0.0009	0.0035	0.0114
Calcareous bedrock	0.0069	0.0013	0.0025	0.02
		^{90}Sr		
Lowland	0.0008	0.0003	—	—
Silicate bedrock	0.0011	0.0004	0.0005	0.0017
Calcareous bedrock	0.0010	0.0008	0.0005	0.0010

small scale heterogeneity in soil and climate parameters, and the specific habits of free ranging animals. Nevertheless, the use of aggregated transfer factors seems to be the most practical approach for the prediction of contamination levels in food products from such environments. Also, the long term development of radionuclide concentration in foodstuffs can generally be estimated by two-component exponential models.

The simplified approach of using T_{ag} values has been adopted because of the complexity of transfer pathways in semi-natural ecosystems, which may, in turn, lead to inappropriate application of T_{ag} values in dose assessment calculations. T_{ag} values should only be used in calculations for those semi-natural systems in which radionuclide fluxes have stabilized, that is, in the medium or long term after deposition. Where effective or ecological half-life data are available, T_{ag} values should not be considered to be constant over time. Finally, in all cases, T_{ag} values should be considered as a means of carrying out screening calculations, rather than as providing a definitive method of calculating transfer. Detailed, site specific dose assessments will require greater consideration of local transfer processes, pathways and rates than T_{ag} values can provide.

9. RADIONUCLIDE TRANSFERS IN FRESHWATER ECOSYSTEMS

Radionuclides dispersed in the environment can be deposited onto the water surface or onto the surface of the catchment (watershed). Washoff of radionuclides from the catchment can represent a long term source of radionuclides in freshwater ecosystems. Once in the water, some radioactivity is typically adsorbed by solid particles; this partitioning between the solid particles and the water affects both transport and biological uptake. Solid particles can settle to the bottom of the lake or river and be removed from the water column. Radionuclides dissolved in water can also be adsorbed by the bottom sediments, transferring to the deep sediment layers. However, adsorbed radionuclides can also be remobilized, becoming available again for uptake by freshwater biota. Detailed information on the physical processes listed above and transfer parameters are provided in the accompanying TECDOC [5]. Here, information is confined to parameters relating to availability of radionuclides sorbed to sediments and to data on radionuclide transfer to freshwater food products.

9.1. FRESHWATER K_d VALUES

The residence time of radionuclides in freshwater streams is strongly affected by their interaction with suspended particulate matter and by settlement in the sedimentation zones of a water system. The uptake of radionuclides by aquatic organisms depends on the concentration and on the speciation of those radionuclides remaining in the dissolved phase. Partitioning of radionuclides between water and suspended matter is often described in terms of distribution coefficients, K_ds, expressed as the concentration ratio of the particulate phase to the dissolved phase under equilibrium conditions (in Bq kg^{-1} of supspended particulate matter per Bq L^{-1}).

Sorption of radioactivity on natural particles results from several kinetic processes, involving rapid, but also slow, processes (e.g. oxidation processes, inner sphere complexation and migration of cations in the clay structure) [5, 186–196]. Kinetics in the interactions of radionuclides at the interface between the water and the suspended particulate matter depends on the element under consideration, but also on other environmental co-factors such as the suspended particulate matter concentration [186, 189, 192], and the ionic strength and age of the contamination (termed an ageing effect) [186–188].

Desorption kinetics may be highly governed by the inner speciation of bound radionuclides (i.e. distribution among easily accessible versus less accessible binding sites) [190].

For sorption of some radionuclides in freshwater ecosystems, the seasonality effect (and the associated biological activity in the water) is important. For cobalt or manganese, for example, oxidation processes, which are partially microbially mediated, govern their slow uptake by suspended particulate matter. Seasonal differences may then reflect strong seasonal variation in the abundance of oxidizing bacteria [190, 196].

The K_d values for all radionuclides were divided into four groups on the basis of data availability [5], namely, K_d values for radionuclides for which large amounts of data are available, K_d values for radionuclides for which moderate amounts of data are available, K_d values for radionuclides for which only single values are available, and K_d values for radionuclides which are mainly the product of expert estimates, primarily given in a review published in 1991 [197]. The fourth group of K_d values were also quoted in TRS-364 [3], without clear referencing. The database used to derive values for the present publication (see Ref [5] for details) contains K_d values in natural freshwater bodies (rivers and lakes) from suspended particulate matter or superficial sediment (top 0–5 cm).

In addition, information on potential co-factors and on criteria allowing estimation of the quality of each referenced datum was collected, especially concerning the following: pH, suspended matter concentration, contact time between water and particles, method for the determination of K_d values (in situ measurements or laboratory experiments under adsorption or desorption conditions with spiked solutions) and redox conditions (especially for iodine). The methodology for data processing in the case where large amounts of data were available (Ag, Am, Co, Cs, I, Mn, Pu, Sr) was as follows: (1) construction of the database with available K_d data and information on corresponding environmental co-factors; (2) application of quality criteria; and (3) determination of non-conditional and (4) conditional probability density functions by a bootstrap statistical procedure to account for parametric uncertainty [5]. For the second group of radionuclides (Be, Ba, Ce, Ra, Ru, Sb, Th), the approach was similar in that steps (1)–(3) were used, but only non-conditional probability density functions were defined (i.e. step (4) was omitted) to reduce the uncertainty over a given range of values for any parameter. Simple statistical data processing was applied for the third group of radionuclides, and the data for the fourth group of radionuclides (Cr, Fe, Zn, Zr, Tc, Pm, Eu, U, Np, Cm) were taken as reproduced in Refs [3, 197].

Reference K_d values with the associated geometric standard deviation are given in Table 53. The data were obtained from field measurements (“Field”) and laboratory adsorption (“Ads”) or desorption (“Des”) experiments. Where

TABLE 53. K_d VALUES IN FRESHWATER ECOSYSTEMS (L kg^{-1})

Element	*N*	GM[a]	GSD[b]	Minimum	Maximum	Data origin
Ag	91	9.5×10^4	2.3	2.2×10^4	3.3×10^5	Ads
	41	4.4×10^5	1.7	1.9×10^5	1.0×10^6	Des
Am	99	2.1×10^5	3.7	2.5×10^4	1.9×10^6	Ads
	42	1.2×10^5	5.7	6.9×10^3	2.0×10^6	Field
Ba	49	2.0×10^3	3.6	2.5×10^2	1.6×10^4	Various
Be	29	4.2×10^4	3.6	5.1×10^3	3.4×10^5	Various
Ce	15	2.2×10^5	2.9	4.2×10^4	1.2×10^6	Various
Co	534	4.3×10^4	9.5	1.1×10^3	1.7×10^6	Ads
	74	4.9×10^5	4.9	3.5×10^4	6.6×10^6	Des
	29	4.4×10^4	3.9	4.9×10^3	3.9×10^5	Field
Cs	569	9.5×10^3	6.7	3.7×10^2	1.9×10^5	Ads
	119	2.9×10^4	2.4	6.9×10^3	1.2×10^5	Des
	219	2.9×10^4	5.9	1.6×10^3	5.2×10^5	Field
I	124	4.4×10^3	14	5.9×10^1	3.4×10^5	Ads[c]
Mn	190	1.3×10^5	12	2.1×10^3	7.4×10^6	Ads
	46	6.9×10^5	6.6	3.2×10^4	1.5×10^7	Des
	17	7.9×10^4	1.9	3.1×10^4	1.9×10^5	Field
Pu	37	7.9×10^4	2.2	2.1×10^4	2.9×10^5	Ads
	41	3.0×10^5	4.2	2.9×10^4	3.2×10^6	Des
	79	2.4×10^5	6.6	1.1×10^4	5.2×10^6	Field
Ra	75	7.4×10^3	3.1	1.1×10^3	5.2×10^4	Various
Ru	74	3.2×10^4	1.9	1.1×10^4	9.3×10^4	Various
Sb	23	5.0×10^3	3.9	5.5×10^2	4.6×10^4	Various
Sr	156	1.9×10^2	4.6	1.4×10^1	2.2×10^3	Ads
	34	6.2×10^2	2.1	1.9×10^2	2.1×10^3	Des
	13	1.2×10^3	2.7	2.3×10^2	6.3×10^3	Field
Th	63	1.9×10^5	21	1.2×10^3	2.7×10^7	Various

[a] GM: Geometric mean.
[b] GSD: Geometric standard deviation.
[c] Given for oxic conditions.

appropriate, separate K_d values are presented for these three types of measurement.

Information related to additional elements (i.e. Cr, Fe, Zn, Zr, Tc, Pm, Eu, U, Np, Cm) is given in Table 54 and reported in TRS-364 [3]. These values are based on a single publication [197] and must be used with caution.

9.2. TRANSFER TO FRESHWATER BIOTA

Although it is generally recognized that accumulation of radionuclides by edible aquatic organisms is a dynamic process, many bioaccumulation models assume that the aquatic organisms are in equilibrium with reference media, such as water or sediments, in their surrounding environment. As a result, radionuclide accumulation in aquatic biota is often represented by simplified ratios that relate radionuclide concentrations in biotic tissues to concentrations in the reference media [5, 198–200].

The steady state models can be subdivided into two categories on the basis of the chemical behaviour of a given radionuclide and its associated transfer processes to edible biotic tissues. These categories are: (1) models that are based on simple radionuclide partitioning between organisms and reference phases (such as surface water or sediments); and (2) specific activity models, which assess partitioning of radionuclides relative to stable analogues in the body [5].

TABLE 54. GROSS AVERAGE K_d VALUES IN AQUEOUS SYSTEMS ($L\ kg^{-1}$) [3]

Element	Expected value	Minimum	Maximum
Cr	Low[a]	—	—
Fe	5.0×10^3	1.0×10^3	1.0×10^4
Zn	5.0×10^2	1.0×10^2	1.0×10^3
Zr	1.0×10^3	1.0×10^3	1.0×10^4
Tc	5.0×10^0	n.d.[b]	1.0×10^2
Pm	5.0×10^3	1.0×10^3	1.0×10^4
Eu	5.0×10^2	2.0×10^2	9.0×10^2
U	5.0×10^1	2.0×10^1	1.0×10^3
Np	1.0×10^1	2.0×10^{-1}	1.0×10^2
Cm	5.0×10^3	1.0×10^1	7.0×10^4

[a] Reproduced according to Ref. [3].
[b] n.d.: Not detectable.

9.2.1. Concentration ratios

Depending on the radionuclide uptake pathway being considered, a number of representations of partitioning can be defined. These include: (1) the concentration ratio (*CR*), which is the ratio of the radionuclide concentration in biota (C_b) from all exposure pathways (including water, sediment and ingestion/dietary pathways) on a per unit tissue fresh weight basis to that in water (C_w); and (2) the biota sediment concentration ratio ($CR_{s\text{-}b}$), which is the ratio of the concentration of a radionuclide in an organism (C_b) on a fresh weight basis to the radionuclide concentration (fresh weight) measured in the sediment (C_{sed}). Fresh weight to dry weight ratios for selected aquatic organisms are given in Table 87 in Appendix I.

$CR_{s\text{-}b}$ is appropriately derived from studies in which only the sediment is contaminated, where the contribution of sediment associated radionuclides can be of particular importance with respect to radionuclide uptake by benthic species.

Most contaminant transfer factors in the literature do not distinguish between uptake pathways, and therefore represent *CR* values (also called the bioaccumulation factor, *BAF*). Water to biota values from the literature have been compiled for radionuclides and their stable analogues, and are listed in Tables 55–58; sediment to biota concentration ratios ($CR_{s\text{-}b}$) are provided in Tables 59 and 60 (largely based on the data from Refs [198, 199]). Additional information on tissue specific radionuclide transfer factors can be found in the accompanying TECDOC [5].

In general, *CR* and $CR_{s\text{-}b}$ values for stable elements are conservative when used to represent radionuclides with relatively short radiological half-lives and relatively long biological half-lives, since physical decay of short lived radionuclides can significantly reduce their concentration in biota tissues [203]. To account for this, *CR* and $CR_{s\text{-}b}$ values can be multiplied by a factor *K* that accounts for the radionuclide specific half-lives, as described by:

$$K = \frac{\lambda_b}{\lambda_b + \lambda_r} \tag{32}$$

where λ_b is the biological decay constant (0.693 t_b^{-1} (d^{-1})); λ_r is the radioactive decay constant (0.693 t_r^{-1} (d^{-1})); t_b is the biological half-life (d); and t_r is the radiological half-life (d). For screening purposes, a t_b of 30 d (or a λ_b of 0.023 d^{-1}) can be assumed [203].

Details outlining how these transfer factors were defined can be found in the accompanying TECDOC [5].

TABLE 55. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR EDIBLE AQUATIC PLANTS[a] (L kg^{-1}, fresh weight)

Element	*N*	Mean[b]	GSD[c]	Minimum	Maximum
Am	16	3.7×10^{3}	9.3×10^{0}	7.5×10^{0}	3.9×10^{4}
C	10	1.6×10^{4}	1.5×10^{1}	4.4×10^{1}	9.9×10^{4}
Cd	5	1.9×10^{4}	6.9×10^{0}	1.1×10^{4}	2.3×10^{4}
Cm	1	9.0×10^{3}	—	n.a.[d]	n.a.
Co	19	7.1×10^{2}	5.1×10^{0}	5.0×10^{1}	2.0×10^{4}
Cs	26	9.7×10^{1}	1.6×10^{1}	1.9×10^{0}	3.3×10^{3}
Cu	5	3.0×10^{3}	3.2×10^{2}	2.4×10^{3}	3.6×10^{3}
Fe	5	9.1×10^{3}	1.9×10^{0}	5.2×10^{3}	1.5×10^{4}
I	3	1.3×10^{2}	3.7×10^{0}	7.9×10^{1}	2.7×10^{2}
Mn	6	1.2×10^{4}	7.2×10^{2}	3.1×10^{-1}	1.5×10^{5}
Ni	5	7.7×10^{2}	1.3×10^{2}	2.5×10^{2}	1.1×10^{3}
Np	2	7.2×10^{3}	—	6.5×10^{3}	9.0×10^{3}
Pb	5	1.9×10^{3}	7.6×10^{1}	1.3×10^{3}	2.2×10^{3}
Pu	40	2.6×10^{4}	1.4×10^{1}	1.2×10^{2}	4.9×10^{7}
Ra	9	2.9×10^{3}	4.1×10^{0}	6.4×10^{2}	1.1×10^{4}
Ru	9	2.9×10^{2}	2.0×10^{0}	7.4×10^{1}	6.7×10^{2}
Se	31	1.4×10^{3}	5.4×10^{0}	9.4×10^{0}	9.2×10^{3}
Sr	17	4.1×10^{2}	3.3×10^{0}	3.9×10^{1}	1.9×10^{3}
Tc	9	5.5×10^{0}	4.9×10^{0}	2.9×10^{-1}	9.9×10^{1}
U	4	2.1×10^{2}	1.9×10^{0}	9.1×10^{1}	5.2×10^{2}
Zn	5	2.1×10^{4}	1.3×10^{1}	1.4×10^{4}	2.7×10^{4}

[a] All types of aquatic plant are included in the assessments.

[b] For $N = 2$, the mean is the arithmetic mean.

[c] GSD: Geometric standard deviation.

[d] n.a.: Not available.

TABLE 56. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR FRESH-WATER INVERTEBRATES (L kg^{-1}, fresh weight)

Element	*N*	Mean[a]	GSD[b]	Minimum	Maximum
Ag	2	2.3×10^{2}		1.3×10^{2}	3.3×10^{2}
Al	2	3.4×10^{3}		3.1×10^{3}	3.7×10^{3}
Am	17	2.4×10^{3}	7.0×10^{0}	5.9×10^{1}	9.0×10^{4}
As	2	1.5×10^{3}		1.0×10^{3}	2.0×10^{3}
Au	2	1.4×10^{3}		1.0×10^{3}	1.5×10^{3}
Ba	2	1.4×10^{2}		1.1×10^{2}	1.6×10^{2}
Br	2	1.3×10^{3}		7.2×10^{2}	1.9×10^{3}
C	24	6.5×10^{4}	2.6×10^{0}	1.3×10^{4}	5.7×10^{5}
Ca	3	3.4×10^{1}	2.5×10^{0}	1.2×10^{1}	6.6×10^{1}
Cd	149	1.0×10^{2}	3.9×10^{1}	1.4×10^{-2}	3.1×10^{4}
Ce	2	4.3×10^{2}		2.9×10^{2}	5.6×10^{2}

TABLE 56. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR FRESH-WATER INVERTEBRATES (L kg^{-1}, fresh weight) (cont.)

Element	*N*	Mean[a]	GSD[b]	Minimum	Maximum
Cl	2	1.6×10^{2}		1.3×10^{2}	1.9×10^{2}
Co	29	2.2×10^{1}	1.3×10^{2}	1.9×10^{-3}	4.1×10^{4}
Cr	2	3.0×10^{2}		2.1×10^{2}	3.9×10^{2}
Cs	29	2.3×10^{1}	7.5×10^{1}	5.4×10^{-3}	6.1×10^{3}
Cu	92	4.2×10^{1}	1.1×10^{1}	5.6×10^{1}	1.4×10^{3}
Cm	2	9.5×10^{3}		9.0×10^{3}	1.0×10^{4}
Eu	2	2.2×10^{2}		2.0×10^{2}	2.3×10^{2}
Fe	2	2.0×10^{3}		1.9×10^{3}	2.1×10^{3}
Hf	2	1.4×10^{3}		1.3×10^{3}	1.5×10^{3}
Hg	31	7.5×10^{2}	2.7×10^{0}	2.0×10^{2}	5.2×10^{3}
I	99	1.7×10^{1}	1.1×10^{1}	4.0×10^{-1}	1.3×10^{3}
K	2	5.9×10^{2}		5.4×10^{2}	6.1×10^{2}
La	2	3.5×10^{2}		3.3×10^{2}	3.7×10^{2}
Lu	1	1.1×10^{3}	—	—	—
Mg	2	3.2×10^{1}		2.1×10^{1}	4.3×10^{1}
Mn	4	2.1×10^{1}	3.9×10^{2}	1.1×10^{-1}	3.7×10^{3}
Mo	33	4.5×10^{-1}	1.3×10^{1}	2.9×10^{-2}	3.0×10^{3}
Na	4	3.4×10^{0}	3.6×10^{1}	1.4×10^{-1}	1.1×10^{2}
Np	2	9.5×10^{3}		9.0×10^{3}	1.0×10^{4}
Pb	79	2.2×10^{1}	2.0×10^{1}	4.5×10^{-2}	7.0×10^{2}
Pu	100	7.4×10^{3}	2.9×10^{1}	3.6×10^{-1}	5.5×10^{6}
Ra	5	1.0×10^{2}	3.0×10^{1}	1.9×10^{0}	1.9×10^{3}
Rb	2	2.0×10^{3}		1.9×10^{3}	2.2×10^{3}
Ru	9	3.9×10^{-2}	2.1×10^{1}	1.9×10^{-3}	9.3×10^{1}
Sb	2	2.1×10^{2}		7.4×10^{1}	3.5×10^{2}
Sc	2	3.5×10^{3}		3.3×10^{3}	3.7×10^{3}
Se	16	5.7×10^{2}	1.5×10^{1}	1.2×10^{1}	6.9×10^{4}
Sm	2	1.6×10^{3}		5.0×10^{2}	2.7×10^{3}
Sr	5	2.7×10^{2}	3.2×10^{0}	7.7×10^{1}	1.3×10^{3}
Tc	10	2.6×10^{1}	9.9×10^{0}	1.9×10^{0}	4.0×10^{2}
Th	2	2.9×10^{3}		2.9×10^{3}	2.9×10^{3}
U	9	1.7×10^{2}	1.9×10^{1}	3.6×10^{0}	6.0×10^{4}
V	2	3.9×10^{2}		3.6×10^{2}	4.0×10^{2}
Zn	92	9.2×10^{1}	2.9×10^{1}	6.3×10^{-2}	1.5×10^{3}

[a] For $N = 2$, the mean is the arithmetic mean.

[b] GSD: Geometric standard deviation.

TABLE 57. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR FRESHWATER FISH TISSUES (L kg^{-1}, fresh weight)

Element	Whole body					Muscle				
	N	Mean[a]	GSD[b]	Minimum	Maximum	*N*	Mean	GSD	Minimum	Maximum
Ag	23	1.1×10^{2}	1.3×10^{0}	5.7×10^{1}	1.9×10^{2}	27	1.1×10^{2}	1.5×10^{0}	4.0×10^{1}	2.1×10^{2}
Al	93	6.6×10^{1}	7.1×10^{0}	4.5×10^{0}	5.2×10^{3}	31	5.1×10^{1}	3.9×10^{0}	5.9×10^{0}	3.0×10^{2}
Am	n.a.[c]	n.a.	n.a.	n.a.	n.a.	2	2.4×10^{2}		7.2×10^{1}	4.0×10^{2}
As	33	3.9×10^{2}	2.3×10^{0}	9.1×10^{1}	1.0×10^{3}	15	3.3×10^{2}	2.1×10^{0}	5.0×10^{1}	9.5×10^{2}
Au	13	2.9×10^{2}	2.3×10^{0}	5.0×10^{1}	1.0×10^{3}	17	2.4×10^{2}	2.1×10^{0}	5.0×10^{1}	9.0×10^{2}
Ba	92	4.7×10^{1}	1.7×10^{0}	5.0×10^{0}	2.2×10^{2}	111	1.2×10^{0}	3.3×10^{0}	5.3×10^{-2}	3.2×10^{1}
Br	37	1.6×10^{2}	2.3×10^{0}	1.5×10^{1}	7.9×10^{2}	15	9.1×10^{1}	2.3×10^{0}	1.9×10^{1}	3.7×10^{2}
C	n.a.	n.a.	n.a.	n.a.	n.a.	6	4.0×10^{5}	2.9×10^{0}	1.9×10^{5}	3.2×10^{6}
Ca	119	1.0×10^{3}	3.4×10^{0}	9.4×10^{1}	5.6×10^{3}	104	1.2×10^{1}	2.5×10^{0}	2.0×10^{0}	9.7×10^{1}
Ce	90	1.2×10^{1}	2.7×10^{0}	3.0×10^{0}	1.1×10^{2}	71	2.5×10^{1}	9.5×10^{0}	9.0×10^{1}	1.2×10^{3}
Cl	37	9.5×10^{1}	1.6×10^{0}	2.5×10^{1}	2.3×10^{2}	16	4.7×10^{1}	2.2×10^{0}	9.9×10^{0}	1.2×10^{2}
Co	119	4.0×10^{2}	1.6×10^{0}	2.3×10^{1}	2.4×10^{3}	65	7.6×10^{1}	2.4×10^{0}	9.0×10^{0}	5.6×10^{2}
Cr	51	2.1×10^{2}	2×10^{0}	3.5×10^{1}	7.6×10^{2}	57	4.0×10^{1}	2×10^{0}	1.3×10^{1}	1.2×10^{2}
Cs	145	3.0×10^{3}	2.6×10^{0}	7.5×10^{1}	2.4×10^{4}	106	2.5×10^{3}	2.4×10^{0}	1.4×10^{2}	1.5×10^{4}
Cu	102	2.7×10^{2}	1.5×10^{0}	9.6×10^{1}	1.2×10^{3}	96	2.3×10^{2}	1.7×10^{0}	9.9×10^{1}	7.2×10^{2}
Dy	1	3.0×10^{2}	—	—	—	2	6.5×10^{2}		2.0×10^{2}	1.1×10^{3}
Eu	53	1.5×10^{2}	3.2×10^{0}	7.6×10^{0}	2.2×10^{3}	24	1.3×10^{2}	4.9×10^{0}	1.1×10^{1}	7.2×10^{2}
Fe	114	1.4×10^{2}	5.7×10^{0}	1.6×10^{1}	5.3×10^{3}	96	1.7×10^{2}	6.9×10^{0}	6.6×10^{0}	2.0×10^{3}
Hf	20	2.1×10^{3}	3.2×10^{0}	3.0×10^{2}	2.9×10^{4}	10	1.1×10^{3}	1.9×10^{0}	3.3×10^{2}	2.0×10^{3}
Hg	20	4.5×10^{3}	2.2×10^{0}	1.1×10^{3}	2.2×10^{4}	14	6.1×10^{3}	1.9×10^{0}	1.9×10^{3}	1.7×10^{4}
I	94	6.5×10^{2}	2.1×10^{0}	1.0×10^{2}	4.5×10^{4}	50	3.0×10^{1}	2.5×10^{0}	1.1×10^{1}	4.0×10^{2}
K	120	4.0×10^{3}	2.0×10^{0}	5.7×10^{2}	1.5×10^{4}	97	3.2×10^{3}	1.6×10^{0}	1.2×10^{3}	9.0×10^{3}
La	102	1.6×10^{1}	3.2×10^{0}	3.6×10^{0}	3.4×10^{2}	74	3.7×10^{1}	4.9×10^{0}	1.1×10^{0}	6.6×10^{2}
Mg	111	1.1×10^{2}	3.0×10^{0}	1.4×10^{1}	4.3×10^{2}	96	3.7×10^{1}	2.2×10^{0}	7.9×10^{0}	1.9×10^{2}
Mn	110	4.5×10^{2}	4.0×10^{0}	4.9×10^{1}	7.0×10^{3}	97	2.4×10^{2}	6.7×10^{0}	1.3×10^{1}	1.4×10^{5}
Mo	91	2.7×10^{1}	1.9×10^{0}	2.1×10^{0}	1.9×10^{2}	64	1.9×10^{0}	2.1×10^{0}	4.0×10^{-3}	2.0×10^{1}
Na	42	1.4×10^{2}	2.1×10^{0}	3.4×10^{1}	6.0×10^{2}	97	7.6×10^{1}	3.0×10^{0}	1.7×10^{1}	6.1×10^{2}
Ni	24	7.1×10^{1}	2.1×10^{0}	1.9×10^{1}	6.6×10^{2}	5	2.1×10^{1}	1.9×10^{0}	1.1×10^{1}	4.4×10^{1}
P	n.a.	n.a.	n.a.	n.a.	n.a.	39	1.4×10^{5}	1.1×10^{0}	1.2×10^{5}	1.7×10^{5}
Pb	92	3.7×10^{2}	3.0×10^{0}	5.9×10^{1}	5.7×10^{3}	39	2.5×10^{1}	2.9×10^{0}	1.0×10^{-1}	2.7×10^{2}
Po	n.a.	n.a.	n.a.	n.a.	n.a.	5	3.6×10^{1}	4.3×10^{0}	6.0×10^{0}	1.7×10^{2}
Pu	n.a.	n.a.	n.a.	n.a.	n.a.	3	2.1×10^{4}	2.6×10^{0}	7.7×10^{3}	5.0×10^{4}
Ra	2	2.1×10^{2}		1.6×10^{2}	2.5×10^{2}	21	4.0×10^{0}	6.9×10^{0}	6.0×10^{-2}	1.5×10^{2}
Rb	113	6.1×10^{3}	1.6×10^{0}	1.2×10^{3}	1.6×10^{3}	92	4.9×10^{3}	1.7×10^{0}	1.0×10^{3}	1.4×10^{4}
Ru	n.a.	n.a.	n.a.	n.a.	n.a.	2	5.5×10^{1}		1.0×10^{1}	1.0×10^{2}
Sb	37	7.1×10^{1}	9.9×10^{0}	4.7×10^{0}	9.3×10^{6}	20	3.7×10^{1}	4.5×10^{0}	1.9×10^{0}	3.6×10^{2}
Sc	30	9.3×10^{2}	3.6×10^{0}	6.7×10^{1}	3.7×10^{4}	14	1.9×10^{2}	2.1×10^{0}	3.3×10^{1}	7.3×10^{2}
Se	29	6.9×10^{3}	1.3×10^{0}	3.6×10^{3}	1.2×10^{4}	14	6.0×10^{3}	1.3×10^{0}	3.5×10^{3}	9.4×10^{3}
Sr	116	1.9×10^{2}	2.2×10^{0}	2.2×10^{1}	7.1×10^{2}	99	2.9×10^{0}	3.9×10^{0}	1.4×10^{-1}	6.9×10^{1}
Tb	19	7.5×10^{2}	2.6×10^{0}	9.0×10^{1}	2.4×10^{3}	11	4.1×10^{2}	1.9×10^{0}	2.0×10^{2}	1.7×10^{3}

TABLE 57. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR FRESHWATER FISH TISSUES (L kg^{-1}, fresh weight) (cont.)

Element	Whole body					Muscle				
	N	Mean[a]	GSD[b]	Minimum	Maximum	*N*	Mean	GSD	Minimum	Maximum
Te	9	4.2×10^{2}	1.5×10^{0}	2.2×10^{2}	9.9×10^{2}	3	1.5×10^{2}	1.5×10^{0}	9.6×10^{1}	2.1×10^{2}
Th	2	1.9×10^{2}		3.9×10^{1}	3.9×10^{3}	3	6.0×10^{0}	—	6.0×10^{0}	6.0×10^{0}
Ti	30	3.7×10^{2}	1.9×10^{0}	1.2×10^{2}	1.3×10^{3}	13	1.9×10^{2}	1.4×10^{0}	1.1×10^{2}	3.5×10^{2}
Tl	91	5.9×10^{2}	1.9×10^{0}	6.4×10^{1}	3.1×10^{3}	59	9.0×10^{2}	2.6×10^{0}	6.6×10^{1}	1.0×10^{4}
U	2	2.4×10^{0}		1.5×10^{0}	3.3×10^{0}	9	9.6×10^{-1}	12×10^{0}	2.0×10^{-2}	2.0×10^{1}
V	103	2.9×10^{2}	2.0×10^{0}	3.0×10^{1}	1.1×10^{3}	91	9.7×10^{1}	1.9×10^{0}	1.0×10^{1}	2.4×10^{2}
Y	12	3.1×10^{1}	1.6×10^{0}	1.1×10^{1}	6.2×10^{1}	19	4.0×10^{1}	2.5×10^{0}	4.5×10^{0}	1.2×10^{2}
Zn	114	4.7×10^{3}	1.9×10^{0}	1.2×10^{3}	1.9×10^{4}	96	3.4×10^{3}	2.9×10^{0}	3.3×10^{2}	1.6×10^{4}
Zr	9	9.5×10^{1}	1.5×10^{0}	5.7×10^{1}	2.4×10^{2}	10	2.2×10^{1}	2.4×10^{0}	9.2×10^{0}	1.2×10^{2}

[a] For $N = 2$, the mean is the arithmetic mean.

[b] GSD: Geometric standard deviation.

[c] n.a.: Not available.

TABLE 58. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR EDIBLE HERPETOFAUNA (L kg^{-1}, fresh weight) [201]

Element	Biota type (tissue)	*N*	Mean[a]	GSD[b]	Minimum	Maximum
Al	Tadpole (whole)	3	1.0×10^{4}	1.3×10^{0}	7.5×10^{3}	1.3×10^{4}
	Frog (muscle)	2	1.3×10^{2}		1.2×10^{2}	1.3×10^{2}
	Frog (carcass)	2	1.3×10^{2}		1.1×10^{2}	1.5×10^{2}
As	Tadpole (whole)	3	1.4×10^{2}	1.3×10^{0}	1.1×10^{2}	1.9×10^{2}
	Frog (muscle)	2	5.2×10^{1}		2.4×10^{1}	9.0×10^{1}
	Frog (carcass)	2	1.2×10^{2}		7.4×10^{1}	1.6×10^{2}
Ca	Tadpole (whole)	3	4.5×10^{1}	1.6×10^{0}	2.6×10^{1}	6.3×10^{1}
	Frog (muscle)	2	3.5×10^{0}		3.4×10^{0}	3.5×10^{0}
	Frog (carcass)	2	2.9×10^{2}		2.9×10^{2}	2.9×10^{2}
	Reptile (carcass)	9	1.6×10^{2}	1.1×10^{1}	5.2×10^{1}	3.4×10^{2}
Cd	Tadpole (whole)	3	2.1×10^{2}	1.4×10^{0}	1.4×10^{2}	2.9×10^{2}
	Frog (muscle)	2	1.2×10^{2}		1.1×10^{2}	1.2×10^{2}
	Frog (carcass)	2	2.4×10^{2}		2.2×10^{2}	2.5×10^{2}
Co	Tadpole (whole)	3	9.3×10^{3}	1.1×10^{0}	7.3×10^{3}	9.5×10^{3}
	Frog (muscle)	2	5.5×10^{2}		1.9×10^{2}	9.0×10^{2}
	Frog (carcass)	2	2.4×10^{3}		1.9×10^{3}	3.0×10^{3}
	Reptile (carcass)	9	2.6×10^{3}	1.9×10^{0}	1.6×10^{3}	4.2×10^{3}
Cr	Tadpole (whole)	3	2.9×10^{2}	1.5×10^{0}	2.1×10^{2}	4.4×10^{2}
	Frog (muscle)	2	9.2×10^{1}		9.2×10^{1}	9.3×10^{1}
	Frog (carcass)	2	2.6×10^{3}		1.9×10^{2}	4.9×10^{3}

TABLE 58. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR EDIBLE HERPETOFAUNA (L kg^{-1}, fresh weight) [201] (cont.)

Element	Biota type (tissue)	*N*	Mean[a]	GSD[b]	Minimum	Maximum
Cs	Tadpole (whole)	3	3.0×10^{3}	1.3×10^{0}	2.5×10^{3}	4.0×10^{3}
	Frog (muscle)	2	2.6×10^{2}		1.7×10^{2}	3.4×10^{2}
	Frog (carcass)	2	2.1×10^{2}		1.6×10^{2}	2.5×10^{2}
	Reptile (carcass)	9	2.9×10^{2}	1.3×10^{0}	1.3×10^{2}	5.0×10^{2}
Cu	Tadpole (whole)	3	2.2×10^{2}	1.3×10^{0}	1.7×10^{2}	2.6×10^{2}
	Frog (muscle)	2	1.1×10^{2}		1.1×10^{2}	1.1×10^{2}
	Frog (carcass)	2	4.4×10^{2}	2.3×10^{0}	2.9×10^{2}	6.0×10^{2}
Fe	Tadpole (whole)	3	2.4×10^{3}	1.2×10^{0}	1.9×10^{3}	2.9×10^{3}
	Frog (muscle)	2	3.5×10^{1}		1.9×10^{1}	5.0×10^{1}
	Frog (carcass)	2	1.0×10^{3}		3.0×10^{2}	1.7×10^{3}
K	Tadpole (whole)	3	4.7×10^{2}	1.5×10^{0}	3.1×10^{2}	7.0×10^{2}
	Frog (muscle)	2	1.5×10^{3}		1.4×10^{3}	1.5×10^{3}
	Frog (carcass)	2	1.6×10^{3}		1.5×10^{3}	1.6×10^{3}
	Reptile (carcass)	9	1.4×10^{3}	7.0×10^{0}	9.9×10^{2}	2.0×10^{3}
Mg	Tadpole (whole)	3	2.7×10^{1}	1.2×10^{0}	2.3×10^{1}	3.4×10^{1}
	Frog (muscle)	2	1.5×10^{1}		9.4×10^{0}	2.1×10^{1}
	Frog (carcass)	2	2.4×10^{1}		2.3×10^{1}	2.4×10^{1}
	Reptile (carcass)	9	3.4×10^{1}	5.9×10^{0}	1.5×10^{1}	7.2×10^{1}
Mn	Tadpole (whole)	3	5.6×10^{2}	2.9×10^{0}	1.7×10^{2}	1.1×10^{3}
	Frog (muscle)	2	2.0×10^{0}		9.3×10^{-1}	3.1×10^{0}
	Frog (carcass)	2	3.0×10^{2}		2.6×10^{2}	3.3×10^{2}
Na	Tadpole (whole)	3	1.1×10^{2}	2.5×10^{0}	4.0×10^{1}	2.5×10^{2}
	Frog (muscle)	2	1.4×10^{2}		9.9×10^{1}	1.9×10^{2}
	Frog (carcass)	2	7.7×10^{1}		7.5×10^{1}	7.9×10^{1}
	Reptile (carcass)	9	7.3×10^{1}	1.1×10^{0}	5.6×10^{1}	1.3×10^{2}
Ni	Tadpole (whole)	3	3.9×10^{2}	1.9×10^{0}	1.9×10^{2}	7.2×10^{2}
	Frog (muscle)	2	2.4×10^{1}		2.1×10^{1}	2.7×10^{1}
	Frog (carcass)	2	2.0×10^{4}		6.6×10^{2}	1.0×10^{4}
Pb	Tadpole (whole)	3	6.4×10^{1}	1.2×10^{0}	5.3×10^{1}	7.6×10^{1}
	Frog (muscle)	2	5.5×10^{0}		2.1×10^{0}	9.9×10^{0}
	Frog (carcass)	2	1.7×10^{1}		1.2×10^{1}	2.1×10^{1}
Zn	Tadpole (whole)	3	5.7×10^{2}	2.7×10^{0}	2.7×10^{2}	1.9×10^{3}
	Frog (muscle)	2	9.0×10^{2}		2.0×10^{2}	1.5×10^{3}
	Frog (carcass)	2	1.0×10^{4}		9.5×10^{3}	1.1×10^{4}

[a] For *N* = 2, the mean is the arithmetic mean.

[b] GSD: Geometric standard deviation.

TABLE 59. SUMMARY OF SEDIMENT TO BIOTA CONCENTRATION RATIOS ($CR_{s\text{-}b}$) FOR WHOLE FRESHWATER INVERTEBRATES [200, 202]

Element	N	Mean	GSD[a]	Minimum	Maximum
Ag	40	7.3×10^{-1}	2.6×10^{0}	4.0×10^{-2}	7.1×10^{0}
Al	136	3.9×10^{-4}	3.9×10^{0}	9.5×10^{-6}	1.7×10^{-1}
As	139	1.5×10^{-1}	2.2×10^{0}	4.3×10^{-3}	5.7×10^{-1}
B	1	1.9×10^{-2}	—	—	—
Ba	137	1.6×10^{-2}	3.6×10^{0}	1.7×10^{-3}	1.7×10^{0}
Be	1	4.0×10^{-2}	—	—	—
Cd	115	7.9×10^{-1}	4.4×10^{0}	1.9×10^{-4}	9.7×10^{0}
Co	136	3.1×10^{-2}	2.0×10^{0}	3.7×10^{-3}	2.0×10^{-1}
Cu	149	4.7×10^{-1}	3.3×10^{0}	9.6×10^{-4}	3.3×10^{1}
Fe	140	3.4×10^{-3}	2.5×10^{0}	2.2×10^{-4}	3.5×10^{-1}
Hg	109	9.4×10^{-1}	3.5×10^{0}	5.6×10^{-2}	1.1×10^{1}
Mo	15	7.4×10^{-2}	1.7×10^{0}	3.6×10^{-2}	1.9×10^{-1}
Ni	131	2.1×10^{-2}	3.9×10^{0}	2.1×10^{-3}	1.6×10^{3}
Pb	75	9.6×10^{-3}	4.6×10^{0}	4.9×10^{-4}	4.5×10^{0}
Sb	1	1.5×10^{-1}	—	—	—
Se	103	1.3	2.2×10^{0}	6.5×10^{-2}	6.0×10^{0}
Sr	135	4.4×10^{-2}	3.0×10^{0}	1.9×10^{-3}	6.2×10^{-1}
Tl	1	2.3×10^{3}	—	—	—
U	6	1.7×10^{-2}	2.9×10^{0}	2.9×10^{-3}	6.4×10^{-2}
V	66	2.4×10^{-3}	2.1×10^{0}	5.3×10^{-4}	1.4×10^{-2}
Zn	151	5.2×10^{-1}	3.0×10^{0}	9.3×10^{-4}	2.3×10^{1}

[a] GSD: Geometric standard deviation.

9.3. RADIONUCLIDE PARTITIONING INTO EDIBLE BIOTIC TISSUES

9.3.1. Application of the specific activity model approach to aquatic ecosystems

Although accumulation factors are utilized to estimate the transfer of many radionuclides from environmental media to edible non-human biota, this approach is not applicable in cases where radionuclides have stable, non-decaying analogues that represent a relatively large proportion of the chemical composition of biotic tissues. In such situations, stable isotopes can essentially ‘dilute’ radioisotopes in the body. To account for this effect, a specific activity model can be applied which assesses concentrations of radionuclides relative to all isotopes of that element found in biotic tissues, such that:

$$SA_{m,r} = \frac{C_{m,r}}{C_{m,a}} \cdot C_{b,a} \tag{33}$$

TABLE 60. SUMMARY OF SEDIMENT TO BIOTA CONCENTRATION RATIOS ($CR_{s\text{-}b}$) FOR EDIBLE TISSUES OF FRESHWATER FISH [191, 193]

Element	Whole fish					Fish muscle					Fish liver				
	N	Mean[a]	GSD[b]	Minimum	Maximum	*N*	Mean	GSD	Minimum	Maximum	*N*	Mean	GSD	Minimum	Maximum
Ag	9	6.9×10^{-1}	3.5×10^{0}	1.2×10^{-1}	4.9×10^{0}	n.a.[c]	n.a.	n.a.	n.a.	n.a.	43	3.5×10^{-1}	3.2×10^{0}	2.4×10^{-2}	1.5×10^{1}
Al	113	9.0×10^{-3}	2.0×10^{1}	3.6×10^{-6}	4.3×10^{1}	15	6.0×10^{-3}	4.1×10^{0}	1.2×10^{-3}	9.3×10^{-2}	41	1.3×10^{-5}	2.6×10^{0}	2.2×10^{-6}	1.0×10^{-4}
As	226	1.4×10^{-1}	5.9×10^{0}	7.9×10^{-4}	6.6×10^{0}	13	2.7×10^{-1}	9.5×10^{0}	7.1×10^{-3}	13	56	1.9×10^{-2}	4.6×10^{0}	2.7×10^{-3}	4.4×10^{0}
Ba	103	4.9×10^{-2}	9.3×10^{0}	4.7×10^{-5}	1.9×10^{0}	3	1.2×10^{-1}	2.3×10^{0}	4.5×10^{-2}	2.0×10^{-1}	39	6.3×10^{-5}	2.4×10^{0}	1.9×10^{-5}	1.9×10^{-3}
Be	2	1.6×10^{-1}		1.3×10^{-1}	1.9×10^{-1}	n.a.	n.a.	n.a.	n.a.	n.a.	1	1.4×10^{-1}	n.a.	n.a.	n.a.
Ca	2	2.6×10^{2}		9.7×10^{1}	4.3×10^{2}	2		2.2×10^{1}	1.9	3.4×10^{1}	n.a.	n.a.	n.a.	n.a.	n.a.
Cd	134	1.3×10^{-1}	5.9×10^{0}	2.1×10^{-6}	3.2×10^{3}	20	6.1×10^{-1}	3.7×10^{0}	2.2×10^{-2}	3.3×10^{0}	72	4.7×10^{-1}	4.1×10^{0}	1.7×10^{-2}	1.4×10^{1}
Co	751	2.9×10^{-1}	4.3×10^{0}	7.1×10^{-4}	2.9×10^{1}	206	2.0×10^{-1}	4.4×10^{0}	3.0×10^{-4}	5.9×10^{0}	133	6.1×10^{-2}	1.1×10^{1}	1.3×10^{-3}	9.7×10^{1}
Fe	71	4.3×10^{-3}	9.7×10^{0}	9.3×10^{-7}	2.3×10^{-1}	3	3.9×10^{-3}	5.2×10^{0}	7.5×10^{-4}	2.0×10^{-2}	79	2.0×10^{-3}	3.4×10^{0}	3.3×10^{-4}	3.2×10^{0}
Hg	353	5.3×10^{0}	5.9×10^{0}	3.1×10^{-4}	1.3×10^{2}	129	7.3×10^{0}	6.5×10^{0}	2.3×10^{-2}	1.9×10^{2}	64	7.0×10^{-1}	4.4×10^{0}	3.0×10^{-2}	6.4×10^{1}
Mg	7	3.7×10^{0}	2.9×10^{0}	3.6×10^{-1}	9.0×10^{0}	2		1.1×10^{0}	7.3×10^{-1}	7.9×10^{-1}	n.a.	n.a.	n.a.	n.a.	n.a.
Mo	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6	2.0×10^{-2}	2.3×10^{0}	7.1×10^{-3}	6.0×10^{-2}
Na	2	4.6×10^{-2}		6.0×10^{-3}	9.6×10^{-2}	1	1.0×10^{1}	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	139	2.1×10^{-1}	5.4×10^{0}	2.9×10^{-3}	2.9	14	4.6×10^{-1}	4.0×10^{0}	4.1×10^{-2}	2.9×10^{0}	45	2.9×10^{-3}	2.7×10^{0}	2.6×10^{-4}	7.3×10^{-2}
Pb	365	2.9×10^{-1}	5.2×10^{0}	9.4×10^{-6}	6.3×10^{1}	20	1.1×10^{-1}	9.5×10^{0}	9.2×10^{-4}	1.2×10^{0}	21	2.2×10^{-3}	7.4×10^{0}	1.9×10^{-4}	4.4×10^{-1}
Sb	9	6.6×10^{-1}	5.3×10^{0}	4.9×10^{-2}	9.9	n.a.	n.a.	n.a.	n.a.	n.a.	2	2.4×10^{-1}		1.9×10^{-1}	2.9×10^{-1}
Se	61	1.6×10^{0}	3.4×10^{0}	9.4×10^{-2}	4.0×10^{1}	16	4.9×10^{0}	2.9×10^{0}	2.6×10^{-1}	1.6×10^{1}	73	1.0×10^{0}	2.3×10^{0}	2.1×10^{-1}	9.6×10^{0}
Sn	2	7.9×10^{-1}		7.5×10^{-1}	9.0×10^{-1}	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	35	1.4×10^{-2}	1.5×10^{1}	1.9×10^{-4}	9.5×10^{-1}	n.a.	n.a.	n.a.	n.a.	n.a.	71	4.7×10^{-4}	2.2×10^{0}	9.9×10^{-5}	2.6×10^{-3}
Ti	1	1.6×10^{-2}				n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Tl	13	2.9×10^{2}	5.6×10^{0}	6.9×10^{0}	2.9×10^{3}	1	7.5×10^{1}	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
V	29	2.1×10^{-3}	2.4×10^{0}	4.2×10^{-4}	1.3×10^{-2}	n.a.	n.a.	n.a.	n.a.	n.a.	51	1.3×10^{-3}	2.1×10^{0}	2.1×10^{-4}	5.4×10^{-3}
Zn	703	2.1×10^{0}	4.0×10^{0}	9.1×10^{-3}	1.3×10^{2}	179	1.1×10^{0}	4.1×10^{0}	1.1×10^{-3}	4.4×10^{1}	90	2.2×10^{-1}	4.9×10^{0}	5.3×10^{-3}	1.2×10^{2}

[a] For $N = 2$, the mean is the arithmetic mean.

[b] GSD: Geometric standard deviation.

[c] n.a.: Not available.

where $SA_{m,r}$ is the specific activity of a given radionuclide, r, in a given environmental medium, m; $C_{m,r}$ is the concentration of a given radioisotope, r, in a given environmental medium, m; $C_{m,a}$ is the concentration of all isotopes of a given element, a, in that same environmental medium, m; and $C_{b,a}$ is the concentration of all isotopes of a given element, a, in a given type of biota or tissue. This approach inherently assumes that the organism is at steady state with its environment, whereby the ratio of the radioisotope of interest relative to all isotopes in the reference environmental medium m is equal to the ratio of the radioisotope to all isotopes in the biota or tissue being considered.

Notable examples of radionuclides for which a specific activity model should be used include tritium, ^{14}C and ^{36}Cl, which are discussed in Section 10. A specific activity approach can also be applied for radionuclides that are analogues to stable elements that have high concentrations in tissues or whole organisms. For example, this is the case for ^{90}Sr and other bivalent cations which are being exchanged for calcium in bone and other hard tissues [204–206].

The fish to water CR for radiocaesium and radiostrontium can be tabulated accounting for the inverse relationship between the CR and the analogous potassium and calcium concentration, respectively, in the surrounding water [207–209].

For radiocaesium in predatory/omnivorous fishes, the CR can be estimated using the following equation [209]:

$$CR(\text{predatory/omnivorous}) = \frac{4880}{[K^+]} \tag{34}$$

where $[K^+]$ is the concentration of potassium (K^+) in lake water (in mg L^{-1}).

For non-predatory fishes, the following relationship can be applied:

$$CR(\text{non-predatory}) = \frac{3290}{[K^+]} \tag{35}$$

Similarly, strontium concentrations can be tabulated based on calcium concentrations in water ([Ca], in mg L^{-1}), since both elements behave in a similar manner, primarily partitioning in the bony parts of aquatic biota (e.g. skeleton, head, fins, bone, fish scales), as follows [198, 207]:

$$CR(\text{muscle}) = \exp(5.2 - 1.2 \ln[\text{Ca}]) \tag{36}$$

$$CR(\text{bone}) = \exp(9.7 - 1.2 \ln[\text{Ca}]) \tag{37}$$

Assuming that 20% of the wet weight of a fish is composed of bony parts, the whole fish *CR* can be estimated using the following equation [199]:

$$CR(\text{whole fish}) = \exp(9.13 - 1.2 \ln[\text{Ca}]) \tag{38}$$

An important consideration in the application of specific activity models is the choice of environmental medium. Indeed, in some instances, organisms may obtain their supplies of an element from multiple sources, for example, from both water and sediments. In such cases, the specific activity in the organism will be some weighted average of the specific activities in the source media, and this weighted average may vary in time and space depending on the relative availability of the different sources.

9.3.2. Parameters for radionuclide partitioning into edible biotic tissues

Depending on the species, radionuclide and tissue under consideration, it may be necessary to estimate the per cent radionuclide loading in specific edible tissues and/or, in cases where whole organisms are consumed, to estimate the radionuclide load in the whole body of an organism based on data that have been collected for individual tissues [210–212].

Such calculations require biomass estimates for biota and their internal components, and concentration measurements for each tissue, as follows:

$$\begin{aligned}\text{Per cent loading in tissue} &= \frac{C_{tissue} \cdot m_{tissue}}{C_{whole} \cdot m_{whole}} \cdot 100\% \\ &= \frac{C_{tissue} \cdot C_{\text{Reference Tissue}} \cdot m_{tissue}}{C_{whole} \cdot m_{whole}} \cdot 100\% \end{aligned} \tag{39}$$

where C_{tissue} is the element concentration in a given tissue (in mg kg^{-1} fresh weight or Bq kg^{-1} fresh weight); m_{tissue} is the mass of that tissue (in kg fresh weight); C_{whole} is the element concentration in the whole organism (in mg kg^{-1} fresh weight or Bq kg^{-1} fresh weight); m_{whole} is fresh weight (in kg); CR_{tissue} is the concentration ratio of the tissue of interest relative to the reference tissue for a given type of biota (based on data from the literature); and $C_{Reference\ Tissue}$ is the concentration of the element of interest measured in the reference tissue (i.e. muscle).

With such information, it becomes possible to estimate the concentration of a given radionuclide in whole fish based on measurements taken for fish muscle tissue, for example, which could be relevant for fish species that humans eat whole. Available information and parameter values for various types of freshwater biota, as well as the data selection criteria that were applied in their development, are summarized in the accompanying TECDOC [5].

9.4. APPLICATION OF DATA

The process of interaction of dissolved radionuclides with solid particles, either in suspension or deposited, is usually modelled according to the 'K_d concept', where K_d is the 'particulate form/dissolved form' partition coefficient based on the hypothesis of a reversible and rapid equilibration between the dissolved and the adsorbed radionuclides. However, this is not generally and rigorously true for every radionuclide. The equilibrium between the concentrations of the dissolved radionuclides and the attached phases may be not instantaneously achieved, and the adsorption and desorption processes are not always rapidly reversible [213, 214].

Although it is generally recognized that accumulation of radionuclides by edible aquatic organisms is a dynamic process, many contaminant bioaccumulation models assume that the aquatic organisms are in equilibrium with reference media, such as water or sediments. In such models, radionuclide accumulation in aquatic biota can be represented by simplified ratios that relate radionuclide concentrations in biotic tissues to concentrations in the reference media (water or sediments).

Radionuclide bioaccumulation factors are often highly variable, being influenced by such factors as water chemistry, and fish feeding rate, size and position on the food chain. It is recommended that, where possible, estimates of radionuclides in water be used to predict accumulation in fish (i.e. that the *CR* be used), as these estimates are expected to be more reliable than fish–sediment accumulation factors. In most cases, radionuclide activity concentrations in the aquatic food chain are controlled by activity concentrations in water, although for sediment dwelling organisms and benthic (bottom dwelling) fish, the sediments may of course play an important role.

10. SPECIFIC ACTIVITY MODELS AND PARAMETER VALUES FOR TRITIUM, ^{14}C AND ^{36}Cl

The data for parameter values described in the previous sections are based on element partitioning and accumulation concepts, which are expressed quantitatively in terms of transfer factors that describe the transport of radionuclides between different environmental compartments. Under equilibrium conditions, the specific activity model provides an alternative approach for long lived isotopes of biologically regulated, essential elements that are highly mobile in the environment. The specific activity of a given radionuclide is defined as the activity per unit mass of the corresponding stable element. Specific activity models are used here for tritium, ^{14}C and ^{36}Cl, based on the environmental behaviour of the stable elements hydrogen, carbon and chlorine, respectively.

In the specific activity model, the radioisotope of interest is assumed to mix physically and chemically with its corresponding stable element within some compartment of the environment, resulting in a certain specific activity. Any organism drawing the stable element from this compartment draws the radioisotope in proportion, and attains the same specific activity as the source compartment. Isotopic exchange with relatively uncontaminated pools of the stable element results in progressive dilution of the isotope with distance from the source.

A brief description of specific acitivity models and parameter values for the transfer of tritiated water (HTO) and ^{14}C through the environment following release to air and water, and for the transfer of ^{36}Cl to animal products, is given below. More details on these models can be found in the accompanying TECDOC [5], which also discusses models and parameter values for the environmental transfer of tritiated hydrogen gas (HT) following release to air, and for HTO and ^{14}C transfer from contaminated soils.

10.1. TRITIUM

Following traditional usage, the specific activity model for tritium is formulated in terms of the tritium concentration in water rather than the ratio of tritium activity to the mass of hydrogen in a given compartment. The concentration of organically bound tritium (OBT, the tritium fixed in the organic matter of plants and animals) is expressed as the activity in the water equivalent of the dry matter (the water produced by complete combustion of the dry material).

10.1.1. Release of HTO to air

HTO released to the atmosphere mixes with air moisture and exchanges with water pools in plants, soil and animals. Tritium is transferred from air to soil through wet and dry deposition from the airborne plume. Here, the soil water concentration (C_{sw}, Bq L^{-1}) is given by:

$$C_{sw} = CR_{s-a}\, C_{air}/H_a \tag{40}$$

where C_{air} (Bq m^{-3}) is the concentration in air (assumed to be known through measurement or modelling), $CR_{s\text{-}a}$ is an empirical constant and H_a is the absolute humidity (L m^{-3}). Equation (40) may underestimate the soil concentration close to an elevated source where air concentrations are low or zero but where soil concentrations are high due to wet deposition from the elevated plume. This is not a serious restriction in practice because the model is usually applied to members of the public, who are located far enough from the source that the plume has already descended to the ground.

$CR_{s\text{-}a}$ is difficult to estimate, and it depends on a number of local factors. The geometric mean of the available data [215, 216] is 0.23, but a slightly larger value (0.3) is used as the reference value because of the uncertainties involved. A value of 0.5 is likely to be conservative, although values as high as 1.0 are possible. The data suggest that southern or wetter regions may have higher $CR_{s\text{-}a}$ values. Values based on local measurements should be used, wherever possible.

The recommended $CR_{s\text{-}a}$ value is shown in Table 61, which gathers together, for the ease of the user, values for all parameters in the tritium and ^{14}C models for which fixed values are suggested.

The HTO concentration in fresh weight plant material (C_{ffw}^{HTO}, Bq kg^{-1} fresh weight) is calculated using a model [217] that explicitly considers contributions to the plant from air moisture (via diffusion through the stomates) and soil water (via the transpiration stream):

$$C_{pfw}^{HTO} = WC_p \left[RH \frac{C_{air}}{H_a} + (1 - RH) C_{sw} \right] / \gamma \tag{41}$$

Here, WC_p is the fractional water content of the plant (L kg^{-1} fresh weight), RH is the relative humidity and $\gamma = 0.909$ is the ratio of the HTO vapour pressure to that of H_2O.

The partitioning between air and soil in Eq. (41) in terms of relative humidity applies specifically to plant leaves, which draw the majority of their tritium from the air. The equation is conservative for fruits, tubers and root crops, which draw a larger fraction of their tritium from the soil, which has a lower concentration than air moisture for an atmospheric release.

Relative and absolute humidities are commonly measured by national weather services, and site specific values for these parameters are usually readily available and are preferred. Water content values for a number of broad plant categories are listed in Table 62.

These are the same categories defined in Section 4, except that some groups have been combined (leafy with non-leafy vegetables, cereals with rice, and grass with fodder and pasture), and the categories for herbs and ‘other’ plants are not

TABLE 61. MODEL PARAMETERS FOR WHICH FIXED VALUES ARE SUGGESTED

Parameter	Symbol	Equation	Value	Unit
Soil water to air moisture ratio for HTO	$CR_{s\text{-}a}$	40	0.3[a]	Dimensionless
Partition factor for plants	R_p	42	0.54	Dimensionless
Water content of fish	WC_f	45	0.78	L kg^{-1} fresh weight
Partition factor for fish	R_f	46	0.66	Dimensionless
Water equivalent factor for fish	WEQ_f	46	0.65	L kg^{-1} dry weight
Stable carbon content of air	S_{air}	47	0.20	g C m^{-3}
Fraction of feed that is contaminated	f_c	48	1.0[a]	Dimensionless
Stable carbon content of fish	S_f	49	117	g C kg^{-1} fresh weight

[a] Nominal value; a site specific value should be used, if available.

TABLE 62. WATER CONTENT VALUES (WC_p, L kg^{-1}, fresh weight) FOR TERRESTRIAL PLANTS [218–228]

Plant category	N	Geometric mean	Geometric standard deviation	Minimum	Maximum
Leafy and non-leafy vegetables	88	0.92	1.0	0.84	0.97
Leguminous vegetables:					
Seed	11	0.12	1.2	0.09	0.17
Vegetative mass	16	0.81	1.1	0.69	0.91
Root crops	39	0.87	1.1	0.77	0.95
Tubers	10	0.75	1.1	0.62	0.82
Fruit	102	0.85	1.1	0.73	0.96
Grass, fodder, pasture	33	0.76	1.1	0.67	0.90
Cereals (including rice)	22	0.12	1.2	0.10	0.16
Maize:					
Sweetcorn	4	0.71	1.1	0.68	0.76
Feed corn	11	0.16	1.5	0.10	0.25
Silage	13	0.66	1.2	0.55	0.82

considered. The dry matter contents reported in Appendix I for individual species have been synthesized, converted to water contents and combined with data from other sources to produce the values in Table 62. These values apply to the edible part of the plant as harvested. Some grasses are dried before use as animal feed, in which case their water contents become more representative of the value for cereals (0.12). A value for silage is also provided, since this is commonly used for animal feed.

The OBT concentration in the combustion water of the plant dry matter is the same as that in the free water of the leaves reduced by a partition factor, R_p, that accounts for isotopic effects and the presence of exchangeable hydrogen in the combustion water. The OBT concentration in the fresh weight plant (C_{pfw}^{OBT}, Bq kg^{-1}) is given by:

$$C_{pfw}^{OBT} = (1 - WC_p) WEQ_p R_p C_{pfw}^{HTO} / WC_p \tag{42}$$

where R_p is a partition factor and WEQ_p is the water equivalent factor (kg of water produced per kg dry weight combusted). R_p values must be determined empirically for steady state conditions. The most reliable estimates come from controlled laboratory experiments, where the plant is exposed to an HTO concentration that is held constant or monitored continuously. The values obtained in such experiments [229–231] are all less than 1, with a geometric mean of 0.54 and a geometric standard deviation of 1.16 for the crops considered (maize, barley and alfalfa). In the absence of other information, a value of 0.54 is assumed to apply to all plant types (Table 61). Regardless of the plant in question, the plant concentration used in Eq. (42) should be the concentration in the plant leaves, the primary location of dry matter production.

The water equivalent factor is difficult to measure but can be calculated reliably from the hydrogen contents of protein, fat and carbohydrate (7, 12 and 6.2%, respectively) and the fractions of protein, fat and carbohydrate in the dry matter of the plant in question. The calculated values, which are shown in Table 63, vary little among the various plant categories.

Animals can ingest tritium as HTO in feed and drinking water and as OBT in the organic fraction of feed. Inhalation and skin absorption are also possible routes of HTO intake. Exchangeable organic tritium and HTO rapidly equilibrate with body water. Most of the HTO taken in by an animal remains as HTO in its body, with a small fraction converted to OBT. In contrast, about half the OBT taken in is converted to HTO, with the other half remaining in organic form.

TABLE 63. WATER EQUIVALENT FACTORS (WEQ_p, L kg^{-1} dry weight) FOR TERRESTRIAL PLANTS
(calculated from data in Refs [221, 224, 228])

Plant category	*N*	Geometric mean	Geometric standard deviation	Minimum	Maximum
Leafy vegetables	10	0.51	1.1	0.47	0.55
Non-leafy vegetables	12	0.53	1.0	0.50	0.55
Root crops	11	0.52	1.1	0.45	0.55
All others	91	0.56	1.0	0.50	0.60

Here, concentrations in animal products are based on a metabolic model [232], the output of which is the ratio CR_a of the concentration in the animal product to the concentration in the feed, drinking water and inhaled air. Separate ratios are determined for HTO and OBT intakes. The total tritium concentrations (HTO + OBT) in the animal product are given by:

$$C_{afw}^{T\_HTO} = CR_a^{HTO} CR_f^{HTO} \tag{43}$$

$$C_{afw}^{T\_OBT} = CR_a^{OBT} CR_f^{OBT} \tag{44}$$

where $C_{afw}^{T\_HTO}$ is the total tritium concentration in the animal product from HTO intake (Bq kg^{-1} fresh weight), CR_a^{HTO} is the concentration ratio for HTO intake ((Bq kg^{-1} fresh weight)/(Bq L^{-1})), CR_f^{HTO} is the average HTO concentration in ingested water (Bq L^{-1}), $C_{afw}^{T\_OBT}$ is the total tritium concentration in the animal product from OBT intake (Bq kg^{-1} fresh weight), CR_a^{OBT} is the concentration ratio for OBT intake ((Bq kg^{-1} fresh weight)/(Bq kg^{-1} dry weight)), and CR_f^{OBT} is the average OBT concentration in feed (Bq kg^{-1} dry weight).

CR_f^{HTO} is the sum of the HTO concentrations in the water taken in with feed, drink and respiration (including skin absorption), weighted by the fractional contribution of each of these sources to the total water intake. Generally speaking, inhalation contributes about 2–5% of the total water intake of the animal, and metabolic water about 10%. The fraction of water coming from the diet varies among practices and must be user defined. CR_f^{OBT} is a weighted average that includes uncontaminated as well as contaminated feed, since local sources supply only a fraction of the total animal feed in modern industrial farming.

Representative concentration ratios for a number of animal products for temperate climates are given in Tables 64 and 65.

For a given product, the central value of the concentration ratio pertains to the specific mass, production rate and intake rate shown in the table. The ranges were derived by considering the variability in animal mass, production level and diet under temperate climate conditions. Larger values are conservative and should be used for animals that are raised in cold climates or have high fat content in their products.

The OBT concentration in the animal product can be found by multiplying the total concentration by f_{OBT} from Tables 64 and 65, where f_{OBT} is the fraction of the total tritium in the animal product in the form of OBT; the HTO concentration is found by multiplying the total concentration by $(1-f_{OBT})$.

TABLE 64. CONCENTRATION RATIOS FOR HTO INTAKE (CR_a^{HTO}) [232]

Product	Animal mass (kg)	Intake rate (kg d^{-1})	Production rate (kg d^{-1} or L d^{-1})	Fraction OBT (f_{OBT})	CR_a^{HTO}(Bq kg^{-1} fresh weight product per Bq L^{-1} intake)		
					Best estimate	Minimum	Maximum
Milk							
Cow	550	14	15	0.04	0.87	0.81	0.92
Sheep	50	1.8	1.3	0.06	0.78	0.76	0.89
Goat	50	2.5	2.5	0.07	0.83	0.81	0.87
Meat							
Beef	500	9.3	0.7	0.11	0.66	0.64	0.82
Veal	160	4.85	0.8	0.08	0.69	0.64	0.82
Mutton	50	1.22	0.08	0.1	0.74	0.67	0.78
Lamb	20	1.0	0.2	0.08	0.78	0.60	0.81
Goat	50	1.2	0.08	0.1	0.67	0.62	0.81
Pork	100	2.7	0.8	0.13	0.67	0.61	0.77
Hen	2.5	0.12	0.01	0.1	0.76	0.70	0.80
Broiler	1.7	0.11	0.03	0.1	0.76	0.70	0.90
Egg	2.5	0.15	0.05	0.08	0.76	0.63	0.81

TABLE 65. CONCENTRATION RATIOS FOR OBT INTAKE (CR_a^{OBT}) [232]

Product	Animal mass (kg)	Intake rate (kg d^{-1})	Production rate (kg d^{-1} or L d^{-1})	Fraction OBT (f_{OBT})	CR_a^{OBT} (Bq kg^{-1} fresh weight product per Bq L^{-1} dry weight intake)		
					Best estimate	Minimum	Maximum
Milk							
Cow	550	14	15	0.47	0.24	0.17	0.37
Sheep	50	1.8	1.3	0.57	0.32	0.23	0.39
Goat	50	2.5	2.5	0.40	0.32	0.25	0.38
Meat							
Beef	500	9.3	0.7	0.80	0.40	0.35	0.53
Veal	160	4.85	0.8	0.72	0.35	0.31	0.45
Mutton	50	1.22	0.08	0.75	0.40	0.35	0.56
Lamb	20	1.0	0.2	0.78	0.55	0.35	0.67
Goat	50	1.2	0.08	0.60	0.43	0.36	0.46
Pork	100	2.7	0.8	0.74	0.64	0.45	0.77
Hen	2.5	0.12	0.01	0.55	0.50	0.42	0.60
Broiler	1.7	0.11	0.03	0.55	0.50	0.42	0.70
Egg	2.5	0.15	0.05	0.78	0.64	0.53	0.69

10.1.2. Release of HTO to water bodies

Fish are the only aquatic organisms considered here, since they are the only aquatic organisms that play a major role in the human diet. The assumption of full specific activity equilibrium is a good approximation to HTO concentrations in most aquatic compartments [233, 234]. The water pools to which freshwater fish are exposed, including lake water and water derived from foods at different trophic levels, all have similar HTO concentrations. This implies that the HTO concentration in the fresh weight fish (C_{ffw}^{HTO}, Bq kg^{-1}, fresh weight) is given by:

$$C_{ffw}^{HTO} = WC_f \cdot C_w \tag{45}$$

where C_w (Bq L^{-1}) is the HTO concentration in the water column (assumed to be known through measurement or modelling) and WC_f is the fractional water content of the fish (L kg^{-1} fresh weight). The water content is roughly constant at 0.78 for most fish that form part of the human diet [221] (see Table 61).

Because fish are immersed in an environment of uniform HTO concentration, it is reasonable to assume that the OBT concentration in the combustion water of the fish is the same as the HTO concentration, apart from a partition factor that takes account of the presence of exchangeable hydrogen in the combustion water and of isotopic effects arising both in the fish and in the different components of its food and water intakes. The OBT concentration in the fresh weight fish is given by:

$$C_{ffw}^{OBT} = (1 - WC_f) \cdot WEQ_f \cdot R_f \cdot C_w \tag{46}$$

where WEQ_f is the water equivalent factor of the fish and R_f is the partition factor.

Values of R_f must be determined empirically. The data for steady state conditions have a geometric mean of 0.66, which is the reference value for all fish, and a geometric standard deviation of 1.5 [233–238]. The water equivalent factor is difficult to measure but can be calculated reliably from the hydrogen contents of protein, fat and carbohydrate (7%, 12% and 6.2%, respectively) and the fractions of protein, fat and carbohydrate in the fish in question. The calculated values for four fish species [221] show a small geometric standard deviation of 1.06, and the geometric mean of 0.65 is the reference value for generic assessments (see Table 61).

10.2.1. Release of ^{14}C to air

The assumption of full specific activity equilibrium throughout the terrestrial environment is completely satisfactory for ^{14}C releases to the atmosphere if, as is usual, the ^{14}C is emitted as $^{14}CO_2$. Accordingly, the ^{14}C concentration in Bq g^{-1} stable carbon is the same in the plant as it is in air, and the ^{14}C concentration in the fresh weight plant (C_{pfw}, Bq kg^{-1} fresh weight) is given by:

$$C_{pfw} = \frac{C_{air} \cdot S_p}{S_{air}} \tag{47}$$

where S_p is the concentration of stable carbon in the plant (g C kg^{-1} fresh weight), C_{air} is the concentration of ^{14}C in air (Bq m^{-3}) (assumed to be known through measurement or modelling), and S_{air} is the concentration of stable carbon in air (g C m^{-3}). The only parameters required for the model are the stable carbon concentrations in air and in the plants of interest. S_{air} is currently about 0.20 g/m^3 (see Table 61). Measured values of the carbon contents for the various plant categories are shown in Table 66. The data are augmented by values calculated from the carbon contents of protein, fat and carbohydrate (52%, 77% and 42%, respectively) and the fractions of protein, fat and carbohydrate in the plant [221].

Similarly, the ^{14}C concentration in animal products (C_{afw}, Bq kg^{-1} fresh weight) is given by:

$$C_{afw} = \frac{f_c \cdot C_{pfw} \cdot S_a}{S_p} \tag{48}$$

where f_c is the fraction of animal feed that is contaminated and S_a is the concentration of stable carbon in the animal product (g C kg^{-1} fresh weight). S_p values are given in Table 66.

The factor f_c is introduced to allow for the fact that animals may be fed supplementary concentrates or feed from remote sources that are uncontaminated. The f_c value should be set based on consideration of local farming practices; if a site specific value is not available, f_c should be conservatively set to 1 (see Table 61).

The carbon contents of various animal products are shown in Table 67. A few of these values were measured directly [239, 241], but most were calculated

TABLE 66. CONCENTRATION OF STABLE CARBON IN TERRESTRIAL PLANTS (S_p)

(*from Refs [221, 224, 228, 239–241]*)

Plant category	Stable carbon content (g C kg^{-1} fresh weight)				
	N	Geometric mean	Geometric standard deviation	Minimum	Maximum
Leafy and non-leafy vegetables	49	3.0×10^{1}	1.40	1.8×10^{1}	6.5×10^{1}
Leguminous vegetables:					
Seed	7	4.1×10^{2}	1.08	3.8×10^{2}	4.7×10^{2}
Vegetative mass	5	5.9×10^{1}	1.46	4.1×10^{1}	1.1×10^{2}
Root crops	23	4.6×10^{1}	1.46	2.2×10^{1}	9.5×10^{1}
Tubers	6	10.3×10^{2}	1.20	8.6×10^{1}	1.3×10^{2}
Fruit	48	6.2×10^{1}	1.27	3.1×10^{1}	1.0×10^{2}
Grass, fodder, pasture	25	1.0×10^{2}	1.31	4.0×10^{1}	1.6×10^{2}
Cereals (including rice)	29	3.9×10^{2}	1.05	3.6×10^{2}	4.3×10^{2}
Maize:					
Sweet corn	3	1.2×10^{2}	1.00	1.2×10^{2}	1.2×10^{2}
Feed corn	1	3.8×10^{2}	—	—	—
Silage	13	1.3×10^{2}	1.42	6.5×10^{1}	1.8×10^{2}

TABLE 67. CONCENTRATION OF STABLE CARBON IN TERRESTRIAL ANIMAL PRODUCTS (S_a)

Animal product	Stable carbon content (g C kg^{-1} fresh weight)				
	N	Geometric mean	Geometric standard deviation	Minimum	Maximum
Milk					
Cow	8	6.5×10^{1}	1.03	6.2×10^{1}	6.9×10^{1}
Sheep	1	1.1×10^{2}	—	—	
Goat	1	7.1×10^{1}	—	—	
Meat					
Beef	14	2.0×10^{2}	1.19	1.6×10^{2}	2.9×10^{2}
Veal	3	1.6×10^{2}	1.21	1.3×10^{2}	1.9×10^{2}
Mutton	1	2.9×10^{2}	–	–	
Lamb	2	2.8×10^{2}	1.26	2.3×10^{2}	3.2×10^{2}
Goat	1	1.7×10^{2}	—	—	
Pork	12	3.0×10^{2}	1.39	1.7×10^{2}	5.5×10^{2}
Hen	1	2.4×10^{2}	—	—	
Broiler	5	1.5×10^{2}	1.23	1.1×10^{2}	2.0×10^{2}
Egg	2	1.6×10^{2}	1.01	$1.\ 6\times10^{2}$	1.6×10^{2}

from the carbon contents of protein, fat and carbohydrate and the fractions of protein, fat and carbohydrate in the product [221].

10.2.2. Release of ^{14}C to water bodies

Modelling ^{14}C in aquatic systems is complicated by the existence of several carbon pools. Here, the fish are assumed to be in full specific activity equilibrium with dissolved inorganic carbon (*DIC*):

$$C_{ffw} = C_{DIC} \cdot S_f \tag{49}$$

where C_{ffw} is the ^{14}C concentration in fresh weight fish (Bq kg^{-1} fresh weight), C_{DIC} is the ^{14}C concentration in *DIC* in the water column (Bq gC^{-1}) (assumed to be known through measurement or modelling), and S_f (g C kg^{-1} fresh weight) is the concentration of stable carbon in the fish.

As was the case for terrestrial animal products, the carbon contents of fish are most reliably determined from the carbon contents of protein, fat and carbohydrate, and the fractions of protein, fat and carbohydrate in the fish [221]. The calculated values have a relatively low geometric standard deviation of 1.18, and the geometric mean of 117 g C kg^{-1} fresh weight is the reference value for use with all species (see Table 61).

10.3. CHLORINE-36

As in the case of ^{3}H and ^{14}C, specific activity modelling for ^{36}Cl takes advantage of stable element contents in the environment and isotopic equilibrium between compartments to generate reliable estimates of ^{36}Cl concentrations. Specific activity is especially important for ^{36}Cl, owing to the lack of discrimination among chlorine isotopes by organisms and the large amount of stable chlorine available for dilution.

Studies of the transfer of ^{36}Cl to beef and to cow's milk have shown that the isotopic ratio in animal products is the same as that in their foodstuffs [242]. The average equilibrium chlorine isotopic ratio in the daily dietary intake can therefore be used to predict the contamination of animal products with ^{36}Cl, as long as the different inputs are well defined. The specific activity in the animal product is given by:

$$\frac{C_{animal}}{S_{animal}} = \frac{q_{water} \cdot C_{water} + q_{foodstuff} \cdot C_{foodstuff}}{q_{water} \cdot S_{water} + q_{foodstuff} \cdot S_{foodstuff}} \tag{50}$$

where q is the intake rate (L d^{-1} or kg, fresh weight, d^{-1}), C is the ^{36}Cl concentration (Bq L^{-1} or Bq kg^{-1} fresh weight) and S is the stable chlorine concentration (g L^{-1} or g kg^{-1} fresh weight). All inputs of stable chlorine to each environmental compartment (fertilizers for plants, salt licks for animals, etc.) should be taken into account in the model, if they contribute significantly to dilution.

Table 68 lists stable chlorine concentrations for various environmental compartments for use in specific activity modelling. These correspond to the means of the data in the literature. They should be used with caution and only when site specific data are not available.

TABLE 68. STABLE INORGANIC CHLORINE CONTENT IN ENVIRONMENTAL MEDIA [243–247]
(*as summarized in Ref. [248]*)

Environmental media/object	Content	Unit	Environmental media/object	Content	Unit
Air[a]			Root vegetables	0.50	g/kg
Gaseous	0.06	mg/m^3	Beet	1.30	g/kg
Aerosol	0.03	mg/m^3	Sugar beet	0.35	g/kg
Water[a]	0.010	g/L	Potatoes	1.00	g/kg
Groundwater[b]	0.016	g/L	Red beet	0.60	g/kg
River[c]	0.007	g/L	Carrot	0.50	g/kg
Rain[d]	0.011	g/L	Celery	0.50	g/kg
Soil	0.2	g/kg (dry weight)	Turnip	0.55	g/kg
Terrestrial plants			Onion	0.25	g/kg
Cereals (grains)	0.50	g/kg (fresh weight)	Radish	0.30	g/kg
Oat	0.50	g/kg	Horseradish	0.17	g/kg
Wheat	0.50	g/kg	Rutabaga	0.30	g/kg
Maize	0.45	g/kg	Salsify	0.31	g/kg
Millet (bird seed)	0.19	g/kg	Leafy vegetables		
Barley	1.04	g/kg	Artichoke	0.22	g/kg
Rice	0.23	g/kg	Celery	1.37	g/kg
Saracen	0.30	g/kg	Cabbage	1.08	g/kg
Cereals (flour)			Brussels sprout	0.10	g/kg
Oat	0.49	g/kg	Cauliflower	0.29	g/kg
Wheat	0.50	g/kg	Red cabbage	0.45	g/kg
Fruits and nuts	0.50	g/kg	Chives	0.43	g/kg
Apricot	0.02	g/kg	Watercress	1.00	g/kg
Almond	0.20	g/kg	Endive	0.71	g/kg
Pineapple	0.30	g/kg	Spinach	0.75	g/kg
Peanut	0.17	g/kg	Curled salad	0.25	g/kg
Eggplant	0.50	g/kg	Lettuce	0.50	g/kg

TABLE 68. STABLE INORGANIC CHLORINE CONTENT IN ENVIRONMENTAL MEDIA [243–247] (*as summarized in Ref. [248]*) (cont.)

Environmental media/object	Content	Unit	Environmental media/object	Content	Unit
Fruits and nuts			Leafy vegetables		
Banana	1.00	g/kg	Corn salad	0.10	g/kg
Nectarine	0.05	g/kg	Sorrel	0.60	g/kg
Cherry	0.03	g/kg	Parsley	1.25	g/kg
Chestnut	0.10	g/kg	Dandelion	1.00	g/kg
Lemon	0.03	g/kg	Leek	0.40	g/kg
Pumpkin	0.18	g/kg	*Animal products*		
Quince	0.02	g/kg	Milk	1.00	g/L
Cucumber	0.27	g/kg	Human	0.40	g/L
Pickle	0.27	g/kg	Cow	1.00	g/L
Courgette	0.18	g/kg	Sheep	1.00	g/L
Date	2.50	g/kg	Buffalo	0.62	g/L
Fig	0.16	g/kg	Camel	1.05	g/L
Strawberry	0.12	g/kg	Goat	0.50	g/L
Raspberry	0.22	g/kg	Horse	0.30	g/L
Guava	0.45	g/kg	Eggs	1.20	g/kg
Currant	0.10	g/kg	Meat	0.75	g/kg
Bean	0.23	g/kg	Beef	0.70	g/kg
Mandarin	0.02	g/kg	Horse	0.09	g/kg
Melon	0.43	g/kg	Mutton	1.00	g/kg
Blackberry	0.20	g/kg	Lamb	0.85	g/kg
Medlar	0.03	g/kg	Veal	0.75	g/kg
Coconut	1.17	g/kg	Pork	0.60	g/kg
Olive	0.04	g/kg	Turkey	1.20	g/kg
Grapefruit	0.02	g/kg	Chicken	0.60	g/kg
Watermelon	0.08	g/kg	Pig liver	0.90	g/kg
Peach	0.03	g/kg	Aquatic plants	0.50	g/kg
Pear	0.02	g/kg	*Aquatic animals*		
Pea	0.36	g/kg	Freshwater fish	1.00	g/kg
Bell pepper	0.19	g/kg	Bream	1.22	g/kg
Apple	0.03	g/kg	Pike	1.00	g/kg
Plum	0.05	g/kg	Perch	0.85	g/kg
Grape	0.03	g/kg	Tench	0.95	g/kg
Rhubarb	0.53	g/kg	Trout	1.00	g/kg
Tomato	0.40	g/kg	Freshwater invertebrates	1.00	g/kg

[a] Dependent on distance from the sea.
[b] Variation: 0.001–0.070.
[c] Variation: 0.001–0.035.
[d] Variation: 0.001–0.020.

10.4. APPLICATION OF DATA

The specific activity concepts upon which the tritium, ^{14}C and ^{36}Cl models depend are theoretically sound for long term safety assessments with constant release rates. However, the models do not apply to short term (accidental) releases where concentrations are time dependent. For example, the ^{36}Cl content of soils varies by more than an order of magnitude between winter and the growing season, and plant uptake depends on the growth stage. This contributes some uncertainty to the predictions of ^{36}Cl concentrations in animal products calculated using the specific activity approach.

In applying the models, all inputs of the stable and active forms of the isotope to each environmental compartment must be taken into account. For example, the stable chlorine taken up by animals from salt licks should be accounted for in calculating ^{36}Cl concentrations.

11. FOOD PROCESSING

11.1. DEFINITIONS AND PROCESSES

The concentration of radionuclides in food can be affected by food processing activities, for example, radionuclide extraction during boiling, removal of certain parts of the raw food (e.g. bran, peel, shell, bone) and drying or dilution [3, 249]. Neglecting radionuclide losses during food processing can lead to overestimation of the calculated dose. Technological food processing allows significant reduction in the radionuclide contamination of foodstuffs. This reduction can be achieved by many of the normal practices used in the preparation, cooking and processing of food. The effects of technological processing on contaminated food depend on the radionuclide, the type of foodstuff and the method of processing. The effectiveness of radionuclide removal from raw material during processing can vary widely; however, processing of raw materials of vegetable and animal origin is often considered the most effective countermeasure for reducing the radioactive contamination of the foodstuff to or below permissible levels, and can be applied both domestically and in industrial processing of food [249–254].

In reporting the quantitative results of food processing, the following food processing transfer parameters are applied: the food processing retention factor, F_r, is the fraction of radionuclide activity that is retained in the food after processing; the processing efficiency, P_e, is the ratio of the fresh weight of the processed food to the weight of the original raw material; the processing factor[1], P_f, for a foodstuff is the ratio of the radionuclide activity concentrations (analogous to the concentration ratio).

There is a simple relationship among these three factors. F_r is the product of P_f and P_e:

$$F_r = P_f \cdot P_e \tag{51}$$

Application of these various factors is illustrated here with reference to caesium and strontium. Thus, an F_r value of 0.4 for caesium in boiled meat indicates that only 40% of the caesium in raw meat is retained after boiling and that 60% is removed into the boiling liquid (see Table 74). In the case of dairy products (see Table 75), the yield of each product is important. For example, an F_r value of 0.61 for strontium in goat cheese indicates that 39% is removed by the conversion of goat's milk to cheese, but, owing to the 12% yield of cheese, the concentration of strontium in goat cheese is 0.61/0.12 = 5 times the concentration in goat's milk. Therefore, the processing factor (P_f) is 5 [3].

F_r values for animal food products are all based on contamination in vivo. All data on plants refer to contamination of the edible product, generally contaminated via root uptake followed by translocation. However, often the radionuclide transfer factors from soil to plant are experimentally determined and reported for the washed and peeled vegetables and fruits (e.g. for potato). In this case, application of the radionuclide losses at washing and peeling to concentrations estimated using experimentally determined transfer factors will lead to underestimation of the predicted activity of radionuclides in foodstuffs. Therefore, it is important to know if the transfer factor values were obtained for washed and peeled vegetables and fruits.

For vegetables, F_r values based on 'external contamination' are also presented. A product is said to be externally contaminated if the leaves are contaminated by spraying, painting, deposition, etc., and the time lag between contamination and processing is short enough to ensure that the majority of the radionuclides have not migrated from the surface into the plant.

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[1] In ICRU Report 65 [6], this value is called the 'food processing retention factor'.

11.2. PROCESSING FACTOR VALUES

Data on the behaviour of many radionuclides during food processing are scarce. The exceptions are caesium, strontium and iodine. Some measurements were made in the 1960s at a time when there was concern about the consequences of radionuclide transfer from nuclear weapons testing into the human food chain. Following the accident at the Chernobyl nuclear power plant, new measurements have become available. Noordijk and Quinault [251] reviewed the existing literature within the framework of the CEC and the IAEA VAMP programmes [51, 255]. These results were mainly reported in TRS-364 [3]. This updated version includes the more recent results and information from various reviews [252–254], as well as the experimental data from the database of the UK Food Standards Agency (for ^{137}Cs, ^{90}Sr and stable Na, K, Ca, Mg, P, Fe, Cu, Zn, Cl, Mn, Se, I, Cd and Pb) [256] and from the database created within the framework of the Franco–German Initiative (FGI) [249, 250]. The main results obtained, focusing on the most effective methods, are shown in Tables 69–80.

Long storage and processing times will reduce the activity contents of short lived radionuclides in foodstuffs, with implications for assessments of doses from releases of radionuclides to the environment [252]. The delay between harvest and consumption is important for short lived radionuclides such as ^{131}I. For instance, processing of milk with a high concentration of ^{131}I during the acute phase of the Chernobyl accident into foodstuffs stored for long periods (such as butter, cheese and dried milk) ensured significant decreases of ^{131}I concentrations in these foodstuffs due to radioactive decay before their eventual consumption. For this reason, storage and processing times for the main foodstuffs are also reported here (see Table 81). More details on processes governing food processing, including all available information sources used for evaluation of the data presented here, are provided in the accompanying TECDOC and in other related publications [5, 257–260].

11.3. APPLICATION OF DATA

The food processing retention factor, F_r, is mainly applied for assessment of the total loss of radionuclides during processing (removal of a radionuclide from the food chain and/or estimation of discharges to waste streams) and for calculations of collective dose [3]. For some processes where the activity remains in the waste product rather than being removed from the foodstuff, notably the production of oil from olives and rapeseed, and of wine from grapes, the parameter P_f is more appropriate [252].

TABLE 69. FOOD PROCESSING RETENTION FACTOR (F_r) AND PROCESSING EFFICIENCY (P_e) FOR VEGETABLES AND FRUIT

(*data are based on total contamination of the plant*)

Method of processing	F_r		P_e
	Element	Value	
Washing of vegetables, berries and fruits	Cs	0.6–1.0	1.0
	I	0.8	1.0
	Ru	0.7–0.9	1.0
	Sr	0.4–1.0	1.0
Peeling of vegetables	Am, Pu	0.1–1.0	0.7–0.9
	Cs	0.5–0.9	0.7–0.9
	Po	0.3–0.5	0.7–0.9
	Sr	0.5–0.9	0.7–0.9
Boiling in water of vegetables, berries and fruits	Am, Ca, Cu, Fe, K, Mg, Na, P, Po, Pu, Ru, S, Zn	0.3–1.0	0.8–1.0
	Cl, T	0.3–0.6	0.8–1.0
	Cs	0.4–0.9	0.8–1.0
	Sr	0.6–1.0	0.8–1.0
Canning, blanching and pickling of vegetables	Cs	0.1–1.0	0.5–0.9
	Sr	0.3–1.0	0.5–0.9
Production of sugar from beetroot	Cs	0.001–0.01	0.12
Production of starch from potato	Cs	0.02–0.03	0.18
Pressing of olives	Cs		
Oil		0.13	0.2
Cake	Cs	0.43	0.5
Processing of rapeseed to oil	Cs	$P_f = 0.004$[a]	
	Sr	$P_f = 0.002$[a]	

[a] Value given is for food processing.

TABLE 70. FOOD PROCESSING RETENTION FACTOR (F_r) AND PROCESSING EFFICIENCY (P_e) FOR VEGETABLES AND FRUIT

(*data are based on external contamination only*)

Method of processing	F_r		P_e
	Element	Value	
Washing of vegetables, berries and fruits	Cs	0.1–0.9	1.0
	I	0.1–0.9	1.0
	Ru	0.2–0.8	1.0
	Sr	0.1–0.5	1.0
Boiling of vegetables and berries	Ba	0.6–0.9	0.8–1.0
	Cs	0.1–0.5	0.8–1.0
	I	0.1–0.5	0.8–1.0
	Ru, Te	0.3–0.7	0.8–1.0
	Sr	0.1–0.2	0.8–1.0
	Zr	1.0	0.8–1.0

TABLE 71. FOOD PROCESSING RETENTION FACTOR (F_r) AND THE PROCESSING EFFICIENCY (P_e) FOR CEREALS

Raw material	Method of processing	F_r		P_e
		Element	Value	
Wheat, rye, barley, oats, grain	Milling to white flour	Am, Pu	0.1–0.2	0.6–0.8
		Cd, Pb	0.5–0.6	0.6–0.8
		Cs	0.2–0.6	0.6–0.8
		Sr	0.1–0.6	0.6–0.8
	Milling to dark flour	Cs	0.05–0.2	0.05–0.1
		Sr	0.1–0.2	0.05–0.1
	Milling to semolina	Cs	0.15–0.5	0.1–0.3
	Milling to bran	Cs	0.4–0.7	0.1–0.4
		Sr	0.6–0.9	0.1–0.4
	Cooking wheat sprouts	Cs	0.8–0.9	1.8–2.4
	Shredding or puffing wheat	Cs	0.1–0.15	0.9–0.95
Rice grain	Polishing	Ca, Fe, K, Mg, P	0.1–0.6	
		Cs	0.2–0.4	
		Cu, Na, Zn	0.7–0.9	
		Mg, P	0.1–0.6	
		Sr	0.1–0.4	
Brown, savoury, ‘easy cook’ white rice	Boiling	Ca, Cl, Cu, Fe, K, Mg, Na, P, Se, Zn	0.3–0.4	
Pasta	Boiling	Cs	0.1–0.4	
		Ca, Cl, Cu, Fe, K, Mg, Na, P, Zn	0.1–0.4[a]	

[a] Value given is for food processing .

TABLE 72. FOOD PROCESSING RETENTION FACTOR (F_r) AND PROCESSING EFFICIENCY (P_e) FOR DRINKS

Raw material	Method of processing	F_r		P_e
		Element	Value	
Surface wastewater	Conventional treatment to tap water	Co	0.4	1.0
		Cs	0.7	1.0
		Ru	0.3	1.0
		Sr	1.0	1.0
		I	0.8	1.0
Tea	Brewing 2–8 minutes	Cs	0.4–0.6	
		Cs	0.9 for external contamination	
Herbal tea	Brewing	Cs	0.4–0.6	

TABLE 72. FOOD PROCESSING RETENTION FACTOR (F_r) AND PROCESSING EFFICIENCY (P_e) FOR DRINKS (cont.)

Raw material	Method of processing	F_r		P_e
		Element	Value	
Berries and fruits	Juice	Am, Pu	0.5	0.3–0.9
		Cs	0.2–0.9	0.3–0.9
		S	0.2	0.3–0.9
		T	0.6	0.3–0.9
Grapes	Wine	Sr	0.2–0.6	0.6–0.8
		Cs	0.3–0.7	0.6–0.8
		Cu, K, P, Zn	0.3–0.8	0.6–0.8

TABLE 73. FOOD PROCESSING RETENTION FACTOR (F_r) AND PROCESSING EFFICIENCY (P_e) FOR TRITIUM

Raw material	Method of processing	F_r		P_e
		HTO	OBT	
Blackberries	Washing and stewing	0.55	0.56	0.59
Broad beans	Boiling	0.28[a]	0.69[b]	0.91
Cabbage	Washing and steaming	0.28[a]	—	0.98
Carrots	Washing and boiling	0.28[a]	0.43[b]	0.85
New potatoes	Scrubbing and boiling	0.55[b]	—	0.92
	Peeling and roasting	0.22[b]	—	0.62
Old potatoes	Peeling and boiling	0.55	0.74	0.92
	Peeling and roasting	0.21	—	0.65
Hulled rice	Boiling	0.84	—	—
Soybean	Boiling	0.77	—	—
Rice flour	Boiling	0.69	—	—
Soybean flour	Boiling	0.74	—	—

[a] Some data are below the detection limit.
[b] Not significant at the 5% level.

TABLE 74. FOOD PROCESSING FACTORS FOR ^{14}C

Raw material	Method of processing	Food processing retention factor (F_r)	Processing efficiency (P_e)
New potatoes	Scrubbing and boiling	0.69	0.92
Hulled wheat	Boiling	0.82	—
Hulled rice	Boiling	0.98	—
Soybean	Boiling	0.86	—
Wheat flour	Boiling	0.92	—

TABLE 75. FOOD PROCESSING RETENTION FACTOR (F_r) AND PROCESSING EFFICIENCY (P_e) FOR DAIRY PRODUCTS

(*bold font denotes recommended values*)

Product	Element	F_r		P_e	
		Ref. value	Range	Ref. value	Range
Cream	Ca, Cl, K, Na, Mg		0.03	**0.08**	0.03–0.24
	Cd		0.06–0.1	**0.08**	0.03–0.24
	Cs	**0.05**	0.03–0.16	**0.08**	0.03–0.24
	I	**0.06**	0.006–0.19	**0.08**	0.03–0.24
	Fe		0.07	**0.08**	0.03–0.24
	P		0.02	**0.08**	0.03–0.24
	Pb, Zn		0.05	**0.08**	0.03–0.24
	Sr	**0.04**	0.02–0.25	**0.08**	0.03–0.24
Sour cream	Cs	**0.1**	0.1–0.2	**0.1**	0.1–0.2
	Sr	**0.1**	0.1–0.13	**0.1**	0.1–0.2
Skimmed milk	I		0.81–0.94	**0.92**	0.76–0.97
	Cs	**0.95**	0.85–0.99	**0.92**	0.76–0.97
	Sr	**0.93**	0.75–0.96	**0.92**	0.76–0.97
Butter	Ca, Cl, K, Na, Mg		0.008	**0.04**	0.03–0.05
	Cd		0.1	**0.04**	0.03–0.05
	Cs	**0.01**	0.003–0.02	**0.04**	0.03–0.05
	I	**0.02**	0.01–0.035	**0.04**	0.03–0.05
	P		0.004	**0.04**	0.03–0.05
	Pb		0.02	**0.04**	0.03–0.05
	Sr	**0.006**	0.0025–0.012	**0.04**	0.03–0.05
	Zn		0.01	**0.04**	0.03–0.05
Buttermilk	Cs	**0.05**	0.02–0.13	**0.04**	0.03–0.14
	I		0.05–0.13	**0.04**	0.03–0.14
	Sr	**0.06**	0.03–0.07	**0.04**	0.03–0.14
Butterfat	I		0.02	**0.04**	0.04–0.04
	Sr		0.001–0.002	**0.04**	0.04–0.04
Milk powder (dried)	Ca, Cl, K, Na, Mg, Zn		1.0	**0.12**	0.11–12
	Cs	**1.0**	1.0	**0.12**	0.11–12
	Sr	**1.0**	1.0	**0.12**	0.11–12
	I	**1.0**	1.0	**0.12**	0.11–12
Condensed milk	Ca, Cl, Cu, Fe, K, Mg, Na, Zn		1.0	**0.4**	0.37
	Cs	**1.0**	1.0	**0.4**	0.37
	I	**1.0**	1.0	**0.4**	0.37
	Sr	**1.0**	1.0	**0.4**	0.37
Cheese[a]					
Goat	I		0.08–0.14	**0.12**	0.08–0.17
	Cs		0.07–0.15	**0.12**	0.08–0.17
	Sr		0.61	**0.12**	0.08–0.17

TABLE 75. FOOD PROCESSING RETENTION FACTOR (F_r) AND PROCESSING EFFICIENCY (P_e) FOR DAIRY PRODUCTS (cont.)
(*bold font denotes recommended values*)

Product	Element	F_r		P_e	
		Ref. value	Range	Ref. value	Range
Cow, rennet	Ca		0.5–0.7	**0.12**	0.08–0.18
	Cd, Fe, Mg, Pb, P		0.2–0.4	**0.12**	0.08–0.18
	Cs	**0.07**	0.05–0.23	**0.12**	0.08–0.18
	Cu		0.4–0.6	**0.12**	0.08–0.18
	I	**0.20**	0.11–0.53	**0.12**	0.08–0.18
	K, Cl		0.1	**0.12**	0.08–0.18
	Sr	**0.7**	0.025–0.80	**0.12**	0.08–0.18
	Zn, Se		0.7–1.0	**0.12**	0.08–0.18
Cow, acid	Cs	**0.06**	0.01–0.12	**0.10**	0.08–0.12
	I		0.22–0.27	**0.10**	0.08–0.12
	Sr	**0.08**	0.04–0.08	**0.10**	0.08–0.12
Cottage cheese, rennet	Cs		0.01–0.05		
	Sr		0.07–0.17		
Cottage cheese, acid	Cs		0.1	**0.12**	0.1–0.14
	Sr	**0.1**	0.2–0.7	**0.12**	0.1–0.14
Whey[a], rennet	Cs		0.73–0.96	**0.90**	0.70–0.94
	I		0.47–0.89	**0.90**	0.70–0.94
	Sr		0.20–0.80	**0.90**	0.70–0.94
Whey, acid	Cs		0.75–0.90		0.82
	I		0.60–0.73		0.82
	Sr		0.70–0.90		0.82
Casein[a], rennet	Cs		0.01–0.08		0.03–0.06
	I		0.02–0.12		0.03–0.06
	Sr		0.10–0.85		0.03–0.06
Casein, acid	Cs		0.01–0.04		0.01–0.06
	I		0.03–0.04		0.01–0.06
	Sr		0.05–0.08		0.01–0.06
Casein whey[a], rennet	Cs		0.77–0.83	**0.76**	0.73–0.79
	I		0.69–0.82	**0.76**	0.73–0.79
	Sr		0.08–0.16	**0.76**	0.73–0.79
Casein whey, acid	Cs		0.83–0.84	**0.78**	0.75–0.79
	I		0.78–0.80	**0.78**	0.75–0.79
	Sr		0.67–0.86	**0.78**	0.75–0.79
Milk[b], ion exchange	Cs	**0.05**		**1.0**	1.0
	I	**0.1**		**1.0**	1.0
	Sr	**0.1**	0.04–0.06	**1.0**	1.0

[a] Separate values are given for the rennet and acid coagulation processes.
[b] Decontamination of milk by ion exchange on a commercial scale.

TABLE 76. FOOD PROCESSING RETENTION FACTOR (F_r) AND THE PROCESSING EFFICIENCY (P_e) FOR MEAT

(*bold font denotes reference values*)

Raw material	Method of processing	Element	F_r		P_e
			Ref. value	Range	
Mammals (cow, pig, sheep, deer, rabbit)	Boiling meat	Cs	**0.4**	0.2–0.7	0.5–0.7
		I		0.6	0.5–0.7
		Sr	**0.5**	0.4–0.9	0.5–0.7
		Ru		0.3	0.5–0.7
	Boiling bone	Cs	**0.3**	0.2–0.3	1.0
		I		0.98	1.0
		Sr		0.99	1.0
		Ru		0.7	1.0
	Frying, roasting or grilling meat	Ca, Cu, Cl, Fe, K, Mg, Na, P, Se, Zn,		0.5–1.0	0.4–0.7
		Cs	**0.7**	0.5–0.8	0.4–0.7
		I		0.2–0.6	0.4–0.7
		Sr		0.8	0.4–0.7
	Microwave baking	Ca, Cl, Fe, K, Mg, Na, P, Se Zn		0.5–1	0.4–0.7
		Cs	**0.5**	0.4–0.5	0.4–0.7
	Pickling wet (salting), marinating	Cs	**0.5**	0.1–0.7	0.9–1.0
	Sausage production	Cs		0.4–1.0	
Birds	Boiling meat	Sr		0.5	
	Baking meat	Cs		0.7–0.8	
	Roasting	Ca, Cl, Cu, Fe I, K, Mg, Mn, Na, P, Se, Zn		0.5–1.0	0.4–0.7
Fish	Boiling flesh	Cs		0.2–0.9	0.5–0.9
		Sr		0.9	
	Frying flesh	Cs		0.8–0.9	0.7–0.8
	Grilling	Ca, Cl, Cu, I, K, Fe, Mg, Mn, Na, P, Se, Zn		P_f = 1.1–1.2[a]	

[a] Value given is for food processing.

TABLE 77. FOOD PROCESSING RETENTION FACTOR (F_r) FOR ^{137}Cs AND ^{90}Sr, AND PROCESSING EFFICIENCY (P_e), FOR FOREST PLANT PRODUCTS (MUSHROOMS AND BERRIES)

(*data are based on total contamination of the plant*)

Raw material	Method of processing	Element	F_r	P_e
Berries (bilberry, blackberry)	Washing	^{137}Cs	0.8–1	1
	Boiling	^{137}Cs	0.5–0.6	1
	Drying	^{137}Cs	1	0.1
	Soaking of dried berries in water	^{137}Cs	0.8	0.1
Mushrooms	Washing	^{137}Cs	0.4	1
	Drying	^{137}Cs	1.0	0.1–0.12
		^{90}Sr	1.0	
	Washing of dried mushrooms	^{137}Cs	0.5	0.1
	Soaking of dried mushrooms in water	^{137}Cs	0.1–0.2	0.1
	Salting	^{137}Cs	0.07–0.1	0.6–0.9
	Boiling (30–60 min)	^{137}Cs	0.1–0.3	0.6–0.8
		^{90}Sr	0.2–0.9	
	Boiling of dried mushrooms	^{137}Cs	0.1	0.15
	Pickling	^{137}Cs	0.06–0.1	0.6
		^{90}Sr	0.5	

Milk products may require careful consideration owing to the variety of processes employed and products generated. It should be determined which coagulation process is used for cheese making — the acid or rennet process. Further, it should not be assumed that all whey will be discarded as waste or animal feed. The food industry uses whey as an additive to human food. If all the whey and the buttermilk is used for human consumption, it is more accurate to use an F_r value of 1.0 for all milk for collective dose assessment. However, such an approach may not be appropriate for individual dose assessments, depending on the mix of milk products consumed by the individuals of interest, and it may be more appropriate to use the food processing factors for the different products and assess the doses to the population groups separately, using their specific consumption rates of the different products.

The values given in this section assume that the water used in cooking is uncontaminated, which may not always be the case. Moreover, it is the custom in some cultures to consume the cooking water, in which case any tritium lost to the water would still be ingested. For these reasons, in the absence of specific information, the reference food processing factor for ^{14}C and T radionuclides should be 1 (i.e. concentrations in food products should not be assumed to be reduced when the food is processed).

TABLE 78. FOOD PROCESSING RETENTION FACTOR (F_r) AND PROCESSING EFFICIENCY (P_e) FOR ^{137}Cs IN SELECTED EDIBLE MUSHROOM SPECIES

Mushroom species	Type of processing	F_r	P_e
Boletus edulis (dry weight)	*Consecutive processing*		
	Washing in flowing water for 10 min	0.90–0.95	1.1
	Soaking in 0.85% salt solution for 10 h, followed by washing in flowing water	0.15–0.20	1.5–1.7
	Boiling for 5 min with extract removal	0.08–0.10	0.8–0.9
	Boiling for 20 min with extract removal	0.03–0.05	0.7
Suillus variegatus (fresh weight)	*Consecutive processing*		
	Cleaning of mushroom cap	0.80–0.85	1.0
	Washing in flowing water for 10 min	0.50–0.55	1.3
	Boiling for 20 min. and washing in flowing water for 10 min	0.15–0.20	0.8
	Pickling	0.05–0.10	0.5
Xerocomus badius (fresh weight)	Boiling for 5 min	0.25–0.30	0.9
	Boiling for 10 min	0.15–0.20	0.8
	Boiling for 20 min	0.05–0.07	0.8
	Soaking for 20 min	0.80–0.85	1.3
	Soaking for 40 min	0.60–0.70	1.3
	Soaking for 60 min	0.30–0.40	1.3
Lactarius deliciosus, *L. necator,* *Russula delica* (fresh weight)	*Consecutive processing*		
	Cleaning of mushroom cap	0.70–0.75	1.0
	Washing in flowing water for 10 min	0.65–0.70	1.0
	Soaking for 24 h	0.25–0.30	1.2
	Soaking for 48 h	0.10–0.12	1.2
	Soaking for 72 h	0.02–0.03	1.2
	Salting in 2–3% salt solution for 72 h	0.003–0.005	1.0

TABLE 79. ^{137}Cs AND ^{90}Sr PROCESSING RETENTION FACTORS (F_r) FOR PREPARATION OF LIQUID WATER MEDICINAL FORMS (INFUSIONS AND BROTHS) FROM AIR DRIED MEDICINAL PLANT RAW MATERIAL

Group of medicinal plant raw material	N	F_r							
		^{137}Cs				^{90}Sr			
		AM[a]	SD[b]	Min	Max	AM	SD	Min	Max
Fruits	25	0.49	0.27	0.11	0.87	0.43	0.09	0.29	0.59
Flowers	20	0.60	0.29	0.15	0.93	0.47	0.21	0.16	0.73
Buds	20	0.55	0.08	0.44	0.58	0.50	0.10	0.40	0.55
Grass, leaves and shoots	115	0.57	0.15	0.20	0.92	0.46	0.12	0.22	0.75
Rhizomes and roots	20	0.48	0.20	0.19	0.89	0.23	0.06	0.14	0.31
Bark	15	0.29	0.06	0.18	0.38	0.16	0.05	0.12	0.28

[a] AM: Arithmetic mean.

[b] SD: Standard deviation.

TABLE 80. FOOD PROCESSING RETENTION FACTOR (F_r) AND PROCESSING EFFICIENCY (P_e) FOR LOWER SEA ORGANISMS

Raw material	Method of processing	Element	F_r	P_e
Shrimp	Washing with tap water	Ca	0.9	1.0
		^{90}Sr	0.7	1.0
	Washing with 1–3% solution of NaCl	Ca	0.9	1.0
		^{90}Sr	0.3–0.4	1.0
	Cooking	Pb	0.0–0.4	0.35
		Po	0.04–0.8	0.35
		Ra	0.04–0.5	0.35
Oyster	Washing with 1–3% solution of NaCl	Ca	0.8	1.0
		^{90}Sr	0.7–0.8	1.0
Mussels	Washing and removal of flesh	Pb	0.5	0.25
		Po	0.02	0.25
		Ra	0.01	0.25
Clam	Washing with tap water	Ca	0.8	1.0
		^{90}Sr	0.7	1.0
	Washing with 1–3% solution of NaCl	Ca	0.7–0.5	1.0
		^{90}Sr	0.3–0.6	1.0
Algae	Alginate production	Ru, Rh	0.07	0.04
		Sr	0.6	0.04
		Te	0.02	0.04
	Satiagum production	Co	0.04	0.08
		Ru, Rh	0.04	0.08

TABLE 81. DELAY TIMES (STORAGE AND PROCESSING TIMES) BETWEEN HARVESTING AND CONSUMPTION OF FOOD PRODUCTS

Raw material	Typical delay time	Minimum	Maximum
Cereals and cereal products	6 months	45 days	1 year
Potatoes and beets	3 months	7 days	6 months
Leafy vegetables	4 days	1 day	7 days
Root vegetables	10 days	7 days	14 days
Fruit vegetables	7 days	2 days	14 days
Fresh apples and pears	3.5 months	0	8 months
Fresh drupe fruits, soft fruit, rhubarb	4 days	0	8 days
Canned fruit	1 year	14 days	2 years
Frozen fruit	6 months	7 days	1 year
Jams and jellies	1 year	1 day	2 years
Milk	2 days	1 day	6 days
Butter	1 month	3 days	3 months
Cream	5 days	2 days	10 days
Condensed milk	6 months	7 days	1 year

TABLE 81. DELAY TIMES (STORAGE AND PROCESSING TIMES) BETWEEN HARVESTING AND CONSUMPTION OF FOOD PRODUCTS (cont.)

Raw material	Typical delay time	Minimum	Maximum
Pasteurized skimmed milk	2 days	1 day	6 days
Cheese (rennet coagulation)	1.5 months	30 days	3 months
Cheese (acid coagulation)	1 month	7 days	2 months
Fresh[a] beef	20 days	14 days	28 days
Fresh[a] pork, veal	4 days	2 days	7 days
Fresh[a] chicken	4 days	2 days	7 days
Fresh[a] lamb	10 days	7 days	14 days
Fresh[a] game	10 days	2 days	20 days
Eggs	14 days	2 days	28 days

[a] Refers to fresh meat; frozen meat would have longer delay times of up to 6 months.

12. USE OF ANALOGUES

In cases where there are no data or relatively few data for environmental transfers of a radionuclide, an analogue, either for a process or for an isotope, may be used to provide relevant information on environmental behaviour. The use of analogues is not an accurate way of modelling, but it may be used in screening models if few or no other data are available. Relevant knowledge such as timescales of processes, physical, chemical and biological properties of the environment, and relevant media, is required to derive parameter values from stable isotopes [5].

There are three main types of analogue that can be used for derivation of values if measured or reference values are not available:

(1) *Analogue isotopes*. Use of a parameter value for a related or similar isotope[2];
(2) *Analogue elements*. Use of a parameter value for a related or similar element;
(3) *Analogue species*. Use of a parameter value for a related or similar species.

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[2] This approach was widely used in the current publication.

12.1. ANALOGUE ISOTOPES

Application of analogue isotopes is the most common form of analogue use and is often used without any specific justification or even recognition that data for an analogue are being used. Short lived fission products whose environmental behaviour has been extensively studied in the context of reactor accidents or routine discharges may be used as analogues for long lived isotopes of relevance for solid waste disposal. For example, data for ^{131}I may be used to predict the behaviour of long lived ^{129}I, or data for the well studied ^{134}Cs or ^{137}Cs may be used to predict the behaviour of long lived ^{135}Cs. Similarly, short lived and readily available tracer radionuclides are often used in experiments as analogues for isotopes found in radioactive discharges or waste.

In general, the behaviour of isotopes of the same element is identical, except for light elements such as hydrogen. An important limitation and consideration when using stable analogues is whether the timescale over which behaviour of a short lived radionuclide can be studied is sufficient to reveal the significance of long term processes that may influence the behaviour of a long lived radioisotope or stable isotope of the same element. In particular, equilibration of a short lived isotope in environmental media may be strongly influenced by its physical decay, whereas equilibration of a long lived or stable isotope may be almost entirely determined by biogeochemical transfer processes [5].

12.2. ANALOGUE ELEMENTS

The chemical properties of elements follow well established patterns that can sometimes be used as a basis for identifying potential analogues. Elements in the same group (column) of the periodic table usually exhibit similar chemical behaviour, because they have the same number of outer electrons available to form chemical bonds (i.e. they form compounds in the same valence state). In the case of essential macroelements for plants located in soil, the uptake and transfer of a chemically similar element (i.e. the element under study) will be influenced by any lack or excess of the essential macroelement. However, generally similar chemistry does not necessarily imply similar metabolic characteristics in plants and animals, because of the high specificity of biochemical pathways. Thus, although chlorine and iodine have many chemical similarities, their behaviour in mammals is very different because of the role of iodine in the production of thyroid hormones [5].

The most commonly used analogue element pairs are K and Cs, Ca and Sr, and Ba and Ra. Ba, Ca and K are regarded as elements that indicate the influence of metabolic processes. Transition elements in the same period (row) of the periodic table also tend to be chemically similar to one another [5]. Lanthanides are oxidation state analogues for actinides, so their distribution can give an indication of the long term behaviour of the radioactive transuranic elements; however, there are exceptions, such as cerium and europium with their 4+ and 2+ oxidation states contrasting with the 3+ oxidation state common to all lanthanides.

Chemical similarity does not necessarily translate into similar behaviour in the environment; sometimes the size of the ionic form of a radionuclide can cause differences, particularly in the association processes.

12.3. ANALOGUE SPECIES

For plants, some analogues may seem relatively obvious, such as pasture grass and forage. However, closer inspection may show that the analogy is not close and may be misleading. Similarly, generic data for ‘grain’ might be expected to provide a good analogue for fruits or rice, but the growing conditions for rice are so different from those for cereals that the analogue is not, in general, a good one (see Section 5).

When making comparisons between animals of different types, consideration also has to be given to the mass of the animal. Conventionally, transfers to animal products have been expressed through the use of transfer factors that are the ratio of the concentration in the product to the rate of intake of the radionuclide. For unit rate of intake, the concentration in a particular product tends to be higher for animals of smaller mass, although this effect may be counteracted by more rapid metabolic turnover in smaller animals.

In the case of different products from the same animal, the assumption of similar transfer factors, for example, between checken and eggs, might seem tempting, but is not appropriate. In the most common of these cases, one product (milk or eggs) is collected during the life of the animal whereas another (meat) is available only after the animal has been slaughtered, and the two products are very different in nature. Other examples are different parts of the slaughtered animal (flesh, liver, etc.): as with humans, many elements concentrate preferentially in certain tissues or organs. In particular, because of the major role of the liver in detoxification, many transition metals, heavy metals, lanthanides and actinides are concentrated in it, giving rise to concentrations that may be an order of magnitude (or more) higher than concentrations in meat.

12.4. OTHER ANALOGUE APPROACHES

Soil K_d values can vary significantly with soil type (see Section 4). Where knowledge of soil characteristics is not available, a generic soil K_d value can be adopted. This may be an average over soil types, a value for the soil type expected to maximize doses, or simply a value for the soil type for which data are most extensive. If data are limited, the K_d for a soil can sometimes be used for a sediment with similar characteristics (pH, Eh, etc.).

12.5. APPLICATION OF DATA

The use of analogues is not the preferred approach to modelling, but it is necessary in those contexts in which directly applicable data are not available or are of dubious quality.

Although care is needed when considering the characteristics of each individual case, the general order of preference for data sources is as follows:

(1) Data for the specific parameter for the specific radionuclide.
(2) Data for the specific parameter for another isotope of the same element (preferably not a short lived isotope for a long lived isotope, as it may not persist for long enough in the environment to reveal the characteristic behaviour).
(3) Data for the specific parameter for an analogue element.
(4) Data for a related parameter (e.g. different plant type or animal product) for the specific radionuclide/element. In general, plant type analogues tend to be more reliable than animal product analogues.
(5) Data for a related parameter for an analogue element.

The ordering of options (3) and (4) in particular will depend on the specific case, and judgement will be necessary. For example, the order shown above would be valid if the choice were between a well recognized element analogue and a cross-species animal product analogue; on the other hand, the order would be reversed if the choice were between data for a similar plant type for an element with high plant uptake and a speculative element analogue.

One can never be sure exactly how good any specific analogue is. An analogue can only be proved to be valid by comparing its behaviour in the conditions of interest with that of the parameter for which it is an analogue. Hence, while confidence in the validity of an analogue will increase as the quality of the justification increases, there will always be some residual uncertainty.

As with any other choice of parameter values for modelling, decisions on using analogues must take account of the assessment context and particularly the level of realism or conservatism of the assessment. The best analogue for a realistic assessment might not be the best for a conservative assessment.

It is preferable to use elemental analogues that lie close to each other in a chemical series; for example, among the lanthanides it could be samarium and europium. However, in practice, by far the most extensive data among the lanthanides are for cerium, so it is often most appropriate to use this as the analogue when information is lacking for other lanthanide elements.

There are two main issues that could affect the validity of using an isotope analogue. The timescales for experiments or observations on short lived isotopes may be limited by radioactive decay and so might not reflect all aspects of environmental behaviour in the long term. An important example is that of iodine isotopes. The majority of experimental data relate to ^{131}I, which is of great importance in the context of accidental releases from nuclear power plants, and has a half-life of about 8 days, whereas the isotope of interest for solid waste disposal is ^{129}I, with a half-life of 17 million years. Observations on ^{131}I are limited by radioactive decay to a period of a few months at most, and so may be of little value for identifying and characterizing long term behaviour, because the timescale of the relevant processes in the environment is much longer than the half-life of ^{131}I. In the opposite case, data for an analogue isotope that is long lived or stable should exhibit the same short term behaviour as a short lived isotope (with the exception of radioactive decay, which is generally modelled explicitly), provided that observations of the long lived species have been made on short enough timescales. However, although some care is needed in cases where there are large differences in half-life — and especially when the analogue isotope is short lived — isotopic analogues can normally be assumed to be more reliable than element or media analogues.

In addition to consideration of the effects of radioactive decay, it should be recognized that although isotopes of an element have similar chemical behaviour, this chemical similarity is not exact and the differences will translate into subtle differences of behaviour in the environment. This effect is demonstrated by the absorption of common elements from the atmosphere — most plants show higher ratios of ^{12}C/^{13}C, ^{14}N/^{15}N and ^{16}O/^{18}O than are found in the atmosphere, owing to the difference in their chemical behaviour. These differences tend to be more important for lighter elements because the relative mass differences are larger (e.g. the relative difference between the ^{7}Be and ^{10}Be nucleus is higher than the difference between ^{226}Ra and ^{228}Ra, which is less than 1% regarding the mass). Except for hydrogen and several light elements, biochemical differences caused by these isotopic differences will in general be much smaller than most other uncertainties in the system. The environmental behaviour of different isotopes may differ even simply because their modes of release or more general entry into the biosphere, and consequently their distribution in the biosphere, are different. The simplest example is the different chemical behaviour of released CH_4 and CO_2 regarding carbon, and from the point of view of hydrogen isotopes, released as CH_4 and H_2O.

For element analogues, chemical similarity does not necessarily translate into similar behaviour in the environment. For chemical group analogues, such as alkali earths, these differences will normally be large. For period analogues, such as the lanthanides, the differences may be much smaller. Key considerations include variations in valence and ionic radius. Thus, in the case of the lanthanides, there is a consistent trend across the series from predominantly 2+ through to 4+, and this trend may be reflected in trends in environmental behaviour. A problem of element analogues is that the initial distribution of elements in the environment can affect the behaviour of the radionuclides being modelled. If the soil is naturally (or as a result of past activities) poor or rich in a particular element that is (or behaves like) an important plant or animal nutrient, then the uptake and transfer of chemically similar radionuclides released to the environment will be affected. This may be a significant factor in selecting data values, but should not affect the selection of analogues, because, by definition, if the analogue is good, it will behave in the same way as the radionuclide of interest would.

Appendix I

REFERENCE INFORMATION ON TERRESTRIAL PLANTS AND ANIMALS

TABLE 82. DRY MATTER CONTENT IN PLANTS (%) [3, 261]

Crop	Seeds	Vegetative mass	Grain
Spring vetch	87	24	
Winter vetch	88	22	
Field pea	85	17	
Garden pea	83	16	
Grass pea vine	86	21	
Soya	87	26	
Lupin yellow	85	14	
Lupin blue	86	18	
Seradella		22	
Broad beans	88	18.3	
Bean (field, kidney and French)		28	
Lentil		25	
Winter rye		23	87
Wheat		18	88
Oats		28	87
Barley		34	87
Maize (corn)		19	85
Sudan grass	90	20	
Sorghum		25	87
Annual rye grass		20	
Millet		23	88
Alfalfa		26	
Sickle alfalfa		33	
Bastard lucerne		23	
Red clover		22	
Ladino clover		26	
Sainfoin		23	
White sweet clover		22	
Yellow sweet clover		22	
Fussian brome grass		21	
Slender wheat grass		34	
Couch grass		37	
Standard crested grass		39	
Timothy grass		26	

TABLE 82. DRY MATTER CONTENT IN PLANTS (%) [3, 261] (cont.)

Crop	Seeds	Vegetative mass	Grain
Meadow fescue		20	
Cock's foot grass		22	
Meadow grass		22	
Cabbage		12	
Lettuce		8.0	
Leek		11	
Onion (above ground part)		11	
Spinach		8.0	
Celery		6.0	
Cauliflower		11	
Kohlrabi		6.0	
Tomato		6.0	
Cucumber		5.0	
Pumpkin (English)		7.5	
Vegetable marrow (English)		9.0	
Zucchini		5.0	
Beetroot (red beet)		16	
Sugar beet		22	
Radish		9.0	
Carrot		14	
Potato		21	
Turnip (swede)		12	
Jerusalem artichoke		22	
Tapioca		38	
Raspberry		16	
Watermelon		7.0	

TABLE 83. DRY MATTER CONTENT IN FRUITS [262]

Feed	Dry matter content (%)
Apple	15.6
Pear	16.8
Peach	10.9
Apricot	14.7
Orange	14
Grape	18.4
Strawberry	10.1
Watermelon	7.4

TABLE 84. DRY MATTER CONTENT IN FEED [263]

Feed	Dry matter content (%)
Concentrate feed	88
Grass silage	26
Pasture	20
Grass hay	86
Lucerne hay	86
Lucerne silage	34
Corn silage	25

TABLE 85. DRY MATTER CONTENT OF WILD BERRIES (%) [264–266]

English name	Latin name	*N*	Arithmetic mean	Standard deviation	Minimum	Maximum
Blueberry	*Vaccinium myrtillus*	307	13.2	1.9	8.6	21
Lingonberry	*Vaccinium vitis-idaea*	254	14.1	1.3	11.3	18.8
Cranberry	*Vaccinium oxycoccus*	16	10.8	0.9	9.3	12.1
Bog bilberry	*Vaccinium uliginosum*	6	12.1	1.1	10.5	13.5
Black crowberry	*Empetrum nigrum*	1	7.4	—	—	—
Cloudberry	*Rubus chamaemorus*	26	14.0	1.6	9	18
Wild raspberry	*Rubus idaeus*	21	17.3	1.8	14.4	21.9
Wild strawberry	*Fragaria vesca*	1	15.4	—	—	—

TABLE 86. CARCASS WEIGHT (kg) AND MEAT FRACTION OF GAME [264–268]

Species of animal	Carcass weight (kg)	Fraction of meat in carcass weight
Moose, adult	1.9×10^{2}	0.80
Moose, calf	8.3×10^{1}	0.78
White-tailed deer	5.0×10^{1}	0.78
Fallow deer	3.3×10^{1}	0.78
Roe deer	1.8×10^{1}[a]	0.78
Brown hare	2.4	0.90
Arctic hare	1.8	0.90
Capercaillie	1.9	0.90
Black grouse	6.6×10^{-1}	0.90
Hazel grouse	2.4×10^{-1}	0.90
Willow grouse	3.6×10^{-1}	0.90
Partridge	2.4×10^{-1}	0.90

TABLE 86. CARCASS WEIGHT (kg) AND MEAT FRACTION OF GAME [264–268] (cont.)

Species of animal	Carcass weight (kg)	Fraction of meat in carcass weight
Pheasant	6.9×10^{-1}	0.90
Goose	2.3	0.90
Eider	1.3	0.90
Long-tailed duck	3.8×10^{-1}	0.90
Mallard	6.6×10^{-1}	0.90
Goldeneye	4.5×10^{-1}	0.90
Teal	1.8×10^{-1}	0.90

[a] Roe deer gain more weight in Northern than in Central Europe.

TABLE 87. WATER CONTENT IN FRESHWATER AND RIPARIAN DIETARY ITEMS AND TISSUES CONSUMED BY HUMANS (%) [269, 270]

Food type	Arithmetic mean	Standard deviation	Minimum	Maximum
Aquatic primary producers				
Algae	84	4.7	71	97
Aquatic macrophytes	87	3.1		
Emergent vegetation			45	93
Aquatic macrophyte tubers	90	0.030	86	92
Emergent vegetation tubers	90	0.020	81	93
Aquatic invertebrates				
Bivalves (without shell)	82	4.5		
Isopods			71	80
Cladocerans			79	87
Aquatic vertebrates				
Bony fishes	75	5.1	67	79
Reptiles and amphibians				
Snakes/lizards	66			
Frogs/toads	85	4.7		
Mammals				
Mice/voles/rabbits	68	1.6		
Birds				
Passerines (with typical fat reserves)	68			
Mallard duck (flesh only)	67			

TABLE 88. CARBON AND PERCENTAGE HYDROGEN CONTENT IN FRESHWATER AND RIPARIAN DIETARY ITEMS AND TISSUES CONSUMED BY HUMANS [271–274]

(*on a per unit dry weight basis*)

Type of organism	Type of tissue	Percentage C (per unit dry weight)					Percentage H (per unit dry weight)				
		N	AM[a]	SD[b]	Minimum	Maximum	*N*	AM	SD	Minimum	Maximum
Algae	Whole	29	47.5	11.5	29.3	70.2	2	4.4	0.4	4.1	4.6
Aquatic macrophytes	Not specified	19	31.0	3.1	25.8	37.6	n.a.[c]	n.a.	n.a.	n.a.	n.a.
Animals	Not specified	2	46.7	2.4	45.0	410.0	2	6.6	0.1	6.5	6.6
Invertebrates	Whole	43	47.5	5.2	34.3	55.1	5	5.6	1.2	4.5	7.3
Molluscs	Soft tissue	1	39.9	n.a.	n.a.	n.a.	1	6.0	n.a.	n.a.	n.a.

[a] AM: Arithmetic mean.

[b] SD: Standard deviation.

[c] n.a.: Not available.

Appendix II

PLANT GROUPS AND ASSOCIATED CROPS

TABLE 89. PLANT GROUPS, WITH COMMON AND LATIN NAMES OF ASSOCIATED CROPS [5]

Plant group	Common name	Latin name
Cereals	Rye	*Secale cereale L. subsp. cereale*
	Wheat	*Triticum aestivum L. non. cons. subsp. aestivum*
	Oats	*Avena sativa L.*
	Barley	*Hordeum vulgare L. subsp. vulgare*
	Maize (corn)	*Zea mays L. subsp. mays*
	Sorghum	*Sorghum bicolor (L.) Moench*
	Millet	*Panicum L.*
	Buckwheat	*Fagopyrum esculentum*
	Foxtail millet, Italian millet	*Setaria italica L.*
Maize	Maize (corn)	*Zea mays L. subsp. mays*
Rice	Rice	*Oryza sativa L.*
Leafy vegetables	Hiroshimana (pot herb, mustard)	*Brassica rapa L.*
	Kikuna (chop suey green)	*Chrysanthemum coronarium L. var. Spatiosum L.H. Bailey*
	Mizuna (green)	*Brassica rapa L. subsp. nipposinica (L.H. Bailey) Hanelt (Mizuna Group)*
	Burdock (great burdock)	*Arcitum lappa L.*
	Asparagus	*Asparagus officinalis L.*
	Purslane	*Portulaca oleracea L.*
	Cabbage, flowering	*Brassica rapa L. var. parachinensis (L.H. Bailey) Hanelt*
	Chinese spinach	*Amaranthus tricolor L.*
	Cauliflower	*Brassica oleracea L. var. botrytis L.*
	Cabbage	*Brassica oleracae L. var. capiatata L.*
	Pak-choi, Chinese cabbage	*Brassica rapa L. chinensis (L.) Hanelt*
	Kale	*Brassica oleracea L. var. viridis L.*
	Kohlrabi	*Brassica oleracea L. var. gonylodes L.*
	Lettuce	*Lactuca sativa L.*
	Leek	*Allium porrum L.*
	Swiss chard	*Beta vulgaris L. subsp. cicla (L.) W.D.J. Koch var. flavescens (Lat.) Lat&DC*
	Spinach	*Spinacia oleracea L.*
	Celery	*Apium graveiolus L. var. dulce (Mill.) Pers.*
	Chinese lettuce	*Lactuca sativa L. var. angustana L.H. Bailey*
	Sorrel	

TABLE 89. PLANT GROUPS, WITH COMMON AND LATIN NAMES OF ASSOCIATED CROPS [5] (cont.)

Plant group	Common name	Latin name
Non-leafy vegetables	Tomato	*Lycopersicon esculentum Mill.*
	Ladies' fingers (gumbo, okra)	*Abelmoschus esculentus (L.) Moench*
	Eggplant (brinjal)	*Solanum melongena L.*
	Bottle gourd	*Lagenaria siceraria (Molina) Standl.*
	Pepper, banana pepper	*Capsicum annuum L. var. annuum*
	Amaranthus (pigweed)	*Amaranthus L. spp.*
	Red chili (pepper)	*Capsicum frutescens L.*
	Eggplant	*Solanum melongena L.*
	Cucumber	*Cucumis sativus L. var. sativus*
	Squash (American)	*Cucurbita pepo L.*
	Pumpkin (English)	*Cucurbita pepo L.*
	Vegetable marrow	*Cucurbita pepo L.*
	Zucchini	*Cucurbita pepo L.*
	Onion	*Allium cepa L.*
	Garlic	*Allium sativum L.*
	American artichoke	*Helianthus tuberosus L.*
	Pepper	*Capsicum annuum L. var. annuum*
Leguminous vegetables	Peas (garden pea, field pea)	*Pisum sativum L.*
	Chickpea, garbanzo	*Cider arietinum L.*
	Hyacinth bean	*Lablab purpureus (L.) Sweet subsp. purpureus*
	Soybean, soya	*Glycine max (L.) Merr.*
	Soya (wild soybean)	*Glycine max (L.) Merr. (= Glycine hispida L.)*
	Bean (field, kidney, French)	*Phaseolus vulgaris L. cultivars*
	Lentil	*Lens culinaris Medik. subsp. culinaris (Ervum lens L.)*
	Asiatic haricot bean (mung bean)	*Phaseolus aurens Roxb. = Vigna radiate (L.) R. Wilczek*
	Horse beans	*Vicia faba L., var. equina Pers.*
Root crops	Beet, beetroot, red beet/mangold	*Beta vulgaris L. subsp. vulgaris (Crassa Group)*
	Sugarbeet	*Beta vulgaris L. subsp. vulgaris*
	Turnip (swede)	*Brassica napus L. var. napobrassica (L.) Rchb.*
	Radish	*Raphanus sativus L.*
	Carrot	*Daucus carota L. subsp. Sativas (Hoffm.) Arcang.*
	Manioc, manihot; cassava, yucca, tapioca	*Manihot esculenta Crantz,* *Manihot ultissima*
Tubers	Potato	*Solanum tuberosum L. subsp. tuberosum*
	Yam	*Dioscorea L. spp.*
	Arrowhead	*Sagittaria sagittifolia L. subsp. Leucopetala (Miq.) Hartog*
	Sweet potato	*Ipomoea batatas L.*

TABLE 89. PLANT GROUPS, WITH COMMON AND LATIN NAMES OF ASSOCIATED CROPS [5] (cont.)

Plant group	Common name	Latin name
Fruits	Apple	*Malus domestica Borkh.*
	Date palm	*Phoenix dactylifera L.*
	Banana	*Musa L.* spp.
	Papaya	*Carica papaya L.*
	Pear	*Pyrus L.* spp.
	Cherry	*Prunus L.* spp.
	Apricot	*Prunus armeniaca L.*
	Peach	*Prunus persica (L.) Batsch var. Persica*
	Prunes or plums	*Prunus domestica L.*
	Strawberry	*Fragaria ananassa Duchesne*
	Black currant	*Ribes nigrum L.*
	Red currant	*Ribes rubrum L.*
	Gooseberry	*Ribes uva-crispa L.*
	Raspberry	*Rubus ideaus L.*
	Blackberry	*Rubus L. spp.*
	Melon	*Cucumis melo L.*
	Watermelon	*Citrullus lanatus (Thunb.) Matsum. & Nakai*
	Lemon	*Citrus limon (L.) Burm.*
	Orange	*Citrus sinensis (L.) Osbeck*
	Grapefruit	*Citrus paradisi Macfad.*
	Mandarin	*Citrus reticulate Blanco*
	Avocado	*Persea Americana Mill. var. americana*
	Mango	*Mangifera indica L.*
	Grapes	*Vitis L.* spp.
	Olive	*Olea europaea L. subsp. europaea*
	Blueberry	*Vaccinium L.* spp.
	Pineapple	*Ananas comosus (L.) Merr.*
	Pomegranate	*Punica granatum L.*
Grasses (cultivated species)	Sudan grass	*Sorghum sudanensis (Piper) Sterf.*
	Perennial ryegrass	*Lolium perenne L.*
	Annual ryegrass	*Lolium multiflorum Lam. var. Westerwoldicum*
	Bromegrass (smooth brome)	*Bromus inermis (Leyss.) Holib.*
	Smooth bromegrass	*Bromus racemosus L.*
	Quack grass, couch grass	*Elytrigia repens (L.) Desv. ex Nevski.*
	Siberian crested wheatgrass	*Agropyron fragile (Roth) P. Candargy subsp. sibircum (Willd.) Melderis*
	Standard crested wheatgrass	*Agropyrum desertorum Fisch. ex Link Schult.*
	Fairway crested wheatgrass	*Agropyrum cristatum (L.) Gaertn.*
	Timothy grass	*Phleum pratense L.*
	Meadow fescue	*Festuca pratensis Huds.*

TABLE 89. PLANT GROUPS, WITH COMMON AND LATIN NAMES OF ASSOCIATED CROPS [5] (cont.)

Plant group	Common name	Latin name
Grasses (cultivated species)	Redtop (Am.) creeping bent grass (Eur.)	*Agrostis gigantean Roth (American) or Agrostis stolonifera L. (European)*
	Orchard grass, cocksfoot	*Dactylis glomerata L.*
	Bluegrass, meadow grass	*Poa annua L.*
	Bluegrass, meadow grass	*Poa steppe (Kryl.) Roshev.*
	"Grass"	*Gramineae*
	Reed grass	*Calamagrostis Adans.* spp.
	Sedge	*Carex L.* spp.
	Sheep fescue	*Festuca ovina L.*
Leguminous fodder (cultivated species)	Spring vetch (common vetch)	*Vicia sativa L.*
	Leucaena	*Leucaena leucocephala (Lam.) de Wit*
	Desmodium	*Desmodium Desv.* spp.
	Winter vetch (hairy vetch)	*Vicia villosa Roth.*
	Peas (field pea)	*Pisum sativum L. subsp. sativum var. arvense (L.) Poir.*
	Grass peavine, grass pea	*Lathyrus sativus L.*
	Lupin yellow	*Lupinus luteus L.*
	Lupin (blue lupin)	*Lupinus angustifolius L.*
	Seradella	*Ornytorus sativus L. Ornithopus satious Brot.*
	Bean (fava bean, broad bean)	*Vicia faba L.*
	Clover (crimson clover)	*Trifolium incarnatum L.*
	Alfalfa (Black Medic)	*Medicago lupulina L.*
	Alfalfa blue	*Medicago sativa L.*
	Alfalfa yellow	*Medicago sativa L. falcate (L.)*
	Alfalfa hybrid	*Medicago sativa L. varia (Martyn)*
	Clover red	*Trifolium pratense L.*
	Clover (hybrid clover)	*Trifolium hybridum L.*
	Clover white	*Trifolium repens L.*
	Esparsetter (animal forage)	*Onobrychis Mill.*
	Sweet clover, white	*Melilotus albus Medik.*
	Sweet clover, yellow	*Melilotus officinalis Lam.*
Pasture (species mixture)	Grass–leguminous mixture (festuca + timothy–clover, oats–clover….)	
	Natural grasses mixture	
	Undefined mixture	
	Canadian thistle	*Cirsium arvense (L.) Scop.*

TABLE 89. PLANT GROUPS, WITH COMMON AND LATIN NAMES OF ASSOCIATED CROPS [5] (cont.)

Plant group	Common name	Latin name
Herbs	White mustard	*Sinapis alba L.*
	Basil, sweet basil	*Ocimum basilicum L.*
	Nigundi	*Vitex negundo L.*
	Coriander, cilantro	*Coriandrum salivum L.*
	Parsley	*Petroselinum crispum (Mill.) Nyman ex A.W. Hill*
	Spearmint	*Mentha spicata L.*
	Dill	*Anethum graveolens L.*
	African spider flower	*Cleome gynadra L.*
	Milkweed, crownplant (giant milkweed)	*Calotropis gigantea (L.) Dryand. ex W.T. Aiton*
	Cassia	*Cassia tora L.*
	Seaside clerodendrum (tubbeflower, Turk's turban)	*Clerodendrum indicum (L.) Kuntze*
	Wild indigo, fish poison	*Tephrosia purpurea (L.) Pers.,* *T. sinapou (Buc'hoz) A. Chev.*
	Hogweed (red hogweed, red spiderling)	*Boerhavia L.*
	Indian and leaf mustard	*Brassica juncea L.*
	Tea	*Camella sinensis L.*
	Thyme	*Thymus L.*
Other crops	Rape (winter rape)	*Brassica napus L.*
	Margosa	*Azadirachta indica A. Juss.*
	Walnut	*Juglans regia L.*
	Canola, rape	*Brassica napus L. napus*
	Sunflower	*Helianthus annuus L.*
	Peanut	*Arachis hypogaea L.*
	Flax	*Linum usitatissiumum L.*
	Tobacco	*Nicotiana tabacum L.*

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This report provides data for use in assessments of routine discharges of radionuclides to terrestrial and freshwater environments. Some of the data may also be useful for assessing the impacts of accidental releases and releases in the future. The report provides information on radionuclides and on processes to be taken into account in assessments of the radiation impact of radionuclide discharge to terrestrial and freshwater ecosystems. The data collected here are relevant to the transfer of radionuclides through food chains to humans. Radionuclide transfers to non-human species are not specifically addressed; however, in many situations the data are also applicable for assessments of such transfers. Although the data primarily relate to equilibrium conditions — that is, conditions where equilibrium has been established between movements of radionuclides into and out of compartments of the environment — some data relevant to time dependent radionuclide transfer in the environment are also included.

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