TRS-XXXX Limited Distribution

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 been publishing documents aimed at the support of the assessment of the radiation impacts on both human beings and the environment. Two major supporting data documents, namely, the Technical Reports Series No. 247 (TRS 247) "Sediment K_ds and Concentration Factors for radionuclides in the Marine Environment" and Technical Report Series No. 364 (TRS 364) "Handbook of parameter values for the prediction of radionuclide transfer in temperate environments" have been published in 1985 and in 1994 respectively. Together, these documents provided a full set of available transfer parameter values for Marine, Freshwater and Terrestrial environments and over many years these documents have been key references for radioecologists, modellers and authorities in Member States, providing environmental impact assessments.

Since publication of these documents, a number of high quality publications have been produced for many of the transfer parameter values which merit consideration. Therefore, in 2000 the IAEA initiated a revision of TRS 247 resulted in the publication of Technical Report Series Document No. 422 “Sediment Distribution Coefficient and Concentration Factors for Biota in the Marine Environment" (2004), covering both the new obtained data and changes in regulatory framework since that time.

In 2003, in the framework of the IAEA EMRAS ("Environmental Modelling for RAdiation Safety") project, the IAEA started a revision of TRS 364. In TRS 364 some important details and recommendations were omitted that constrained usefulness in helping assessors to make appropriate choices of necessary transfer parameters. This problem has being resolved by publishing the IAEA TECDOC “Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments”, overcoming the limitations of the former document, and comprises both updated transfer parameter values and radioecological concepts that were found to be important for radiation safety. Thus, the current report contains parameters of radionuclide transfer in the environments, referring for the necessary details to the IAEA TECDOC “Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments”.

The document was prepared by members of the EMRAS project Working Group 1, Theme 1 “Revision of the IAEA Technical Reports Series No. 364: Handbook of parameter values for the prediction of radionuclide transfer in temperate environments”. The group was initially chaired by P. Santucci (IRSN, France), followed by P. Calmon (IRSN, France). The IAEA scientific officers for this Working group were S. Fesenko and G. Voigt of the Department of Nuclear Sciences and Applications.

The IAEA wishes to express its gratitude to the WG members who provided contribution to the TRS and assisted in its drafting and review. A full listing of the contributors is given at the end of the document.

The IAEA officer responsible for this publication was S. Fesenko of the Department of Nuclear Sciences and Applications

CONTENTS

INTRODUCTION

1.1. BACKGROUND

The impacts of planned discharges of radionuclides to the environment are being assessed by means of mathematical models which approximate the transfer of radionuclides through the compartments of the environment [1.1]. These models can be used as tools to assess 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 of 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 impractical and/or overly costly and reliance is placed, in the first instance, on data obtained from the literature. Often such data can provide a sufficiently accurate 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 [1.1, 1.2] and 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 as IAEA Technical Reports Series no 364 [1.3]. A similar collection relevant to transfer in the marine environment has also been published by the IAEA and updated in 2004 [1.4]. These data collections draw upon data collected in many countries of the world and have come to be regarded as international reference values.

Since the publication of TRS 364, new data sets have become available, and it has been considered timely to update the document. The present document supersedes TRS 364, considerably expanding information for ecosystems others than temperate, radionuclides and processes to be taken into account in the assessment of the radiation impact of radionuclide discharge into the terrestrial and freshwater environments.

The data in this document relate mainly to equilibrium conditions, that is, where equilibrium has been established between the movement of radionuclides into and out of the compartments of the environment. Such a situation may exist during the controlled and continuous release of radionuclides into 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 included in this document, for example, for foliar uptake: weathering and translocation, for root uptake: long term dynamic of transfer factors, and some semi-natural ecosystems.

The data contained in this document are generally presented as ranges of observed values together with mean values determined by statistical methods - where the available data permit. The statistical approach is described in Chapter 2. The data can be used for various purposes, in particular:

- 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 under-prediction. If, with the use of this approach, regulatory targets are met, then no further assessment is usually needed. This is the approach described in IAEA Safety Reports Series No. 19 “Generic Models for Assessing the Impact of Discharges of Radioactive Substances to the Environment” [1.1]. 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.

- 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 for obtaining realistic estimates of radiation dose, generic data sets are no substitute for site specific data.

A specific task of the TRS-364 revision was to provide transfer parameter values which are the most commonly used in radiological assessment models. However, some important details and recommendations on how to use these parameters were also omitted in TRS 364 that constrained usefulness in helping assessors to make appropriate choices of necessary transfer parameters. Besides, the data sets reviewed for the purpose of producing this document are very extensive and in some topic areas the tables contain only summaries of the available data. The document is therefore supported by a TECDOC which accompanies this document and contains the full collection of the reviewed data and the methods used to obtain the tabulated data values [1.6]. This TECDOC also gives necessary clarifications how the tabulated values were derived and provides radioecological concepts and models facilitating use of these values in specific situations.

1.2. OBJECTIVES

This document 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 parts of the data may also find use for assessing the impact of accidental releases and releases in the far future.

1.3. SCOPE

This document covers radionuclide transfer in the terrestrial and freshwater environments. The data collected in this document are relevant to the transfer of radionuclides through foodchains to humans and are not specifically addressed to the radionuclide transfers to non-human species. However, in many situations, they are also applicable for the assessments of radionuclide transfer to non-human species. The data relate mainly to equilibrium conditions, that is, where equilibrium has been established between the movement 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 the document is on transfer parameter values; the models in which they are used are not usually described here. Typical models applied in the context of the control of routine releases are described in another IAEA publication [1.1].

1.4. STRUCTURE

The report consists of 12 chapters and 2 appendixes. Definitions and units, classifications used as well as necessary details of data analysis are given in Chapter 2. The next nine chapters give data relevant to parameters for a range of different environmental transfer processes. Chapters 3, 4 and 5 are all directly related to contamination of plants, foliar uptake, mobility in soil and uptake from soil by plants, respectively. Chapter 6 considers radionuclide transfers to agricultural animal products. Data for parameters for modelling radionuclide transfer to products from semi-natural extensive ecosystems (forests, uplands and polar ecosystems) are given in Chapters 7 and 8. Chapter 9 is devoted to transfer of radionuclides to food products in freshwater ecosystems. For some radionuclides, in particular, 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 presented in Chapter 10. Chapter 11 gives information on the impact of different methods of food processing on decontamination of food. Finally the application of analogues approaches to filling data gaps are described in Chapter 12. The Appendixes provide reference information applicable to one of more of the preceding chapters.

REFERENCES

[1.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances, IAEA Safety Reports Series No. 19, Vienna (2001).

[1.2] INTERNATIONAL ATOMIC ENERGY AGENCY, Generic Models and Parameters for Assessing the Environmental Transfer of Radionuclides from Routine Releases: Exposures of Critical Groups, Safety Series No. 57, IAEA, Vienna (1982).

[1.3] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, Technical Reports Series No. 364, IAEA, Vienna (1994).

[1.4] INTERNATIONAL ATOMIC ENERGY AGENCY, Sediments and Concentration Factors for Radionuclide in the Marine Environment, Technical Reports Series No. 422, IAEA, Vienna (2004).

[1.5] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of radionuclide transfers in terrestrial and freshwater environments for radiological assessments, TECDOC No. xxx, IAEA, Vienna (2009).

2. DEFINITIONS AND DATA ANALYSIS

2.1. BASIC DEFINITIONS

Generic quantities and units used across the entire document are given below (Table 2.1). Generic quantities and terms are either as defined by the ICRU report on quantities and units [2.1] as used by the IAEA or are those in common usage. The definitions of specific terms are also given in each chapter.

TABLE 2.1. QUANTITIES AND UNITS USED IN THIS DOCUMENT

Symbol used in the current document	Name	Definition	Unit
Foliar uptake			
α	Interception coefficient	The interception coefficient, α, is the ratio of the initial mass activity density on the plant (A_m in Bq kg^{-1}) per unit area activity density (A_α in Bq m^{-2}) on the terrestrial surface (soil plus vegetation).	m^2 kg^{-1}

TABLE 2.1. QUANTITIES AND UNITS USED IN THIS DOCUMENT (Cont.)

Symbol used in the current document	Name	Definition	Unit
f_{tr}	Translocation ratio, translocation factor, translocation coefficient	The translocation ratio is 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 coefficient can be calculated as: (i) the mass activity density in the edible tissue (Bq kg^{-1}) in another tissue of the same plant or crop (ii) 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	K_s is the ratio of the volumetric activity density, A_v, measured in air or water (Bq m^{-3}) to the areal activity density. A_a, measured on the soil or sediment surface (Bq m^{-2}).	m^{-1}
Soil mobility			
K_d	Distribution coefficient	K_d is 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}) in the specified liquid phase.	L kg^{-1}
Soil to plant transfer			
F_v	Concentration ratio	F_v is 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 absorbed fraction is the fraction of the ingestion intake by an animal that is transferred to a specified receptor tissue.	dimensionless
F_m, F_f	Feed transfer coefficient	C_{fr} is the mass or volumetric activity density in the receptor tissue or product of an animal (Bq kg^{-1} wet mass or Bq L^{-1}) divided by the daily intake (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	T_{ag} is the mass activity density (Bq kg^{-1}) in a specified object per unit area activity density, A_a (Bq m^{-2}) in the soil.	m^2 kg^{-1}
Transfer in freshwater ecosystems			
CR	Concentration ratio water-biota	*CR* is the ratio of the contaminant concentration in biota (C_b) from all exposure pathways (including water, sediment and ingestion/dietary pathways) on a per unit of fresh mass of the tissue relative to that of water (C_w)	dimensionless
CR_s	Concentration ratio sediment-biota	CR_s is the ratio of the concentration of a radionuclide in an organism (C_b) on a per unit tissue (fresh weight) relative to the value measured in the sediment (C_{sed}) on a per unit fresh sediment basis	dimensionless
Specific activity approaches			
CR_s	Concentration ratio	CR_s is the ratio of the tritiated water (HTO) concentration in soil water to that in air moisture.	dimensionless
R_p, R_f	Partition factor	The partition factor for plants (R_p) is the ratio of non-exchangeable organically bound tritium (OBT) concentration in the combustion water of plant dry matter to the concentration of tissue free water tritium in plant leaves. The partition factor for fish (R_f) is the ratio of OBT concentration in the combustion water of fish dry matter to the HTO concentration in fish flesh.	dimensionless

TABLE 2.1. QUANTITIES AND UNITS USED IN THIS DOCUMENT (Cont.)

Symbol used in the current document	Name	Definition	Unit
CR_a^{HTO}, CR_a^{OBT}	Concentration ratio	CR_a^{HTO} is the ratio of the total tritium concentration (HTO plus 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 food processing retention factor is 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 processing factors which is 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	Processing efficiency s the ratio of the fresh weight of processed food divided to weight of original raw material	dimensionless

2.2. DATA ANALYSIS

International databases of bibliographical references, reports from scientific institutions and some relevant national databases were consulted to derive values on radionuclide transfer in the environment. Priority was given to data from original publications rather then review sources, although the latter have bee used in some chapters.

The data presented here are derived from the TECDOC "Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments" [2.2], where the available data have been 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 a bibliographical search has been limited to: (i) published documents within the international scientific community and, depending on their accessibility, (ii) reports from different scientific institutions. Priority was given to data from original publications to ensure all the information that they contained, rather than relying on summaries of such information. During the second step, databases were elaborated, where necessary (see [2.2] for details).

Estimation of the transfer parameter values and the extent of uncertainty about every such value has been carried out by applying statistical analysis, where possible. In the ideal case, if three or more values were available, a geometric mean (GM) has been given as the mean value. The uncertainties assigned to the geometric mean were estimated by the geometrical standard deviation (GSD). The two values are shown in the reported ranges with minimum and maximum values, the arithmetic mean (AM) and the standard deviation (SD). Thus mean given in the tables of the TRS depending on number of values used for a statistical analysis may be as a geometric as an arithmetic mean with corresponding uncertainties. The number of data (N) is also reported. In some cases, the values were given without a statement of uncertainty or range because of the limited data available. The values in such cases should be used with a great caution (see [2.2] for details).

2.3. TIME DEPENDENCE OF RADIONUCLIDE TRANSFER FACTORS

By definition, both concentration-based 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 migration of radionuclides down 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 time changes in radionuclide activity concentrations in environmental compartments are often termed as 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 give organ (or tissues) because of action of all possible factors, excepting radioactive decay. For example, if a sheep contaminated with radiocaesium is fed uncontaminated feed for a period, 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:

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

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

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

In most cases, however, animals (or plants) remain in the contaminated environment, ingesting contaminated food, so they continue to intake radionuclides. Thus, long term declines in activity concentrations in plants and animals occur at slower rates 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 all processes (except radioactive decay) which 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, e.g., 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:

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

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

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

If radioactive decay (characterized by a 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 $T_{1/2}^{eff}$ is given by:

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

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

$$T_{ag}(t) = T_{ag}(0) \cdot \left(a_1 \cdot e^{-\frac{\ln 2}{T_1^{eff}} \cdot t} + (1-a_1) \cdot e^{-\frac{\ln 2}{T_2^{eff}} \cdot t} \right) = T_{ag}(0) \cdot e^{-\frac{\ln 2}{T_r} \cdot t} \cdot \left(a_1 \cdot e^{-\frac{\ln 2}{T_1^{ecol}} \cdot t} + (1-a_1) \cdot e^{-\frac{\ln 2}{T_2^{ecol}} \cdot t} \right)$$

where T_{eff1} is the fast loss component; T_{eff2} is the slow loss component, $T_{ag}(0)$ is the initial concentration and a_1 is the initial fraction of the concentration associated with the fast loss term (numbered 1). 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 splitting parameters according to food types, soil groups, type of deposition or environmental conditions. Where possible, this has been done in this handbook, however, where data were few, or not specified in sufficient details 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. In the FAO/UNESCO soil classification, there are 28 units and 125 sub-units [2.4]. F_v values are not available for all units or sub-units, 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 are available for each category.

For this document, four soil groups were defined: sand, loam, clay and organic (Table 2.2).

TABLE 2.2. TYPICAL RANGES OF VALUES FOR VARIOUS SOIL PARAMETERS FOR THE SOIL GROUPS ADOPTED

Soil group	pH	% OM	CEC, $cmol_c$/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	-	-

Soils were grouped according to the sand and clay mineral percentages referred to 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 former TRS-364. For the mineral soils, three groups were created according to the sand and clay percentages referred to the mineral matter [2.5]: “Sand group”: sand fraction ≥ 65 %; clay fraction < 18 %; “Clay group”: clay fraction ≥ 35 %; “Loam group”: rest of cases. 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, or 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 IAEA TECDOC [2.2].

Based on the analyses of available information on radionuclide transfer to plants [2.4-2.6], fourteen plant groups have been identified (Table 2.3).

TABLE 2.3. PLANT GROUPS AND PLANT COMPARTMENTS

Plant groups	Plant compartments
Cereals	Grain, seeds and pods
	Stems and shoots
Maize	Grain, seeds and pods
	Stems and shoots
Rice	Grain, seeds and pods
	Stems and shoots
Leafy vegetables	Leaves
Non-Leafy vegetables	Fruits, heads, berries, buds
Leguminous-vegetables	Grain, seeds and pods
Root crops	Roots
Tubers	Tubers
Fruits	Fruits, heads, berries, buds
Grasses (cultivated species)	Stems and shoots
Fodder Leguminous (cultivated species)	Stems and shoots
Pasture (species mixture - natural or cultivated)	Stems and shoots
Herbs	Leaves; Grain, seeds and pods; Fruits, heads, berries, buds
Other crops	Grain, seeds and pods; Leaves; Stems and shoots; Fruits, heads, berries, buds; R – roots; T – tubers

Assignment of individual plants to these groups is given in the Appendix II while plant compartments are also shown in Table 2.3.

REFERENCES

[2.1] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, ICRU Report 65. Quantities, Units and Terms in Radioecology. Journal of the ICRU 1 2 (2001).

[2.2] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments, TECDOC No. xxx, IAEA, Vienna (2009).

[2.3] INTERNATIONAL UNION of RADIOECOLOGIST, Sixth report of the working group soil-to-plant transfer factors. European Community Contract B16-052-B, (1989).

[2.4] FOOD AND AGRICULTURE ORGANISATION, UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION, Soil map of the world 1 : 5 000 000. UNESCO, Paris (1994).

[2.5] INTERNATIONAL ATOMIC ENERGY AGENCY, Classification of soil systems on the basis of transfer factors of radionuclides from soil to reference plants, IAEA-TECDOC-1497, IAEA, Vienna (2006).

[2.6] INTERNATIONAL UNION of RADIOECOLOGIST. Working group soil to plant transfer. Protocol developed between 1982 and 1992. Contact address for protocol: e-mail frisselm@bart.nl. Contact address for IUR secretariat e-mail: Per.Strand@nrpa.no.

3. AGRICULTURAL ECOSYSTEMS: FOLIAR UPTAKE

The deposition of radionuclides on vegetation and soil represents the starting point for 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 within 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 in activity concentration due to effective dilution. There is also a systemic transport (translocation) of radionuclides in the plant subsequent to foliar uptake, leading to the redistribution of a chemical substance, once it has been 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 chapter 1). The simplest way is the interception fraction f (dimensionless), which is defined as the ratio of the activity initially retained by the standing vegetation A_i immediately subsequent to the deposition event to the total activity deposited A_t:

$$f = \frac{A_i}{A_t} \qquad (3.1)$$

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}):

$$f_B = \frac{f}{B} \qquad (3.2)$$

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

Chamberlain [3.1] defined the interception fraction f (eq. 1) for dry deposition in terms of a dependence on the standing biomass B (kg/m², dry mass) and the empirically derived mass interception coefficient α :

$$f = 1 - \exp(-\alpha \cdot B) \quad (3.3)$$

The mass interception fraction f_B (eq. 3.2) is then derived to take into account the dependence of the interception fraction on the biomass *B* using:

$$f_B = \frac{1 - \exp(-\alpha \cdot B)}{B} . \quad (3.4)$$

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

3.1.2. Interception fraction

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 a plant canopy. The interception increases during a rainfall event until the water storage capacity is achieved 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 a water film (in mm) that covers the foliage. Since the capacity of plant canopy to retain water is limited, the interception fraction decreases in general with increasing amount of rainfall in a rainfall event. The interception of a wet-deposited radionuclide 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 properties of a cation exchanger. Therefore, the initial retention of anions such as iodide is less than for polyvalent cations, which seem to be effectively retained on the plant surface.

For dry deposition, particle size is the other key parameter. Interception is more effective for small particles and reactive gases. Interception of wet-deposited radionuclides 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.

More details on processes governing interception of radionuclides by plants, including all available information sources, are given elsewhere [3.2] while summaries of available interception fraction values for wet and dry depositions are presented in Tables 3.1-3.2.

TABLE 3.1. OBSERVED INTERCEPTION FRACTION VALUES FOR WET DEPOSITION TO CROPS

Element	Crop	Standing biomass (kg m^{-2})	Amount of rainfall, mm	f	f_B, m² kg^{-1}	Ref.
Chernobyl deposits						[3.3-3.6]
Ba	Grass	n.a.			1.7	
Cs	Grass				1.1	
I	Grass				0.7	
Ru	Grass				0.48	
Simulated Rain						
Be			1		3.2±0.91	[3.7-3.9]
			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[a]	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	[3.13]
Cd					1.8	
Cr					1.3	
Sr					1.0	
Ce					0.94	
S					0.35	
I					0.27	

TABLE 3.1. OBSERVED INTERCEPTION FRACTION VALUES FOR WET DEPOSITION TO CROPS

Element	Crop	Standing bio-mass (kg m^{-2})	Amount of rainfall, mm	f	f_B, m² kg^{-1}	Ref.
Cs[b]	Wheat	n.a.	0.4	0.03[c]	1.4	[3.14]
			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 [3.10-3.12]						
Mixture of nuclides	Rice	0.079	0.03-0.04	0.48	6.0	
		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	
		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	
		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	
		0.044		0.67	15	
		0.089		0.82	9.3	
		0.15		0.86	5.9	
		0.17		0.86	5.2	

[a]retention of radionuclide-free water, [b] Rainfall intensity: 4.4 mm h^{-1}; [c] *LAIF*: Interception fraction per unit leaf area

TABLE 3.2. INTERCEPTION FRACTION VALUES FOR DRY DEPOSITION TO CROPS

Deposited material	Particle Diameter (μm)	Crop	f or f_B (m² kg^{-1}) or (α) or (f/LAI) AM±SD	Reference
Lycodium spores	32	Grass	3.1±0.15 (α)	[3.1]
		Wheat, dry	3.2±0.5 (α)	[3.1]
		Wheat, moist	9.6±3.7 (α)	[3.1]
Quartz particles	44-88	Grass	2.7±0.3 (α)	[3.15]
Sand particles	40-63	Grass, dry	0.44±0.15 (α)	[3.16]
		Grass, wet	0.88±0.13 (α)	[3.16]
	63-100	Grass, dry	0.23±0.07 (α)	[3.16]
		Grass, wet	0.69±0.16 (α)	[3.16]
	100-200	Grass, dry	0.24±0.07 (α)	[3.16]
		Grass, wet	0.46±0.11 (α)	[3.16]
Pu particles	≈1	Corn	3.6±0.05 (α)	[3.17]
I vapour		Grass	2.8±0.14 (α)	[3.17]
Pb vapour		Artificial grass	13 (α)	[3.18]
Ba, Cs, Sr[a]	3.5	Beans 30 d[b]	1-1.2 (α)	[3.19]
		45 d	1.1 (α)	[3.19]
		65 d	0.85-0.93 (α)	[3.19]
Ba, Cs, Sr, Te[a]		85 d	0.3 (α)	[3.19]
Ba, Cs, Sr, Te[a]	3.5	Grass	0.84±0.06 (f)	[3.19]
			3.27±1.15 (α)	[3.19]
Cs, Sr[a]		Wheat	$f = 1 - \exp(-0.316 \cdot LAI)$	[3.4]
			$f = 0.85 \cdot (1 - \exp(-13.1 \cdot B))$ [c]	[3.4]
Spherical porous silica particles	4	Lettuce	0.71±0.1 (f)	[3.20]
	10		0.88±0.07 (f)	[3.20]
	18		0.88±0.08 (f)	[3.20]
	22		0.81±0.23 (f)	[3.20]
	4	Wheat	0.56±0.29 (f)	[3.20]
	22		0.65±0.13 (f)	[3.20]
Spherical porous silica particles	4	Wheat	1.6 (f)	[3.21]
	22		1.2 (f)	[3.21]
Uranium particles (wind tunnel)	0.82	Spruce (LAI=3.1)	0.97 (f)	[3.22]
Cs, Sr		Rice	0.04-0.12 (f_{LAI}), n=6	[3.23]
		Wheat	0.05-0.09 (f_{LAI}), n=2	[3.23]
		Carrot	0.1-0.3 (f_{LAI}), n=2	[3.23]
		Cabbage	0.18-0.2 (f_{LAI}), n=2	[3.23]
		Tomato	0.08-0.9 (f_{LAI}), n=2	[3.23]

[a] dissolution in rain water after 2 h: Cs, Ba: 95%, Sr: 75%, Te: 8%; [b]days after sowing, [c] B - Yield (kg m^{-2}, dry mass)

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 [3.9]. The biomass density or the leaf area index may be used to quantify the development of the plant. During vegetative growth, both approaches are equally appropriate, whereas, during the generative phase, the leaf area index is a more adequate 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 are less if it is normalised to the standing biomass or to the leaf area index.

The existing data show 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. A deeper knowledge about 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, f_{LAI} are all determined during single experiments; before the application, it should be checked whether the experimental conditions are consistent with specific deposit. The parameter f represents absolute interception, whereas α, f_B and f_{LAI} are normalized to the biomass and the leaf area index respectively; therefore the variability for of the latter parameters are less pronounced.

The interception of wet deposits decreases with increasing amount of rainfall during which the deposition occurs. For wet deposits, these dependencies on rainfall and are taken into account in the approach described in Müller and Pröhl (1993) [34] 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:

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

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 the water storage capacity, 0.2 mm is assumed for grass, cereals and corn, and 0.3 mm 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 both, dry and wet deposits, for continuous releases, average values for the standing biomass or for the leaf area indices should be applied. If the growth functions for a specific crop or 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 characterised by a first-order rate constant λ_w or a weathering half-life T_w:

$$\lambda_w = \frac{Ln(2)}{T_w} \qquad (3.6)$$

3.2.2. Weathering half lives

Results from numerous studies showed limited differences between cationic species (Mn, Co, Sr, Ru, Cs) for most plant species, but also showed that T_w values are dependent on plant characteristics such as plant growth stage at the time of deposition [3.24]. Available data summarised based on information presented in the accompanying TECDOC [3.2] for different elements and plant groups are given in Table 3.3.

TABLE 3.3. WEATHERING HALF LIVES FOR DIFFERENT ELEMENTS AND GENERIC PLANT TYPES[1], days [3.2]

Element	Plant group	N	AM[2]	Min	Max
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; [2]arithmetic mean

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 of penetration into the inner flesh and ability for leaching 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 a very complex interaction of those factors may be the cause of the observed difference in weathering loss among radionuclides, 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 the other parts that have not been contaminated directly. Translocation factors have been defined differently by different authors. In the current document the translocation factor is defined as the ratio between the activity, on a ground area basis, of the edible part of a crop at harvest time (Bq m^{-2}) and 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 their transfer from the foliage to edible parts depends on many physical, chemical and biological factors [3.9, 3.25]. 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 [3.26-3.28]. Biological factors are mainly associated with the vegetative cycle at the time of the foliar deposit [3.29-3.32].

Experimental protocols for measurement of translocation have not yet been standardised. Hence, experimental protocols vary widely and results remain very heterogeneous. The main contamination scenarios include:

- simulations of sprinkling irrigation or contaminating rain at various timescales and intensities over the whole vegetation cover with or without soil protection, followed or not by non-contaminated rainfalls. That operating mode is the most realistic for investigation purposes;

- sprays of contaminated solution over the foliage, followed or not after drying by a non-contaminated rain deposit;
- foliar contamination by using a deposit of dry or wet aerosols, followed or not after drying by a non-contaminated rain deposit;
- deposit of droplets over part of or all the plant foliage with a view to detecting translocation and mobility mechanisms within the plant. However, the method is unable 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 the section were derived from compiling the data into a database, further information on source data, data analysis and a description of the factors governing translocation are given in the accompanying TECDOC [3.2]. Translocation factor values, as defined above, for cereals, root crops, tubers and fruits are presented in Tables 3.4-3.8.

TABLE 3.4. TRANSLOCATION FACTOR VALUES (f_{tr}) FOR CESIUM IN CEREALS (GRAIN), %

Plant growth stage	N	Mean	Min	Max
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 3.5. TRANSLOCATION FACTORS (f_{tr}) FOR STRONTIUM IN CEREALS (GRAIN), %

Plant growth stage	N	Mean	Min	Max
Wheat, barley and rye (grain)				
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 3.6. TRANSLOCATION FACTOR (f_{tr}) FOR OTHER ELEMENTS IN CEREALS (GRAIN), %

Element	Plant growth stage	N	Mean	Min	Max
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.[1]	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.d.	8	0.11	0.04	1.18

TABLE 3.6. TRANSLOCATION FACTOR (f_{tr}) FOR OTHER ELEMENTS IN CEREALS (GRAIN), % (Cont.)

Element	Plant growth stage	N	Mean	Min	Max
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
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	na	6	0.7	0.025	3.8
Ba	na	6	0.2	0.001	4.3
Hg	na	6	0.5	0.01	8
Na	na	6	2.0	0.17	7.0
Cr	na.	7	1.0	0.02	7.4
Be	na	6	0.2	0.001	2.7
Pb	na	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		

[1] .na. means not available

TABLE 3.7. TRANSLOCATION FACTORS (f_{tr}) FOR ROOT VEGETABLES AND TUBERS[1], %

Element	N	Mean	Min	Max
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

TABLE 3.8. TRANSLOCATION FACTORS (f_{tr}) FOR FRUITS[2], %

Element	Type of fruits	N	Mean	Min	Max
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		

3.3.3. Application of data

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

Many radioecological models use values based on poorly justified extrapolations or chemical analogies. This method is arbitrary insofar as the concept of analogy refers only to the chemical properties of the elements e. g. chemical analogy does not necessarily imply the same behaviour inside the plant, as shown for Ca and Sr [3.33] and Cs, K and Rb [3.34]. Besides, it does not take into account the various physiological and physicochemical mechanisms inside the plant which govern the translocation processes.

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[1] Plant growth stages are not given, it can be expected that the values are for mature vegetables.
[2] Plant growth stages are not given, it can be expected that the values are for mature fruits.

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 growth stage indication should be used with caution indicating the 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, as well as the aerodynamic loads related to the flow of wind. According to wind erosion models, three types of processes are used to describe the dispersion of particular contaminants deposited on surface soil [3.35-3.37]: 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 overland flow transport [3.38-3.40].

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 between the volumetric air concentration ($C_V(t)$, Bq m^{-3}) above the soil / vegetation surface and the initial surface soil contamination ($C_{S,0}$, Bq m^{-2}).

$$K(t) = \frac{C_V(t)}{C_{S,0}} \quad \left(m^{-1}\right)$$

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

3.4.2. Resuspension factor

The resuspension of radionuclides from accidentally contaminated sites has been documented for *in situ* measurements concerning plutonium and caesium contamination from the Chernobyl accident (see Table 3.10).

The characterisation of resuspension factors is a complicated task because of the number of processes involved. An extent of the resuspension depends on the material (particle size, shape and adherence), the surface type (roughness, humidity), the time lapsed after deposition and 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 should be used in the context of accidental releases to air. However, other types of model may be more appropriate in other contexts, e.g. in assessing the radiological impacts from contaminated land on sites that currently or formerly handled or processed radioactive materials [3.44].

For rural conditions, the model suggested by Garland [3.45]:

$$K_s(t) = 1.2 \cdot 10^{-6}\, t^{-1} \quad m^{-1} \qquad (3.13)$$

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 units in which time is expressed. Generally, time has units of days unless otherwise stated. Garland [3.45] advised that this formula should be applied to deposits older than 1 day.

For the urban environment, the Linsley model [3.46] provided the best results in the intercomparison exercises:

$$K_s(t) = 10^{-6} \exp(-0.01 \cdot t) + 10^{-9} \qquad m^{-1} \qquad (3.14)$$

This expression yields a resuspension factor that lies within the range of those estimated in *in situ* experiments. However, this expression tends to over-estimate short-term concentrations and to underestimate the long-term values. Moreover, 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 of [3.36] should be used. This gives values that are intermediate between those observed for urban and rural environments in the long term. The model form is:

$$K_s(t) = 10^{-6} \exp\left(-0.15\sqrt{t}\right) + 10^{-9} \qquad m^{-1} \qquad (3.15)$$

In the first days and first months that follow depositions, the values of the resuspension factor generally ranges between 10^{-5} m^{-1} in residential area, on a site undergoing cleanup operations and on an arid site and 10^{-6} m^{-1} on a rural site [3.41– 3.43]. In humid or semi-humid climates, resuspension is generally more important in urban conditions than in rural systems. However, this might not be the case in desert or semi-desert conditions environments. More details about processes governing resuspension as well as main achievements in resuspension modelling are given elsewhere [3.2].

3.4.2. Application of data

The values and models presented here are adapted for impacts studies focusing on the resuspension of radionuclides deposited accidentally in the natural environment. The measurements carried out in the context of Chernobyl provide a relatively homogeneous base to estimate 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 in the above table, especially on dry deposition, weathering and resuspension, 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 in parameter values were originally obtained is compatible with the way in which they are to be used in assessment calculations. This is particularly important in regard to the consistent use of units in which individual parameters are expressed.

REFERENCES

[3.1] CHAMBERLAIN, A.C, CHADWICK, R.C., Deposition of spores and other particles on vegetation and soil, Annals of Applied Biology **71** (1970), 141-158.

[3.2] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments, TECDOC No. xxx, IAEA, Vienna (2009).

[3.3] JACOB, P., MÜLLER, H., PRÖHL, G., VOIGT, G., BERG, D., PARETZKE, H.G., REGULLA, D., Environmental behaviour of radionuclides deposited after the reactor accident of Chernobyl and related exposures, Radiation and Environmental Biophysics **32** (1993) 193-207.

[3.4] VANDECASTEELE, C.M., BAKER, S., FÖRSTEL, H., MUZINSKY, M., MILLAN, R., MADOZ-ESCANDE, C., TORMOS, J., SAURAS, T., SCHULTE, E., COLLE, C., Interception, retention, translocation under greenhouse conditions of radiocaesium and radiostrontium from a simulated accidental source, Science of the Total Environment **278** (2001) 199-214.

[3.5] TOBA, L., OHTA; T., An observational study of the factors that influence interception loss in boreal and temperate forests, Journal of Hydrology **313** (2005) 208-220.

[3.6] ERTEL, J., PARETZKE, H.G., ZIEGLER, H., Cs-137 penetration by contact exchange through isolated plant cuticles: cuticles as asymmetric transport membranes, Plant Cell Environment **15** (1992) 211-219.

[3.7] ANGELETTI, L., LEVI, E.: Etude comparative des facteurs de transfert de l`eau, de l'iode et du strontium sur le ray-grass et le trèfle. Centre d'Etude Nucléaires, Fontenay-aux-Roses, France, Rapport CEA-R-4860, (1977)

[3.8] ANGELETTI, L., La contamination des paturages par l'iode-131; CEA-R-5056, (1980).

[3.9] HOFFMAN, F.O., THIESSEN, K.M., RAEL, R.M., Comparison of interception and initial retention of wet-deposited contaminants on leaves of different vegetation types, Atmospheric Environment **29** (1995) 1771-1775.

[3.10] CHOI, Y.H., LIM, K.M., YU, D., PARK, H.G., CHOI, Y.G., LEE, C.M., Transfer pathways of ^{54}Mn, ^{57}Co, ^{85}Sr, ^{103}Ru and ^{134}Cs in rice and radish plants directly contaminated at different growth stages, Annals of Nuclear Energy **29** (2002) 429-446

[3.11] CHOI, Y.H., LIM, K.M., PARK, H.G., LEE, W.Y., LEE, C.W., Contamination of Chinese cabbage with ^{85}Sr, ^{103}Ru and ^{134}Cs related to time of foliar application, Journal of the Korean Association for Radiation Protection **23** (1998) 219-227 (in Korean).

[3.12] LIM, K.M., PARK, D.W., PARK, H.G., CHOI, Y.H., CHOI, S.D., LEE, C.M., Analysis of the direct contamination pathway of ^{85}Sr, ^{103}Ru and ^{134}Cs in soybean (Proc. Korean Nuclear Society Spring Meeting, Cheju, Korea, May 24-25. 2001) (2001) (CD in Korean).

[3.13] HOFFMAN, F.O., THIESSEN, K.M., FRANK, M.L., BLAYLOCK, B.G., Quantification of the interception and initial retention of radioactive contaminants deposited on pasture grass by simulated rain; Atmospheric Environment **26** (1992) 3313-3321

[3.14] KINNERSLEY, R.P. GODDARD, A.J.M., MINSKI, M.J., SHAW, G., Interception of Caesium-contaminated rain by vegetation, Atmospheric Environment **31** (1997) 1137-1145.

[3.15] PETERS, L.N., WITHERSPOON, J.P., Retention of 44-88 μm simulated fallout particles by grasses, Health Physics **22** (1972) 261-266.

[3.16] ERIKSSON, A., Direct uptake by vegetation of deposited materials, Agricultural College of Sweden, Uppsala, Report SLU-IRB-42 (1977).

[3.17] PINDER III, J.E., CIRAVALO, T.G., BOWLING, J.W., The interrelationships among plant biomass, plant surface area, and the interception of particulate deposition on grasses, Health Physics **55** (1988) 51-58.

[3.18] CHAMBERLAIN, A.C., Interception and retention of radioactive aerosols by vegetation, Atmospheric Environment 4 (1966) 57-58.

[3.19] MADOZ-ESCANDE, C., HENNER, P., BONHOMME, T., Foliar contamination of *Phaseolus vulgaris* with aerosols of ^{137}Cs, ^{85}Sr, ^{133}Ba and ^{123m}Te: influence of plant development stage upon contamination and rain, Journal of Environmental Radioactivity **73** (2004) 49-71.

[3.20] WATTERSON, J.D., NICHOLSON, K.W., Dry deposition and interception of 4-22μm diameter particles to a lettuce crop, Journal of Aerosol Science **5** (1996) 759-767.

[3.21] NICHOLSON, K.W., WATTERSON, J.D., "Dry deposition of particulate material onto wheat" Precipitation Scavenging and Atmosphere-Surface Exchange, Vol.2, (SCHWARTZ, S.E. and SLINN, Eds) W.G.N., 673-683, Hemisphere, Washington DC (1992).

[3.22] OULD-DADA, Z., Dry deposition profile of small particles within a model spruce canopy, Science of the Total Environment **286** (2002) 83-96.

[3.23] SHANG, Z., Radioecological parameters Reference for China; Prepared for EMRAS working group on Revision of TRS 364, (2006).
[3.24] BUKOVAC, M.J., WITTWER, S.H. et al., “Above ground plant parts as a pathway for entry of fission products into the food chain with special reference to $^{89\text{-}90}$Sr and ^{137}Cs” Radioactive fallout, soils, plants, foods, man, (FLOWER, E., Ed.), Elsevier Press New York (1965) 82-109.
[3.25] KINNERSLEY, R.P., SCOTT, L.K., Aerial contamination of fruit through wet deposition and particulate dry deposition, Journal of Environmental Radioactivity **22** (2001) 191-213
[3.26] FRANKE, W., Mechanisms of foliar penetration of solutions, Annual Review of Plant Physiology **18** (1967) 281-300.
[3.27] AARKROG, A., LIPPERT, J., Direct contamination of barley with Cr-51, Fe-59, Co-58, Zn-65, Hg-203 and Pb-210, Radiation Botany **11** (1971) 463-472.
[3.28] AARKROG, A., Direct contamination of barley with Be-7, Na-22, Cd- 115, Sb-125, Cs- 134 and Ba- 133. RISOE report No. 256. Dannish Atomic Energy Commission (1972) 163-175.
[3.29] AARKROG, A., Radionuclide levels in mature grain related to radiostrontium content and time of direct contamination, Health Physics **28** (1975) 557-562.
[3.30] CARINI, F., Radionuclides in plants bearing fruit: an overview, Journal of Environmental Radioactivity **46(1)** (1999) 77-97.
[3.31] MIDDLETON, L.J., Radioactive strontium and caesium in the edible parts of crop plants after foliar contamination, International Journal of Radiation Biology **4** (1959) 387-402.
[3.32] SHAW, G., MINSKI, M.J. et al., Retention, loss and translocation of radionuclides applied to foliar surfaces of wheat. Environmental and Experimental Botany **32(4)** (1992) 391-404.
[3.33] KOPP, P., GORLICH, W. et al., Foliar uptake of radionuclides and their distribution in the plant, Proc. of Environmental Contamination Following a Major Nuclear Accident **2** (1990) 37-46.
[3.34] LEVI, E., Penetration, retention and transport of foliar applied single salts of Na, K, Rb and Cs, Physiologia Plantarum **23** (1970) 811-819.
[3.35] GARGER, E.K., HOFFMAN, F.O., THIESSEN, K.M., Uncertainty of the long-term resuspension factor, Atmospheric Environment **31** (1997) 1647-1656.
[3.36] ANSPAUGH, L. R., SHINN, J. H., PHELPS, P. L., KENNEDY, N.C., Resuspension and redistribution of plutonium in soils, Health Physics **29** (1975) 571-582.
[3.37] US DEPARTMENT OF ENERGY, Airborne Release of fractions/rates and respirable fractions for non-reactor nuclear facilities, DOE-HDBK-3010-94, December 1994
[3.38] VAN HEERDEN, W.M., An analysis of soil transportation by raindrop splash, Trans. ASAE **10** (1967) 166– 169.
[3.39] POESEN, J., An improved splash transport model, Zeitschrift fuer Geomorphologie **29** (1985) 193–221.
[3.40] WRIGHT, A.C., A physically based model of the dispersion of splash droplets ejected from a water drop impact, Earth Surface Processes and Landforms **11**(4) (1987) 351–367.
[3.41] LANGHAM, W.H., “Plutonium Distribution as a Problem in Environmental Science”, Proc. of Environmental Plutonium Symposium, (FOWLER, E.B., HENDERSON R.W., MILIGAN M.R., Eds.), Los Alamos National Laboratory, Los Alamos, NM, LA-1756 (1971) 3-11.
[3.42] INTERNATIONAL ATOMIC ENERGY AGENCY, Modelling of resuspension, seasonality and losses during food processing. Report of the Terrestrial Working group. IAEA-TECDOC-647, ISSN 1011-4289, IAEA, Vienna (1992).
[3.43] US DEPARTMENT OF ENERGY, Airborne Release of fractions/rates and respirable fractions for non-reactor nuclear facilities, DOE-HDBK-3010-94, December 1994
[3.44] NCRP Report No. 129, Recommended Screening Limits for Contaminated Surface Soil and Review of Factors Relevant to Site-Specific Studies. Issued January 29, 1999.
[3.45] GARLAND J.A., PATTENDEN N. J., PLAYFORD K., “Ressuspension following Chernobyl”, Modelling of resuspension, seasonality and loses during food processing. First report of the VAMP Terrestrial Working Group. IAEA-TECDOC-647, IAEA, Vienna (1992).
[3.46] LINSLEY, G. S. “Resuspension of the Transuranium Elements: A Review of Existing Data”, National Radiological Protection Board., Harwell, United Kingdom, (1978).

[3.47] LANGHAM, W.H., "Plutonium Distribution As a Problem in Environmental Science", Proc. of Environmental Plutonium Symposium, (FOWLER, E.B., HENDERSON R.W., MILIGAN M.R., Eds.), Los Alamos National Laboratory, Los Alamos, NM, LA-1756 (1971) 3-11.

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 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 affects their mobility, the residence time within the soil rooting zone, and uptake by biota.

The degree of radionuclide sorption to 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. The 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 [4.1]:

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

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 elapsed time 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 [4.2-4.3] (see accompanying TECDOC).

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 (e.g., from atmospheric nuclear weapons testing, or from Chernobyl), K_d values determined in situ may be higher than those determined in short-term laboratory experiments [4.1].

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 [4.4-4.10], and they can be used to group K_d values and to reduce the variability of K_d values with respect to when the grouping is based on fundamental properties, such as soil texture and organic matter. More detail of the use of co-factors in K_d grouping is provided in the corresponding paper in the accompanying TECDOC.

4.1.2. Vertical transfer of radionuclides in undisturbed soil profiles

The basic processes controlling 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 physico-chemical interactions with the soil matrix. In addition to abiotic processes, soil fauna may contribute to the transport of radionuclides in soils [4.11], and their action under general conditions results in a dispersion-like translocation [4.12].

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

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

Results from the serial compartment model to describe the vertical migration in soil are generally expressed as migration rates (cm/a). On the other hand, 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 *t*, the first two moments of the depth-distribution function are asymptotically:

$$E[z] \cong v_s \cdot t \tag{4.1}$$

$$\mathrm{var}[z] \cong 2 \cdot D_s \cdot t. \tag{4.2}$$

where D_s is the effective (or apparent) dispersion coefficient (cm² a^{-1}), and v_s is the convection velocity (cm a^{-1}) [4.13]. 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 ca. 0.6 $\left(= \frac{1}{\sqrt{\mathrm{e}}} \right)$ of its maximum:

$$v_s = \frac{z_M}{t} \tag{4.3}$$

$$D_s = \frac{(\Delta z)^2}{2t} \tag{4.4}$$

Values of D_s and v_s can be used in the convection-dispersion equation for a chosen time *t* to produce a vertical profile of the radionuclide. In some cases authors not only report 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 to that resulting from compartment model calculations. Therefore, all kind of migration rates may be combined, as shown in Table 4.5. For large migration times, the migration rate becomes equal to the convection velocity.

4.1.2. Relationship between K_d and other parameters characterizing radionuclide mobility

4.1.2.1. Relationship between K_d and vertical migration

In a porous medium like soils, the radionuclide diffusion process differs from diffusion in free water. An effective diffusion coefficient (D_e; m^2/s) must, therefore, be defined. Only the 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 one and for cationic radionuclides) to use 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) can be calculated from the diffusion profile into the sample.

The latter diffusion coefficient takes into account the retardation of the radionuclide due to interactions with the porous material. We may write:

$$D_a = \frac{D_e}{f_{ret}} \tag{4.5}$$

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, the f_{ret} can be defined as:

$$f_{ret} = 1 + (\frac{\rho}{\varepsilon}) \cdot K_d \tag{4.6}$$

where ρ is the dry bulk density of the soil.

If sorption of a radionuclide in 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:

$$D_s = \frac{D}{f_{ret}} \tag{4.7}$$

$$v_s = \frac{v_w}{f_{ret}} \tag{4.8}$$

where D_s, v_s are the effective dispersion coefficient and 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.

4.1.2.2. Relationship between K_d and root uptake

The radionuclide soil-to-plant 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 it) and in the soil (Bq kg^{-1} dry weight plant tissue / Bq kg^{-1} dry weight soil). The concentration factor can be assumed to be mostly controlled by the root uptake, since other sources of plant contamination (*i.e.*, foliar uptake; soil adhesion by resuspension) are often of lesser 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):

$$C_v = C_{ss} \cdot B_p \tag{4.9}$$

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

Therefore, the plant-soil solution bioaccumulation factor is assumed dependent on the concentrations of radionuclide competitive species in the soil solution [4.14], as has been fully described for the K-Cs pair [4.15 – 4.17].

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

$$C_{ss} = C_s f_{rev} / K_d \qquad (4.10)$$

in which 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 into the solid phase.

Combining these equations, we may obtain:

$$F_v = C_v / C_s = C_{ss} \cdot B_p / C_s = f_{rev} B_p / K_d \qquad (4.11)$$

Attempts to correlate field data on F_v to any one of the parameters in the equation (4.11) 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, excepting when comparing soils of contrasting properties (*e.g.,* high clay-content soils compared with peat soils) [4.18 – 4.19]. In any case, its range of variation would be much narrower than the range of variation of K_d. Therefore, radionuclide availability may be quantified solely in terms of the K_d.

Summarising, when comparing the concentration factor in the medium-term and in a set of similar soils, the equation 4.11 may be simplified as follows:

$$F_v = B_p / K_d \qquad (4.12)$$

and after a log-transformation of this equation, it results:

$$\log F_v = \log B_p - \log K_d \qquad (4.13)$$

The resulting log-equation has been successfully used to predict radiocaesium and radiostrontium transfer factor from K_d both measured in contaminated soils or calculated from soil properties [4.16, 4.20]. For other radionuclides, as is the case of actinides and transuranides, this approach may not be valid and it should be further tested.

4.2. SOLID-LIQUID DISTRIBUTION COEFFICIENT VALUES

As it was mentioned earlier (see section 2.4) the K_d values were classified on the basis of four main soil groups (sand, loam, clay and organic; see Table 4.1) defined according to the sand and clay mineral percentages, referred to the mineral matter, and the organic matter (OM) content in the soil.

Table 4.1 provides K_d values for selected radionuclides grouped according this criterion. For the same radionuclides, K_d values are also grouped according to co-factors (Table 4.2). Finally, Table 4.3 provides a compendium of K_d values for a large number of elements, also grouped according to "texture/OM" criterion.

TABLE 4.1. K_d VALUES FOR SELECTED RADIONUCLIDES FOR SOILS GROUPED ACCORDING TO THE TEXTURE/OM CRITERION, L/kg

Element	Soil group	N	Mean	GSD	Min	Max
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}

TABLE 4.2. K_d VALUES FOR SELECTED RADIONUCLIDES FOR SOILS GROUPED ACCORDING TO THE CO-FACTOR CRITERION, L kg^{-1}

Element	Soil group	N	Mean	GSD	Min	Max
Sr	CEC/M_{ss}[a] < 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[b] < 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[c]	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[c]	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[c]	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[c]	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] M_{ss}: Sum of Ca and Mg concentrations in soil solution; [b] RIP: Radiocaesium Interception Potential; [c] Mean values only for mineral soils.

TABLE 4.3. K_d VALUES FOR MISCELLANEOUS RADIONUCLIDES FOR SOILS GROUPED ACCORDING TO THE TEXTURE/OM CRITERION, L/kg

Element	Soil group	N	Mean	GSD	Min	Max
Ac	All soils[a]	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[a]	3	6.3×10^{2}	2.8	2.4×10^{2}	1.3×10^{3}
	Organic[a]	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[a]	1	1.5×10^{3}	-	-	-
Br	All soils[a]	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[a]	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}

TABLE 4.3. K_d VALUES FOR MISCELLANEOUS RADIONUCLIDES FOR SOILS GROUPED ACCORDING TO THE TEXTURE/OM CRITERION, L/kg (Cont.)

Element	Soil group	N	Mean	GSD	Min	Max
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}
	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}	$3. 1 \times 10^{2}$
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[a]	1	5.4×10^{3}	-	-	-
Hg	All soils	1	6.3×10^{3}	-	-	-
Ho	All soils[a]	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}

TABLE 4.3. K_d VALUES FOR MISCELLANEOUS OF RADIONUCLIDES FOR SOILS GROUPED ACCORDING TO THE TEXTURE/OM CRITERION, L/kg (Cont.)

Element	Soil group	N	Mean	GSD	Min	Max
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[a]	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[a]	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[a]	1	6.7×10^{2}	-	-	-
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[a]	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[a]	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}	-	-	-

TABLE 4.3. K_d VALUES FOR MISCELLANEOUS RADIONUCLIDES FOR SOILS GROUPED ACCORDING TO THE TEXTURE/OM CRITERION, L/kg (Cont.)

Element	Soil group	N	Mean	GSD	Min	Max
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[a]	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[a]	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[a]	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[a]	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[a]	1	3.0×10^{3}	-	-	-
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}

TABLE 4.3. K_d VALUES FOR MISCELLANEOUS RADIONUCLIDES FOR SOILS GROUPED ACCORDING TO THE TEXTURE/OM CRITERION, L/kg (Cont.)

Element	Soil group	N	Mean	GSD	Min	Max
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] K_d value originates from the TRS-364

Although the "texture/OM" criterion defines five soil groups, soil groups in the tables 4.2-4.4 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 following data compilation takes into account literature data on the vertical migration of radionuclides in undisturbed meadow soils (agricultural and semi-natural) [4.22-4.24]. Most data refer to ^{137}Cs and ^{90}Sr from Chernobyl and weapons fallouts. Other radionuclides are covered only in very few literature sources.

TABLE 4.4. MIGRATION RATES (cm a^{-1}) FOR ^{137}Cs AND ^{90}Sr IN UNDISTURBED MEADOW SOIL PROFILES DERIVED BY DIFFERENT CALCULATION METHODS (COMPARTMENT MODELS, HALF DEPTH, REPEATED MEASUREMENTS, CDE-APPROACHES)

Case study	Soil	N	Mean	GSD	Min	Max
			^{137}Cs			
Chernobyl	All soils	103	0.31	2.7	0.07	10.0
Fallout	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	All soils	19	0.28	2.0	0.09	0.85
Fallout	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

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 [4.22]. For details see the accompanying TECDOC (Section 4.2). Table 4.6 gives values for the parameters of the CDE model mostly for radiocaesium and radiostrontium, derived from undisturbed grassland soil profiles.

TABLE 4.5. PARAMETERS OF THE CONVECTION DISPERSION EQUATION (CDE) MODEL FOR ^{137}Cs AND ^{90}Sr FROM DIFFERENT SOURCES OF CONTAMINATION

Case study	Parameter	Soil group	N	Mean	GSD	Min	Max
^{137}Cs	D (cm^2 a^{-1})	All soils	31	0.22	3.1	0.02	1.9
Chernobyl		Sand	11	0.11	2.3	0.03	0.6
fallout		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		Sand	3	0.13	5.9	0.04	1.0
fallout		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		Sand	11	0.15	1.7	0.07	0.6
fallout		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		Sand	2	0.20	6.1	0.06	0.7
fallout		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 x 10^{-1}	2.7		
	v_s (cm a^{-1})	All soils	55			3.5 x 10^{-1}	3.1 x 10^{-1}
^{125}Sb	D_s (cm^2 a^{-1})	All soils	87	2.6 x 10^{-1}	3.0		
	v_s (cm a^{-1})	All soils	53			2.9 x 10^{-1}	2.7 x 10^{-1}
^{110m}Ag	D_s (cm^2 a^{-1})	All soils	10	3.1 x 10^{-1}	3.5		
	v_s (cm a^{-1})	All soils	4			8.4 x 10^{-1}	4.7 x 10^{-1}
^{144}Ce	D_s (cm^2 a^{-1})	All soils	4	7.6 x 10^{-1}	10		
	v_s (cm a^{-1})	All soils	3			6.8 x 10^{-1}	8.4 x 10^{-1}

4.4. APPLICATION OF DATA

Data for K_d come from a variety of different sources: field and laboratory experiments, with various contamination sources, and from references mostly from 1990 onwards, including the former TRS-364 and related reports, reviewed papers, and grey literature (PhD theses; reports).

Data originated 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 of values of K_d for a high number of radionuclides and soil types. This fact restricts the possibility of proposing expected values for individual soil groups in most cases. When proposed they must be considered only as approximate values, 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) is an option to be considered, although it must be undertaken with care.

Besides the inherent variability derived from grouping the soils according to soil properties not directly related to the mechanisms governing the soil-radionuclide interaction, the large number of approaches and contrasting experimental conditions used are partially responsible for the wide ranges of K_d values being obtained for similar soil and radionuclide combinations.

There is a need to have information on the reversibility of sorption and how it may change with time. The dynamics of the soil-radionuclide interaction is especially significant for a such radionuclides 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 is one of the key soil properties affecting sorption, the classification of the K_d on 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 are considered as much as possible.

The main soil parameters controlling the interaction should be measured and monitored to improve the prediction of the K_d, and they should also be included in models of environmental decision support systems. Modellers can choose to use the GM values derived from soils grouped according to texture and organic matter or, when available, according to other criteria such as specific soil properties (CEC, RIP, 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 a time-dependence of migration rates. The fixation of radionuclides to soil components like clay minerals or humus takes some time, and as it progresses, 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 radionuclide into the soil profile, as radionuclides contained in hot particles are protected against leaching until radionuclides are released from the particles by weathering (for details see accompanying TECDOC, Chapter 4.2).

At the moment no data for D and v in tropical meadow soils are available. 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 there may exist distinct differences in the ecological conditions driving vertical migration of radionuclides in soil.

A comparison of migration parameters (*v*, *D*) from alpine soils with lowland soils does not show significant differences. For migration rates derived by compartment models, values in alpine soils are considerably smaller (geometric mean = 0.21 cm a^{-1} vs. 0.31 cm a^{-1} in Table 4.5).

Results from recent studies show that mathematical constraints exist that can lead to artefacts when applying compartment models for the description of vertical distributions of radionuclides in soil profiles. Especially, 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 valuable for comparison of radionuclides in different soil types, but not as the first choice for predictive purposes. For the modelling of vertical migration in undisturbed soils, it is highly recommended to rely on CDE-approaches or other innovative calculation methods, because they offer a more realistic representation of the observed processes.

REFERENCES

[4.1] HILTON, J., COMANS, R. N. J., Chemical forms of radionuclides and their quantification in environmental samples, Radioecology, Radioactivity and Ecosystems (VAN DER STRICHT, E., KIRCHMANN, R., Eds.), Fortemps, Liège (2001) 99-111.

[4.2] KONOPLEV A. V., VIKTOROVA, N. V., VIRCHENKO, E. P., POPOV, V. E., BULGAKOV, A. A., DESMET, G. M., Influence of agricultural countermeasures on the ratio of different chemical forms of radionuclides in soil and soil solution, Science of the Total Environment **137** (1993) 147.

[4.3] ABSALOM, J. P., YOUNG S. D., CROUT N. M., Radio-cesium fixation dynamics: measurement in six Cumbrian soils, European Journal of Soil Science **46** (1995) 461.

[4.4] RAURET, G., FIRSAKOVA, S., The transfer of radionuclides through the terrestrial environment to agricultural products, including the evaluation of agrochemical practices, EUR 16528 EN, European Commission, Luxembourg (1996).

[4.5] WAUTERS, J., ELSEN, A., CREMERS, A., KONOPLEV, A., BULGAKOV, A. A., COMANS, R. N. J., Prediction of solid liquid distribution coefficients of radiocaesium in soils and sediments. Part one: A simplified procedure for the solid phase characterization, Applied Geochemistry **11** (1996) 589.

[4.6] RIGOL, A., VIDAL, M., RAURET, G., SHAND, C. A., CHESHIRE, M. V., Competition of organic and mineral phases in radiocaesium partitioning in organic soils of Scotland and the area near Chernobyl, Environmental Science and Technology **32** (1998) 663.

[4.7] WAUTERS, J., VIDAL, M., ELSEN, A., CREMERS, A., Prediction of solid liquid distribution coefficients of radiocaesium in soils and sediments. Part two: a new procedure for solid phase speciation of radiocaesium, Applied Geochemistry **11** (1996) 595.

[4.8] ECHEVARRIA, G., SHEPPARD, M., MOREL, J. L., Effect of pH on the sorption of uranium in soils, Journal of Environmental Radioactivity **53** (2001) 257.

[4.9] VANDENHOVE, H., VAN HEES, M., WANNIJN. J., Can we predict uranium bioavailability based on soil parameters, Part 1: Effect of soil parameters on soil solution uranium concentration, Environmental Pollution **145** (2007) 587.

[4.10] YOSHIDA, S., MURAMATSU, Y., UCHIDA, S., Adsorption of I^- and IO_3^- onto 63 Japanese soils, Radioisotopes **44** (1995) 837.

[4.11] MUELLER-LEMANS, H., VAN DORP, F., Bioturbation as a mechanism for radionuclide transport in soil: Relevance of earthworms, Journal of Environmental Radioactivity **31** (1996) 7.

[4.12] BOUDREAU, P., Mathematics of tracer mixing in sediments: I. Spatially-dependent, diffusive mixing, American Journal of Science **286** (1986) 161.

[4.13] BOSSEW, P., KIRCHNER, G., Modelling the vertical distribution of radionuclides in soil. Part 1: the convection-dispersion equation revisited, Journal of Environmental

Radioactivity **73** (2004) 127.
[4.14] LEMBRECHTS, J. F., VAN GINKEL, J. H., DESMET G. M., Comparative study on the uptake of strontium-85 from nutrient solutions and potted soils by lettuce, Plant and Soil **125** (1990) 63.
[4.15] SACCHI, G. A., ESPEN, L., NOCITO, F., COCUCCI, M., Cs^+ uptake in subapical maize root segments: mechanism and effects on H^+ release, transmembrane electric potential and cell pH, Plant Cell Physiology **38** (1997) 282.
[4.16] SMOLDERS, E., VAN DEN BRANDE, K., MERCKX, R., Concentration of ^{137}Cs and K in soil solution predicts the plant availability of ^{137}Cs in soils, Environmental Science and Technology **31** (1997) 3432.
[4.17] CASADESUS, J., SAURAS, T., GONZE, M. A., VALLEJO, R., BRÉCHIGNAC, F., A nutrient-based mechanistic model for predicting the root uptake of radionuclides, Radioactive pollutants: Impact on the environment (BRECHIGNAC, F., HOWARD, B., Eds.). EDP Sciences, Les Ulis (France), 2001, 209-239.
[4.18] KROUGLOV, S. V., KURINOV, A. D., ALEXAKHIN, R. M., Chemical fractionation of ^{90}Sr, ^{106}Ru, ^{137}Cs and ^{144}Ce in Chernobyl–contaminated soils: an evolution in the course of time, Journal of Environmental Radioactivity **38** (1998) 59.
[4.19] RIGOL, A., ROIG, M., VIDAL, M., RAURET, G., Sequential extractions for the study of radiocaesium and radiostrontium dynamics in mineral and organic soil from Western Europe and Chernobyl areas, Environmental Science and Technology **33** (1999) 887.
[4.20] CAMPS, M., RIGOL, A., HILLIER, S., VIDAL, M., RAURET, G., Quantitative assessment of the effects of agricultural practices designed to reduce ^{137}Cs and ^{90}Sr soil-plant transfer in meadows, Science of the Total Environment **332** (2004) 23.
[4.21] INTERNATIONAL ATOMIC ENERGY AGENCY, Classification of soil systems on the basis of transfer factors of radionuclides from soil to reference plants, IAEA-TECDOC-1497, IAEA, Vienna (2006).
[4.22] KIRCHNER, G., Applicability of compartmental models for simulating the transport of radionuclides in soil, Journal of Environmental Radioactivity **38** (1998) 339.
[4.23] SCHIMMACK, W., BUNZL, K., ZELLES, L., Initial rates of migration of radionuclides from the Chernobyl fallout in undisturbed soils, Geoderma **44** (1989) 211.
[4.24] GASTBERGER, M., STEINHAEUSLER, F., GERZABEK, M.H., HUBMER, A., LETTNER, H., ^{90}Sr and ^{137}Cs in environmental samples from Dolon near the Semipalatinsk nuclear test site, Health Physics **79** (2000) 257.

5. ROOT UPTAKE OF RADIONUCLIDES IN AGRICULTURAL ECOSYSTEMS

The transfer of radionuclides along food chains has been studied extensively over the last 50 years following nuclear weapons testing, releases from military sites and civilian uses of nuclear energy. Based on this information, extensive databases of soil-to-plant transfer factor values from worldwide literature were compiled to obtain the values and ranges included in the tables given in this chapter [5.1].

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 plants to the dry weight concentration in a specified soil layer. The dry weight was used to reduce uncertainty, with the exception of fruits. When the transfer factor (concentration ratio) values or the plant concentrations reported in the literature were expressed relative to fresh weight, the fresh weight/dry weight conversion factors given by Appendix I were applied.

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

In defining soil-plant transfer factors, this publication follows the IUR [5.2, 5.3] standardization of rooting depth.

Thus, instead of the real rooting depth, a standardized depth of soil 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 value is 10 cm and for all other crops (fruit trees included) the value is 20 cm. When applying the transfer factors presented here, estimates of the activity concentration in the standardized soil layer (10 cm for grass, 20 cm for other crops) 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 soil management practices [5.4].

Different types of radioactive materials in routine or accidental releases from the nuclear fuel cycle can be identified according to their mobility in soil-plant systems [5.4-5.10]. Transfer factor F_v values given here are relevant for the soluble form of radionuclides.

Radionuclides in the particulate state (usually oxides or carbonates) often have low solubility [5.11-5.12]. Leaching of ^{137}Cs from fuel matrices can be a significant factor affecting the bioavailability of the radionuclide over time after deposition [5.11-5.14]. Recommended F_v values given here are addressed o the case of the soluble form of radionuclides. Information on ^{137}Cs and ^{90}Sr transfer to plants for the case of the presence of fuel particles in the environment is given elsewhere [5.10-5.14].

The accumulation of radionuclides in farm crops varies considerably for different soils [5.15, 5.16]. 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 values include mineralogical and granulometric composition, organic matter content, pH, and fertility [5.4, 5.10, 5.15 -5.18].

The biological variability inherent in plants and distinctions between different varieties and species are also a likely source of much variability in transfer factors. The sources of this variability depend on: (i) the chemical nature of the radionuclide; (ii) variations in metabolic and biochemical mechanisms of radionuclide uptake by plants; (iii) detoxification mechanisms; (iv) hydrological conditions within the soil; and (v) plant-available concentrations in soil within the rhizosphere [5.1, 5.2, 5.4, 5.10, 5.16].

Soil fertility, duration of the vegetative period, and character of the root distribution in soil also influence radionuclide transfer factors. Interspecific variation in radionuclide accumulation across the root interface can be a factor of 100 [5.19]. Radionuclides often transfer in greater concentrations to leaves and stems and in much lower concentrations to generative parts [5.1, 5.2, 5.19].

Cultivation of agricultural crops is based on application of various methods of soil processing, different doses and combinations of fertilizers, irrigation in dry areas, and drainage in boggy territories etc. Technologies of crop cultivation change soil properties or lead to redistribution of radionuclides in the root zone, and, consequently, change radionuclide accumulation in crops [5.4, 5.10, 5.20].

A decrease in the radionuclide content in farm crops as time elapses is a typical phenomenon observed in agricultural ecosystems [5.4, 5.11-5.15, 5.20-5.21]. A variety of processes are involved, including fixation to soil minerals, incorporation by microorganisms, and migration within the rooting zone [5.4]. As a result, the biological availability of radionuclides for incorporation into food chains is reduced.

Detailed discussion of the properties and factors governing root uptake of radionuclides is given in the accompanying TECDOC [5.1].

5.2. TEMPERATE ENVIRONMENTS

5.2.1. Radionuclide transfer to plants

Information sources for radionuclide transfer to plants in temperate environments totalled 1167 including books, journals, proceedings of conferences, institutional reports, as well as international and national databases including IAEA CRP [5.10], and the IUR-1989 data base [5.22] used by the former TRS 364 [5.23].

The most extensive information obtained relates to cereals, vegetables, and pasture grasses. With respect to soil groups, the most information was found for sand and loam soils. Information for organic soils was rather limited.

To minimise artefacts and misinterpretations, the recommendations given in TRS 364 have been retained and used for data selection. In particular, these recommendations included [5.23] the following:

- Measures to ensure sufficient equilibrium between the radionuclide applied and the corresponding stable nuclides present in the soil;
- The application of fertilisers at rates used in routine agriculture; and
- Use data from lysimeter, or pot experiments only if other data are unavailable.

Transfer factor values from soil to plants for the temperate environment are given in Table 5.1. In comparison to TRS 364, the current document contains many more data for radionuclide transfers to crops of various plants groups and for different soils (according to the classification accepted by this document), and allows better differentiation between site-specific contamination scenarios.

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v)

Element	Plant Group	Plant Compartment	Soil Grou	N	Mean	GSD	Min	Max
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}	6.4×10^{-4}	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	Root	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}
	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}	4.1	6.0×10^{-5}	4.1×10^{-4}
			Organic	2	1.5×10^{-7}	1.4×10^{-4}	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 pod	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	Root	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	Tuber	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}	4.5×10^{-3}	9.0×10^{-5}	6.5×10^{-3}
			Organic	2	8.1×10^{-4}	1.1×10^{-3}	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}
	Fodder Leguminous	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}
	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}

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartme	Soil Group	N	Mean	GSD	Min	Max
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	Root	All	1	5.0×10^{-3}			
	Tubers	Tuber	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			
	Fodder Leguminous	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	$4.2\ 10^{-1}$			
Ca	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
	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
Cd	Cereals	Grain	All	11	8.8×10^{-1}	2.7	1.4×10^{-1}	2. x 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}	9.9×10^{-2}	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	All	2	1.3	1.3	3.5×10^{-1}	2.2
		shoots	Sand	1	2.2			
			Clay	1	3.5×10^{-1}			
	Leguminous Vegetables	Seeds, Pod	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	Tuber	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}			

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
Ce	Leguminous Vegetables	Seeds, Pod	All	2	1.3×10^{-2}	9.9×10^{-3}	6.0×10^{-3}	2.0×10^{-2}
			Sand	1	2.0×10^{-2}			
			Loam	1	6.0×10^{-3}			
	Root Crops	Root	All	1	6.0×10^{-3}			
	Tubers	Tuber	All	1	4.0×10^{-3}			
	Grasses	Stems and shoots	All	2	2.0×10^{-2}	1.4×10^{-2}	1.0×10^{-2}	3.0×10^{-2}
			Loam	2	2.0×10^{-2}	1.4×10^{-2}	1.0×10^{-2}	3.0×10^{-2}
	Fodder Leguminous	Stems, 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			
			Clay	4	1.4×10^{1}	2.0	8.1	3.6×10^{1}
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, Pod	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	Root	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	Tuber	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}	2.1×10^{-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}
Element	Plant Group	Plant Compartme	Soil Group	N	Mean	GSD	Min	Max
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}	2.3×10^{-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}

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
Co	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}			
	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}	1.2×10^{-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 pod	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	Root	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}	0.0	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	Tuber	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}
	Fodder Leguminous	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	Root	All	1	1.0×10^{-3}			
	Tubers	Tuber	All	1	5.0×10^{-4}			
	Pasture	Stems and shoots	All	1	2.0×10^{-3}			

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
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 pod	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	Root	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}
		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}	2.4×10^{-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	Tuber	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	1.610^{-2}	5.4×10^{-1}

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
	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}
	Fodder Leguminous	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, 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}	1.3	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}	1.3	3.0×10^{-1}	4.8×10^{-1}
	Root Crops	Root	All	1	1.0×10^{-3}			
	Tubers	Tuber	All	1	5.0×10^{-4}			
	Pasture	Stems and shoots	All	3	2.0×10^{-3}			
I	Cereals	Grain	All	13	6.3×10^{-4}	2.3	1.0×10^{-4}	1.1×10^{-2}
			Sand	2	5.8×10^{-3}	6.7×10^{-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}	4.6×10^{-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}	4.5	1.6×10^{-3}	1.3×10^{-2}
	Non-leafy Vegetables	Fruits, heads, berries, buds	All	1	1.0×10^{-1}			

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
I	Leguminous Vegetables	Seeds and pod	All	23	8.5×10^{-3}	7.4	2.0×10^{-4}	1.4×10^{-1}
			Sand	2	3.5×10^{-3}	2.8×10^{-4}	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}	7.1×10^{-5}	2.0×10^{-4}	3.0×10^{-4}
	Root Crops	Root	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	Tuber	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}	4.2×10^{-4}	8.4×10^{-3}	9.0×10^{-3}
K	Cereals	Grain	All	2	7.4×10^{-1}	3.5×10^{-3}	7.3×10^{-1}	7.4×10^{-1}
	Leafy Vegetables	Leaves	All	2	1.3	1.2×10^{-1}	1.2	1.3
	Pasture	Stems and shoots	All	1	7.3×10^{-1}			
	Cereals	Stems and shoots	All	2	1.1	2.0×10^{-1}	9.3×10^{-1}	1.2
La	Cereals	Grain	All	1	2.0×10^{-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}	7.1×10^{-5}	5.9×10^{-3}	6.0×10^{-3}
	Leguminous Vegetables	Seeds and pod	All	4	4.2×10^{-4}	3.0	1.6×10^{-4}	1.8×10^{-3}
	Root Crops	Root	All	9	1.6×10^{-3}	2.7	4.5×10^{-4}	6.0×10^{-3}
	Tubers	Tuber	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}			
	Maize	Stems and shoots	All	2	8.8×10^{-5}	1.6×10^{-5}	7.6×10^{-5}	9.9×10^{-5}
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}

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
Mn	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 pod	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	Root	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	Tuber	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}
	Fodder Leguminous	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
	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}			
	Leafy Vegetables	Leaves	All	1	5.1×10^{-1}		2.1×10^{-1}	8.0×10^{-1}
	Root Crops	Root	All	3	3.2×10^{-1}		2.3×10^{-2}	4.2×10^{-1}
	Maize	Stems and shoots	All	3	7.3×10^{-1}		1.0×10^{0}	3.8×10^{1}
	Fodder Leguminous	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	Root	All	1	3.0×10^{-2}			
	Tubers	Tuber	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	Root	All	2	1.7×10^{-2}		8.0×10^{-3}	2.5×10^{-2}
	Tubers	Tuber	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}			

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
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}
Ni	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}
	Fodder Leguminous	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}	7.9×10^{-4}	2.9×10^{-4}	1.4×10^{-3}
			Clay	2	3.9×10^{-5}	2.2×10^{-5}	2.3×10^{-5}	5.4×10^{-5}
			Organic	1	9.7×10^{-5}			
	Maize	Grain	All	2	4.8×10^{-3}	6.6×10^{-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 pod	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	Root	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	Tuber	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}
	Fodder Leguminous	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}	2.8×10^{-3}	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	Root	All	1	1.0			
	Tubers	Tuber	All	1	5.0×10^{-1}			
	Pasture	Stems and shoots	All	1	2.0			

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
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}
	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	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
	Fodder Leguminous	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}	2.0×10^{-1}	1.3×10^{-1}	4.2×10^{-1}
	Leguminous-Vegetables	Seeds and pod	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	Root	All	5	4.2×10^{-2}	1.2	3.6×10^{-2}	6.0×10^{-2}
	Tubers	Tuber	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}

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
Po	Cereals	Grain	All	2	2.4×10^{-4}	2.6×10^{-5}	2.2×10^{-4}	2.6×10^{-4}
	Maize	Grain	All	2	2.4×10^{-4}	3.2×10^{-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}	2.5×10^{-4}	1.6×10^{-5}	3.7×10^{-4}
	Leguminous-Vegetables	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}	2.7×10^{-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
	Fodder Leguminous	Stems and shoots	All	2	1.1×10^{-2}	2.0	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}	7.6×10^{-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	$2. \times 10^{-6}$	3.2×10^{-4}
			Sand	58	5.2×10^{-5}	2.7	$2. \times 10^{-6}$	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 pod	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}
	Root Crops		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}			

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
Pu	Tubers	Tuber	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}	5.6×10^{-4}	1.3×10^{-5}	8.0×10^{-4}
	Grasses	Stems and shoots	All	2	1.6×10^{-4}	1.6×10^{-4}	5.0×10^{-5}	2.7×10^{-4}
	Fodder Leguminous	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
	Leguminous-Vegetables	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 x 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 x 101	1.1×10^{-5}	1.1×10^{-1}

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
Ra	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 x 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-3/peanut-1	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}
	Fodder Leguminous	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}	4.0×10^{-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}	4.9×10^{-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}
	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}	7.1×10^{-3}	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}			

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
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}	1.6×10^{-5}	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
	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 pod	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

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
Sr	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}
	Fodder Leguminous	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
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}

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
Th	Maize	Grain	All	18	6.4 x 10^{-5}	9.2	1.2 x 10^{-6}	1.1 x 10^{-2}
			Loam	10	2.0 x 10^{-4}	9.3	1.4 x 10^{-5}	1.10x 10^{-2}
			Clay	7	1.5 x 10^{-5}	3.7	1.2 x 10^{-6}	5.4 x 10^{-5}
		Stems and shoots	All	2	1.8 x 10^{-3}	1.7 x 10^{-3}	5.4 x 10^{-4}	3.0 x 10^{-3}
	Leafy Vegetables	Leaves	All	24	1.2 x 10^{-3}	6.0	9.4 x 10^{-5}	2.1 x 10^{-1}
			Loam	13	8.6 x 10^{-4}	3.3	9.4 x 10^{-5}	5.8 x 10^{-3}
			Clay	7	4.9 x 10^{-4}	2.8	1.9 x 10^{-4}	4.1 x 10^{-3}
	Non-leafy Vegetables	Fruits, heads, berries, buds	All	17	7.8 x 10^{-4}	6.8	6.2 x 10^{-5}	1.6 x 10^{-2}
			Loam	10	2.0 x 10^{-4}	9.3	1.4 x 10^{-5}	1.1 x 10^{-2}
			Clay	7	1.5 x 10^{-5}	3.7	1.2 x 10^{-6}	5.4 x 10^{-5}
		Stems and shoots	All	6	2.2 x 10^{-3}	5.1	3.3 x 10^{-4}	2.4 x 10^{-2}
	Leguminous Vegetables	Pods	All	22	5.3 x 10^{-4}	9.4	2.5 x 10^{-5}	4.8 x 10^{-1}
			Loam	14	1.8 x 10^{-3}	3.9	1.7 x 10^{-4}	2.4 x 10^{-2}
			Clay	10	4.1 x 10^{-4}	2.3 x 10^{1}	2.5 x 10^{-5}	4.8 x 10^{-1}
			Organic	4	4.5 x 10^{-4}	7.6	8.0 x 10^{-5}	4.0x 10^{-3}
		Stems and shoots	All	7	4.3 x 10^{-3}	4.0	5.3 x 10^{-4}	2.4 x 10^{-2}
	Root Crops	Roots	All	33	8.0 x 10^{-4}	1.3 x 10^{1}	8.2 x 10^{-6}	9.5 x 10^{-2}
			Loam	14	1.1 x 10^{-3}	1.6 x 10^{1}	8.2 x 10^{-6}	5.3 x 10^{-2}
			Clay	14	2.6 x 10^{-4}	5.4	4.5 x 10^{-5}	2.3 x 10^{-2}
		Stems and shoots	All	8	8.7 x 10^{-3}	4.4	2.1 x 10^{-3}	7.8 x 10^{-2}
	Tubers	Tubers	All	24	2 x 10^{-4}	9.9	1.3 x 10^{-5}	1.8 x 10^{-2}
			Loam	10	2.5 x 10^{-4}	6.4	1.3 x 10^{-5}	3.6 x 10^{-3}
			Clay	12	9.6 x 10^{-5}	1.1 x 10^{1}	1.3 x 10^{-5}	1.8 x 10^{-2}
		Stems and shoots	All	2	1.9 x 10^{-2}	1.9 x 10^{-2}	4.8 x 10^{-3}	3.2 x 10^{-2}
	Other Crops	Tea Leaves		2	3.4 x 10^{-3}			
	Grasses	Stems and shoots	All	1	4.2 x 10^{-2}	3.1	7.4 x 10^{-4}	6.5 x 10^{-1}
	Pasture	Stems and shoots	All	64	9.9 x 10^{-2}	5.5	2.9 x 10^{-3}	2.7
	Fodder Leguminous	Stems and shoots	All	36	2.6 x 10^{-3}	1.6	1.5 x 10^{-3}	4 x 10^{-3}
Y	Cereals	Grain	All	5	5.0 x 10^{-4}			
	Leafy Vegetables	Leaves	All	1	2.0 x 10^{-3}			
	Non-leafy Vegetables	Fruits, heads, berries, buds	All	1	2.0 x 10^{-3}			
	Root Crops	Roots	All	1	2.0 x 10^{-3}			
	Tubers	Tubers	All	1	1.0 x 10^{-3}			
	Pasture	Stems and shoots	All	1	5.0 x 10^{-3}			

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
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}	1.2×10^{-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
	Root Crops	Roots	All	3	1.9	13.5	1.0×10^{-1}	1.5×10^{1}
	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}			

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
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	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}
	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}

TABLE 5.1. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
U	Other Crops	Leaves (sunflower)	All	39	7.1 x 10^{-2}	3.9	8.9 x 10^{-3}	7.8
			Sand	5	4.1 x 10^{-1}	5.3	1.6 x 10^{-1}	7.8
			Loam	22	7.1 x 10^{-2}	2.9	1.0 x 10^{-2}	6.4 x 10^{-1}
			Clay	11	2.7 x 10^{-2}	2.1	8.9 x 10^{-3}	1.0 x 10^{-1}
		Grain (sunflower)	All	2	1.5 x 10^{-2}	2.4	8.2 x 10^{-3}	2.9 x 10^{-2}
	Grasses	Stems and shoots	All	147	1.7 x 10^{-2}	9.4	2.0 x 10^{-4}	5.5
			Sand	19	1.6 x 10^{-2}	1.7 x 10^{1}	5.5 x 10^{-4}	1.8
			Loam	34	9.8 x 10^{-3}	8.4	3.1 x 10^{-4}	4.6 x 10^{-1}
	Pasture	Stems and shoots	All	53	4.6 x 10^{-2}	5.3	1.3 x 10^{-3}	1.4 x 10^{1}
			Sand	3	2.7 x 10^{-3}	1.8	1.3 x 10^{-3}	3.9 x 10^{-3}
			Loam	7	7.2 x 10^{-2}	3.3 x 10^{1}	1.8 x 10^{-3}	1.4 x 10^{1}
	Fodder Leguminous	Stems and shoots	All	15	1.5 x 10^{-2}	4.2	2.0 x 10^{-3}	1.6
			Sand	12	1.0 x 10^{-2}	2..0	2.0 x 10^{-3}	2.1 x 10^{-2}
W	Unspecified		All	1	1.0 x 10^{-1}			

By definition, the soil-plant transfer factors concept implies equilibrium or quasi equilibrium conditions in the soil-plant system. This precondition is valid, with some accuracy, while flows of the radionuclide from soil to plants are negligible compared with the total amount of the radionuclide in soil. Special care was taken in data selection for the current document to avoid data obtained in non-equilibrium conditions because of interference by soil sorption/adsorptions processes and it has been assumed that radionuclide flows from soil to plants are were low compared to the available pool of radionuclide in soil.

It is not the case for very mobile radionuclides (such as chlorine and technetium), i.e. for radionuclides with soil-plant transfer factors values which are around 100 or even higher. It should be mentioned that these values have been also determined correctly, as the ratio of the activity concentrations in plants and soil at harvest; but those values can only be determined, since there are no equilibrium conditions in soil.

Another point is that chlorine and technetium are very mobile in soil and may be subject to a considerable migration to deeper soil layers; i.e. the soil activities at the end of the vegetation are much lower than at the beginning. Such observations are made in the study by Kashparov et al. [5.24-5.25], where the chlorine activity dropped by a factor of 10-100 due to heavy rainfall during the growing period. However, the activity in plant is due to uptake from soil during the whole vegetation period. Deriving transfer factors from the radionuclide activity concentrations in soil and plant are being usually determined at the end of the vegetation period, this may lead to very high values for the transfer factor. Applying those values to activity concentration determined for the start of the vegetation period may cause serious overestimations.

Therefore, for the current document average values for Cl concentration in soil were selected. Besides, for some of these radionuclides, e.g., ^{3}H, ^{14}C, and ^{36}Cl, transfer parameters and models are normally formulated in terms of specific activity concepts. Therefore, data for these particular radionuclides are mainly treated separately and given in Chapter 11.

TABLE 5.2. TEMPERATE ENVIRONMENTS: SOIL-TO PLANT TRANSFER FACTORS (F_v) FOR Cl AND Tc

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
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}	0.64	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}	1.2×10^{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}	1.3×10^{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}	7.9×10^{1}	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, Pod	All	7	1.1×10^{1}	1.3	7.0	1.5×10^{1}
			Sand	2	1.3×10^{1}	2.8	1.1×10^{1}	1.5×10^{1}
			Clay	2	9.0	2.8	7.0	1.1×10^{1}
	Root Crops	Root	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	1.6	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}	4.7	2.3×10^{1}	3.0×10^{1}
	Root Crops	Roots	All	2	4.6×10^{1}	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}	1.2×10^{-1}	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}

For 5 radionuclides (Cu, Nd, Pr, Rh, W), no additional information was obtained; as a result, the database contains F_v values only from TRS 364 [5.23] which are given in Table 5.1 in italics. The reference values for these radionuclides are mainly a product of expert judgment and based only on one reference, namely [5.5]. Therefore, results of radiological assessments with these values involved should be interpreted with a caution.

5.2.2. Radionuclide transfer to fruits

Data presented in this section relate to fruit plants grown in agricultural ecosystems of temperate regions. Data on fruits that grow in tropical and sub-tropical environments are reported in Section 5.3 Information available on the subject is scarce, and, therefore all available information has been included. More details on the information sources and processes governing radionuclide transfer to fruits are reported elsewhere [5.1, 5.26-5.29].

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 where necessary from dry weight, see Appendix I, Table A1.1). In the absence of this information, an average water content of 80% has been assumed, as proposed by [5.29].

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

Fruits are derived from plants that have widely varying growth features and morphological and physiological traits. The data have therefore been divided into three groups: woody trees, shrubs, and herbaceous plants. Data reported under the heading "woody trees" include apple, pear, peach, apricot, grapevine, olive and orange. Data reported as "shrubs" include gooseberry, blackcurrant, red raspberry and redcurrant, whereas those reported as "herbaceous plants" include strawberry, melon, watermelon and rhubarb [5.1]. This subdivision is moiré extensive than that of the plant classification scheme elsewhere in this document.

As for other plants, the variability in 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 textured 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 [5.26-5.28].

A smaller contribution to the variability of transfer factors depends on the type of plant. Given the paucity of data, it is difficult to determine which species generally has the largest soil-to-fruit transfer of radionuclides [5.27]. The contamination of fruits borne by woody trees in the years following an initial deposition can occur by remobilisation of reserves 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 [5.26, 5.27].

Generally, the activity concentrations in fruits in the years following deposition show a decrease of several orders of magnitude, depending on not only the kind of radionuclide and the species of plant, but presumably, on different human interventions in the soil-plant system [5.27].

Radionuclide activity concentrations in fruit depend on the yield. Low yield correlates with high concentrations of radionuclides [5.26]. The radionuclide concentration in fruit 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 towards ripening because of water loss by aging [5.27].

Transfer factors to fruits, evaluated based on of information presented in the accompanying TECDOC [5.1], are given in Table 5.3.

TABLE 5.3 TEMPERATE ENVIRONMENTS: SOIL-TO- FRUITS TRANSFER FACTORS (F_v)

Element	Plant Group	Soil Group	N	Mean	GSD/SD	Min	Max
Am	Woody trees	All	6	3.1×10^{-5}	2.4×10^{0}	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}	1.2×10^{-4}	6.5×10^{-5}	2.3×10^{-4}
	Herb. 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}	1.3×10^{-4}	4.4×10^{-4}	6.2×10^{-4}
	Herb. 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}
	Herb. 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}	3.7×10^{-4}	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}	1.7×10^{-3}	9.8×10^{-4}	3.3×10^{-3}
		Loam	2	3.8×10^{-3}	2.8×10^{-3}	1.8×10^{-3}	5.7×10^{-3}
		Unspecified	2	2.0×10^{-3}	1.9×10^{-3}	6.9×10^{-4}	3.3×10^{-3}
Cs	Herb. 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}
Cu	Herb. plant	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}
	Herb. plants	Unspecified	1	1.5×10^{-2}			
Mn	Fruit	Unspecified	1	3.9×10^{0}			
Na	Woody tree	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}

TABLE 5.3 TEMPERATE ENVIRONMENTS: SOIL-TO- FRUITS TRANSFER FACTORS (F_v)

Element	Plant Group	Soil Group	N	Mean	GSD/SD	Min	Max
	Shrubs	Unspecified	2	1.7 x 10^{-4}	1.5 x 10^{-4}	6.4 x 10^{-5}	2.7 x 10^{-4}
	Herbaceous plants	All	9	1.2 x 10^{-4}	1.2 x 10^{0}	2.7 x 10^{-5}	8.3 x 10^{-4}
		Loam	1	8.8 x 10^{-5}			
		Sand	1	1.6 x 10^{-4}			
		Organic	1	7.3 x 10^{-5}			
		Unspecified	6	1.3 x 10^{-4}	1.5 x 10^{0}	2.7 x 10^{-5}	8.3 x 10^{-4}
Ru	Woody trees	Unspecified	2	1.3 x 10^{-3}	3.3 x 10^{-4}	1.1 x 10^{-3}	1.6 x 10^{-3}
	Herb. plants	Unspecified	1	7.4 x 10^{-4}			
Sr	Woody trees	All	18	1.7 x 10^{-2}	9.7 x 10^{-1}	1.2 x 10^{-3}	7.0 x 10^{-2}
		Loam	4	3.9 x 10^{-2}	8.2 x 10^{-1}	1.2 x 10^{-2}	7.0 x 10^{-2}
		Sand	1	2.5 x 10^{-2}			
		Organic	1	1.2 x 10^{-3}			
		Unspecified	12	1.6 x 10^{-2}	6.1 x 10^{-1}	4.3 x 10^{-3}	3.4 x 10^{-2}
	Shrubs	All	9	4.4 x 10^{-2}	7.6 x 10^{-1}	1.4 x 10^{-2}	1.1 x 10^{-1}
		Clay	2	5.4 x 10^{-2}	3.9 x 10^{-2}	2.6 x 10^{-2}	8.1 x 10^{-2}
		Loam	2	3.6 x 10^{-2}	2.7 x 10^{-2}	1.7 x 10^{-2}	5.5 x 10^{-2}
		Unspecified	5	5.0 x 10^{-2}	8.5 x 10^{-1}	1.4 x 10^{-2}	1.1 x 10^{-1}
	Herb. plants	All	8	3.3 x 10^{-2}	1.0	1.2 x 10^{-2}	2.1 x 10^{-1}
		Loam	1	1.0 x10^{-1}			
		Sand	1	2.1 x 10^{-1}			
		Organic	1	1.2 x 10^{-2}			
		Unspecified	5	2.2 x 10^{-2}	3.7 x 10^{-1}	1.5 x 10^{-2}	4.0 x 10^{-2}

5.3. TROPICAL AND SUB-TROPICAL ENVIRONMENTS

Largely, 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 the values characteristic of temperate environments. In typical tropical environments, almost all organic materials that reach the soil surface are being decomposed 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, usually the decomposition of organic debris is slower, and the accumulation of soil organic matter is greater than the rate of decomposition, resulting in highly organic surface soil [5.1, 5.30-5.33]. In the tropics, due to high mineral weathering rates, clays of low exchange activity such as kaolinite are more common than in the temperate zone [5.30]. This leads to soils that have a low exchange capacity in spite of having high clay content [5.30].

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 crops properties, can be significant [5.30-5.32]. Transfer factor values for tropical and subtropical environments are given in Tables 5.4-5.5.

TABLE 5.4. TROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
Am	Fruits	Fruits	Others[1]	2	3.7×10^{-5}	1.6×10^{-5}	2.6×10^{-5}	4.8×10^{-5}
		Coconut Milk[2]	Others	1	3.7×10^{-5}			
	Non-leafy Vegetables	Fruits	Others	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}
K	Fruits	Fruits	Organic	2	5.5×10^{1}	2.1	4.0×10^{1}	7.0×10^{1}
		Leaves[2]	All	2	3.2×10^{1}	4.3×10^{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[2]	Unspecified	2	4.3	5.6	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}	2.1	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}	$2. \times 10^{-2}$	3.20
			Others	1	1.9			

[1] Others refer to soils which are out of the classification schema used by the current document such as Marsharll Island soils, classified by authors as coral sand soil. [2] The plant compartment is beyond of the classification schema used by the current document.

TABLE 5.4. TROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
Cs	Leguminous Vegetables	Grain	All	7	1.1	4.45	1.9 x 10^{-1}	4.1
			Sand	6	1.4	4.07	2.2 x 10^{-1}	4.1
			Loam	1	1.9 x 10^{-1}			
		Stems and shoots	Sand	4	7.3	1.30	5.4	9.6
		Leaves	All	61	1.1 x 10^{-1}	3.94	1.0 x 10^{-2}	3.9
			Sand	1	4.4 x 10^{-1}			
			Clay	53	1.0 x 10^{-1}	3.67	1.0 x 10^{-2}	7.7 x 10^{-1}
			Unspecified	1	3.9			
	Other Crops	Leaves	All	19	5.9 x 10^{-1}	7.19	4.0 x 10^{-2}	2.1 x 10^{1}
			Unspecified	6	5.6	2.65	1.1	2.1 x 10^{1}
		Fruits	Unspecified	2	6.6	3.4	4.2	9.0
		Stems and shoots	Loam	4	7.0 x 10^{-2}	1.1	6.0 x 10^{-2}	8.0 x 10^{-2}
	Non-leafy Vegetables	Fruits, heads, berries, buds	All	38	7.0 x 10^{-1}	3.3	5.0 x 10^{-2}	1.1 x 10^{1}
			Clay	26	9.3 x 10^{-1}	1.7	3.6 x 10^{-1}	2.3
			Sand	4	5.6 x 10^{-2}	1.1	5.0 x 10^{-2}	6.3 x 10^{-2}
			Unspecified	2	7.3	5.2	3.6	1.1 x 10^{1}
	Root Crops	Roots	All	9	4.3 x 10^{-1}	2	1.3 x 10^{-1}	8.1 x 10^{-1}
			Clay	5	6 x 10^{-1}	1.3	4.5 x 10^{-1}	8.1 x 10^{-1}
	Tubers	Tubers	All	8	4.3 x 10^{-1}	3.4	6.0 x 10^{-2}	3.0
			Sand	1	2.0 x 10^{-1}			
			Clay	4	3.7 x 10^{-1}	3.5	6.0 x 10^{-2}	10 x 10^{-1}
			Unspecified	1	3.0			
	Leafy Vegetables	Leaves	All	49	9.8 x 10^{-1}	2.3	1.1 x 10^{-1}	2.9
			Clay	39	1.3	1.5	3.6 x 10^{-1}	2.9
			Unspecified	1	4.1 x 10^{-1}			
	Maize	Grain	Unspecified	2	2.0	7.8 x 10^{-1}	1.4	2.5
Pu	Fruits	Fruits	Unspecified	2	2.3 10^{-5}	9.2 10^{-6}	1.6 10^{-5}	2.9 10^{-5}
		Coconut milk	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 x 10^{-3}			
	Grasses	Leaves	Sand	9	2.1 x 10^{-1}	2.2	5.9 x 10^{-2}	1.00
	Herbs	Leaves	Sand	2	3.7 x 10^{-1}	4.9 x 10^{-1}	2.0 x 10^{-2}	7.1 x 10^{-1}
	Leguminous Vegetables	Grain	All	9	3.3 x 10^{-3}	2.4	6.5 x 10^{-4}	8.9 x 10^{-3}
			Sand	3	3.4 x 10^{-3}	1.3	2.8 x 10^{-3}	4.4 x 10^{-3}
			Loam	6	3.2 x 10^{-3}	3.0	6.5 x 10^{-4}	8.9 x 10^{-3}
	Other crops		Sand	18	2.3 x 10^{-1}	2.7	1.4 x 10^{-2}	1.0
	Non-leafy Vegetables		All	2	7.0 x 10^{-3}	0.0	7.0 x 10^{-3}	7.0 x 10^{-3}
	Pasture	Stems and shoots	Unspecified	1	3.0 x 10^{-1}			
	Root Crops	Roots	Loam	3	2.4 x 10^{-3}	1.5	1.8 x 10^{-3}	4.0 x 10^{-3}

TABLE 5.4. TROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD/SD	Min	Max
Pb	Tubers	Tubers	All	16	5.7 x 10^{-4}	2.4	1.5 x 10^{-4}	2.3 x 10^{-3}
			Sand	1	1.6 x 10^{-3}			
			Loam	15	5.3 x 10^{-4}	2.4	1.5 x 10^{-4}	2.3 x 10^{-3}
	Maize	Grain	All	6	8.5 x 10^{-4}	2.1	5.2 x 10^{-4}	3.8 x 10^{-3}
			Sand	1	5.2 x 10^{-4}			
			Loam	5	9.3 x 10^{-4}	2.2	5.9 x 10^{-4}	3.8 x 10^{-3}
Ra	Cereals		All	3	3.5 x 10^{-3}	2.5	1.7 x 10^{-3}	1.0 x 10^{-2}
			Sand	2	2.1 x 10^{-3}	5.7 x 10^{-4}	1.7 x 10^{-3}	2. x 10^{-3}
	Fruits	Leaves	Loam	1	1.0 x 10^{-1}			
	Grasses	Stems and shoots	All	33	1.7	4.3	1.8 x 10^{-2}	5.8 x 10^{1}
			Loam	1	1.9 x 10^{-1}			
	Herbs	Stems and shoots	Unspecified	4	7.5 x 10^{-2}	1.4 x 10^{1}	1.0 x 10^{-2}	3.0
		Leaves	Unspecified	11	1.1 x 10^{-1}	4.8	1.1 x 10^{-2}	1.0
	Leguminous Vegetables	Grain	All	31	2.1 x 10^{-2}	4.3	7.6 x 10^{-4}	2.7 x 10^{-1}
			Sand	5	3.6 x 10^{-2}	3.0	5.7 x 10^{-3}	8.7 x 10^{-2}
			Loam	26	1.9 x 10^{-2}	4.5	7.6 x 10^{-4}	2.7 x 10^{-1}
	Other Crops	Leaves	All	12	1.1 x 10^{-1}	2.1	3.7 x 10^{-2}	3.7 x 10^{-1}
			Loam	11	1.2 x 10^{-1}	2,0	4.0 x 10^{-2}	3.7 x 10^{-1}
		Roots	All	3	9.8 x 10^{-2}	5.8	1.3 x 10^{-2}	2.7 x 10^{-1}
		Stems and shoots	All	6	1.2 x 10^{-1}	2.5	2.0 x 10^{-2}	2.7 x 10^{-1}
			Loam	5	1.6 x 10^{-1}	1.4	1.0 x 10^{-1}	2.7 x 10^{-1}
			All	57	2.6	5.5	5.7 x 10^{-2}	1.3 x 10^{2}
			Loam	1	8.0 x 10^{-2}			
	Non-leafy Vegetables	Fruits, heads, berries, buds	All	9	3.2 x 10^{-3}	5.6	5.2 x 10^{-4}	7.0 x 10^{-2}
			Loam	6	1.4 x 10^{-3}	3.4	5.2 x 10^{-4}	1.4 x 10^{-2}
	Pasture	Stems and shoots	Unspecified	1	7.0 x 10^{-2}			
			Loam	22	1.1 x 10^{-2}	4.9	1.2 x 10^{-3}	2.2 x 10^{-1}
	Tubers	Tubers	All	42	1.9 x 10^{-3}	3.8	2.6 x 10^{-4}	1.9 x 10^{-1}
			Sand	1	1.6 x 10^{-3}			
			Loam	41	2.0 x 10^{-3}	3.9	2.6 x 10^{-4}	1.9 x 10^{-1}
	Leafy Vegetables		Loam	22	2.7 x 10^{-2}	4.5	3.0 x 10^{-3}	4.3 x 10^{-1}
	Maize	Grain	All	18	1.1 x 10^{-3}	2.4	1.9 x 10^{-4}	8.3 x 10^{-3}
			Sand	3	3.8 x 10^{-3}	2.0	2.0 x 10^{-3}	8.3 x 10^{-3}
			Loam	15	8.7 x 10^{-4}	2.0	1.9 x 10^{-4}	3.8 x 10^{-3}
Sr	Cereals	Grain	All	2	6.0 x 10^{-1}	2.3 x 10^{-1}	4.4 x 10^{-1}	7.6 x 10^{-1}
			Sand	1	4.4 x 10^{-1}			
			Loam	1	7.6 x 10^{-1}			
	Fruits	Fruits	Others	3	1.7 x 10^{-2}	6.2	3.7 x 10^{-3}	1.3 x 10^{-1}
	Grasses	Grain	Sand	24	1.9 x 10^{-1}	7.9	1.4 x 10^{-2}	6.8
		Leaves	Sand	24	3.0 x 10^{-1}	7.6	2.8 x 10^{-2}	9.7
	Herbs	Leaves	All	1	3.6			

TABLE 5.4. TROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD	Min	Max
Sr	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}	1.8×10^{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}			
	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	1.1	1.2	2.8
	Tubers	Tubers	All	2	6.8×10^{-1}	3.0×10^{-2}	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}	2.8×10^{-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}

TABLE 5.4. TROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant Group	Plant Compartment	Soil Group	N	Mean	GSD	Min	Max
U	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}	1.5×10^{-3}	2.3×10^{-3}	4.4×10^{-3}
			Loam	1	3.2×10^{-3}			
		All plant	Unspecified	2	8.5×10^{-1}	2.8×10^{-3}	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}
	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}	7.1×10^{-4}	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}	1.2×10^{-1}	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}	5.7 x	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}	3.5	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

TABLE 5.5. SUBTROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v)

Element	Plant group	Plant compartment	Soil group	N	Mean	GSD/SD	Min	Max
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	Stem, shoots	Sand	1	3.0×10^{-3}			
		Fruits	Sand	1	1.0×10^{-2}			
		Tubers	Sand	2	1.2×10^{-2}	4.2×10^{-3}	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}	0.0	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	Stem, shoots	Loam	2	2.8×10^{-1}	7.1×10^{-3}	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 x
			Loam	7	5.1×10^{-1}	2.0	2.0×10^{-1}	1.2
		Roots	Loam	2	4.7×10^{-2}	5.1×10^{-2}	1.1×10^{-2}	8.3×10^{-2}
		Stem, shoots	Loam	2	1.1×10^{-2}	1.4×10^{-3}	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}
		Stem, 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}
		Stem, 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}			

TABLE 5.5. SUBTROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean	GSD/SD	Min	Max
Cs	Leguminous vegetables	Grain	All	31	1.6 x 10^-2	4.1	2.0 x 10^-3	3.1 x 10^-1
			Loam	28	1.5 x 10^-2	4.1	2.0 x 10^-3	3.1 x 10^-1
			Clay	2	5.9 x 10^-2	7.2 x 10^-2	8.0 x 10^-3	1.1 x 10^-1
	Other crops	Grain	Clay	1	3.0 x 10^-4			
		Leaves	All	10	1.3 x 10^-1	1.1 x 10^1	3.7 x 10^-3	1.9
			Sand	4	8.9 x 10^-3	2.4	3.7 x 10^-3	2.9 x 10^-2
		Roots	All	2	6.2 x 10^-2	3.0 x 10^-2	4.0 x 10^-2	8.3 x 10^-2
			Sand	1	8.3 x 10^-2			
			Loam	1	4.0 x 10^-2			
		Stem, shoots	Unspecified	9	5.5 x 10^-1	2.4	2.1 x 10^-1	1.5
			All	18	6.9 x 10^-1	9.6	3.0 x 10^-3	1.0 x 10^1
			Loam	6	2.4 x 10^-1	4.6	2.6 x 10^-2	8.9 x 10^-1
			Clay	2	5.7 x 10^-2	7.6 x 10^-2	3.0 x 10^-3	1.1 x 10^-1
			Others[1]	3	7.3	1.8	3.8	1.0 x 10^1
	Non-leafy vegetables	Fruits, heads, berries, buds	All	13	1.9 x 10^-2	6.5	2.3 x 10^-3	3.0 x 10^-1
			Loam	10	2.5 x 10^-2	7.8	2.3 x 10^-3	3.0 x 10^-1
			Clay	3	7.3 x 10^-3	1.8	4.0 x 10^-3	1.2 x 10^-2
		Leaves	Loam	6	2.6 x 10^-2	2.1	1.0 x 10^-2	8.0 x 10^-2
		Roots	Loam	6	5.3 x 10^-3	3.3	1.0 x 10^-3	2.3 x 10^-2
			All	6	3.2 x 10^-2	4.1	2.0 x 10^-3	1.1 x 10^-1
			Loam	2	5.0 x 10^-2	0.0	5.0 x 10^-2	5.0 x 10^-2
			Clay	2	1.7 x 10^-2	2.1 x 10^-2	2.0 x 10^-3	3.1 x 10^-2
	Pasture	Stems, shoots	All	34	1.9 x 10^-1	2.5	2.0 x 10^-2	6.3 x 10^-1
			Loam	6	7.5 x 10^-2	2.8	2.0 x 10^-2	2.2 x 10^-1
	Root crops	Leaves	Unspecified	10	3.5 x 10^-2	4.5	3.9 x 10^-3	3.5 x 10^-1
		Roots	All	15	1.5 x 10^-2	4.4	1.4 x 10^-3	2.3 x 10^-1
			Loam	2	2.6 x 10^-2	6.4 x 10^-3	2.1 x 10^-2	3.0 x 10^-2
	Tubers	Tubers	All	34	6.5 x 10^-2	2.4	9.0 x 10^-3	4.1 x 10^-1
			Sand	8	1.5 x 10^-1	2.3	4.8 x 10^-2	4.1 x 10^-1
			Loam	8	4.2 x 10^-2	2.0	9.0 x 10^-3	8.0 x 10^-2
			Clay	4	4.7 x 10^-2	1.6	3.0 x 10^-2	8.0 x 10^-2
	Leafy vegetables	Leaves	All	35	3.8 x 10^-2	6.2	1.1 x 10^-3	1.4
			Sand	6	1.0 x 10^-2	5.49	1.1 x 10^-3	8.9 x 10^-2
			Loam	22	4.1 x 10^-2	6.0	6.0 x 10^-3	8.9 x 10^-1
			Clay	1	8.0 x 10^-3			
	Maize	Grain	Clay	2	5.0 x 10^-3	4.2 x 10^-3	2.0 x 10^-3	8.0 x 10^-3
I	Cereals	Grain	Unspecified	1	1.5 x 10^-4			
		Leaves	Unspecified	1	2.0 x 10^-2			
		Stems, shoots	Unspecified	3	1.0 x 10^-2	4.5	4.1 x 10^-3	5.8 x 10^-2
	Herbs	Leaves	Unspecified	1	2.4 x 10^-1			
	Leguminous vegetables	Grain	Unspecified	1	3.0 x 10^-3			

[1]Others refer to sawdust as a substrate where this plants group was grown

TABLE 5.5. SUBTROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean	GSD/SD	Min	Max
I	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}			
	Root Crops	Leaves	Unspecified	1	1.2×10^{-1}			
		Roots	Unspecified	2	5.6×10^{-2}	7.1×10^{-3}	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		Others	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}	3.3×10^{-1}	1.5×10^{-1}	6.2×10^{-1}
		Stems, shoots	Unspecified	2	1.6×10^{-1}	9.2×10^{-2}	9.0×10^{-2}	2.2×10^{-1}
Pu	Non-leafy vegetables	Fruits	Unspecified	2	8.2×10^{-4}	5.4×10^{-4}	4.3×10^{-4}	1.2×10^{-3}
	Root crops	Roots	Unspecified	2	4.6×10^{-3}	5.7×10^{-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}	1.3×10^{-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}	1.8×10^{-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 5.5. SUBTROPICAL ENVIRONMENT: SOIL TO PLANT TRANSFER FACTORS (F_v) (Cont.)

Element	Plant group	Plant compartment	Soil group	N	Mean	GSD/SD	Min	Max
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}	4.8×10^{-2}	5.2×10^{-2}	1.2×10^{-1}
	Maize	Grain	Clay	2	3.4×10^{-2}	1.6×10^{-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}	4.2×10^{-1}	2.0×10^{-1}	8.0×10^{-1}
	Non-leafy vegetables	Fruits	Unspecified	2	3.0×10^{-1}	0.0	3.0×10^{-1}	3.0×10^{-1}
		All plant	Unspecified	2	3.0×10^{-1}	2.8×10^{-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 and 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}	1.1×10^{-1}	2.5×10^{-1}	4.1×10^{-1}
		Stems, shoots	Unspecified	2	2.2×10^{-1}	9.9×10^{-2}	1.5×10^{-1}	2.9×10^{-1}

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

5.4. TRANSFER TO RICE

One of the critical foods for the intake of radionuclides by humans is rice (*Oryza sativa L.*), which is the dominant staple food crop in humid tropical countries across the globe [5.1].

Although rice is also grown in temperate environments, the major source is tropical and sub-tropical environments.

Most rice is produced under flooded conditions, namely in fields with a water layer of 5-15 cm. Cultivation methods have important effects on plant uptake of radionuclides from soil. Under flooded conditions, oxygen is depleted quickly by the respiration of soil micro organisms and plant roots [5.34-5.36]. 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 [5.34-5.36]. This farming practice is significantly different from the cultivation of cereals in unsaturated fields. Therefore, there is a need to consider the soil-to-rice transfer factors (F_v) separately from other crops [5.32].

Transfer factor values for rice were evaluated based on the information presented in the accompanying TECDOC [5.1]. The values derived from radionuclide studies are given in Table 5.6 while the values derived from stable element data are presented in Table 5.7. Transfer factor values (F_v) values for both brown and white rice are reported separately in [5.1]. It should be mentioned that compared with other crops, the difference in F_v values between brown and white rice are generally rather small for the majority of elements, so F_v values reported here combine information for both types of rice.

TABLE 5.6. TRANSFER FACTORS (F_v) FROM SOIL TO RICE

Element	Soil Type	N	Mean	GSD	Min	Max
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}	5.2×10^{-3}	4.7×10^{-3}	1.2×10^{-2}
Po	All	2	1.3×10^{-2}	5.2×10^{-3}	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	$<2 \times 10^{-4}$			
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}

TABLE 5.6. TRANSFER FACTORS (F_v) FROM SOIL TO RICE (Cont.)

Element	Soil Type	N	Mean	GSD	Min	Max
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}

TABLE 5.7. TRANSFER FACTORS OF STABLE ELEMENTS TRANSFERFROM SOIL TO RICE

Element	Soil Type	N	Mean	GSD	Min	Max
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}
Cs	Loam	26	1.0×10^{-3}	3.7	1.1×10^{-4}	1.6×10^{-2}
Cs	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}
Pb	Loam	26	2.4×10^{-4}	2.1	7.2×10^{-5}	1.1×10^{-3}
Pb	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}
Sr	Loam	26	1.6×10^{-3}	2.1	4.1×10^{-4}	6.4×10^{-3}
Sr	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}

5.5. TIME DEPENDENCY OF RADIONUCLIDES TRANSFER TO PLANTS

This chapter largely describes radionuclide transfers from soil to plants for equilibrium conditions, i.e. the time after the deposition, which allows approaching to such conditions. However, radionuclides can also be transferred to plants from soil in the year of deposition. Such a situation can be of importance, in particular, for the case of acute (short-term) period after a deposition. Many models allow the contamination of plants to be calculated for this scenario with some uncertainty. In contrast to radionuclides acutely deposited during plant growth period are being localised within the soil surface till harvest because farmlands are not ploughed within the growing period. This makes the use of F_v inappropriate and makes it necessary to use aggregated transfer factors (T_{ag}) specified for the time from deposition until harvest (5.37-5.40). The T_{ag} values for such time-dependent scenarios for some radionuclides T, Co, Mn, Sr, Cs are given in the accompanying TECDOC [5.1].

The rate of decrease of radionuclide uptake by plants is irregular by its nature, and several time periods should be considered in applying a half-life approach for data evaluation. In the first years after deposition, bioavailability of some radionuclides in soil reaches its maximum, resulting in maximum radionuclide transfer rate to plants. The data allows the conclusion that ecological half-lives for ^{137}Cs in plants are in range of 1-2 years in first years after the deposition, declining up to 12-20 years in the long term after the deposition. The half-lives of ^{90}Sr tend to be slightly longer and may be estimated as 20-30 years. Unfortunately, existing literature data are rather scarce 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 in the course of time after single release of radionuclides into the environment. This arises 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 into 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 (see Chapter 2), ecological half-life is equal to the period over which the concentration of a radionuclide, in some definite 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 with time after clearly defined depositions are rather scarce, there are three prime sources of the information on the radionuclides half-lives in plants: global fallout and the Kyshtym and Chernobyl accidents [5.13, 5.15, 5.17, 5.20, 5.21, 5.42, 5.43].

5.6. APPLICATION OF DATA

Assessment of F_v values based on the literature sources is always associated with various shortcomings, and often considerable judgment must be exercised in evaluating the available data. Firstly, some data are normally based on studies that were not originally intended for transfer factors assessments. Secondly, the experimental design of the research may deviate from 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 physical and chemical forms of the radionuclide in the soil, soil properties, plant species, plant compartment, farming practices, etc. Such factors result in high variability, and the individual F_v values themselves can vary over five orders of magnitude [5.1].

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

The available data entries for tropical and subtropical ecosystems are much less than those used for the data evaluation from the temperate environments. Additional uncertainty in the application of the tropical/subtropical data provided by this TRS can be assigned with the use of different climate classification schemes.

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 the climatic conditions should be considered when using the F_v values from the tables given in this chapter.

Transfer factors are not appropriate for natural and semi-natural ecosystems because of the layered structure of those soils and highly inhomogeneous distribution of root systems. Therefore, aggregated transfer factors (T_{ag}) are used as an alternative 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 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 depends on the site.

REFERENCES

[5.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments, TECDOC No. xxxx, IAEA, Vienna (2009)

[5.2] FRISSEL, M.J., Van BERGEIJK, K.E., "Mean Transfer Values Derived by Simple Statistical Regression Analysis", VIth Report of the IUR Working group Soil-to-Plant Transfer Factors: Report of the working group meeting in Guttannen Switzerland Bilthoven, RIVM 240 (1989) 24-26.

[5.3] INTERNATIONAL UNION of RADIOECOLOGIST. Working group soil to plant transfer. Protocol developed between 1982 and 1992. Contact address for protocol: e-mail frisselm@bart.nl. Contact address for IUR secretariat e-mail: Per.Strand@nrpa.no.

[5.4] ALEXAKHIN, R.M., KORNEEV, N.A. (Eds.), Agricultural Radioecology, Kolos, Moscow (1992) (in Russian).

[5.5] Soil-to-Plant Concentration Factors for Radiological Assessments, Final report, Y.C. Ng, S.E. Thompson, C.S. Colsher, Lawrence Livermore national Laboratory. National Technical Information Service. NUREG/CR-2975 UCID-19463, (1982) 132.

[5.6] Literature Review and Assessment of Plant and Animal Transfer Factors Used in Performance Assessment Modelling, U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research. Washington, DC 20555-0001. (2003) 170.

[5.7] Environmental Research on Actinide Elements, (J.E. PINDER III, J.J. ALBERTS, K.W. MCLEOD, R.G. SCHRECKHISE Eds.) CONF-841142 (DE86006713) U.S. DOE OHER Symposium Series 59. (1987).

[5.8] NISBET, A.F., WOODMAN, R.F.M., Soil-to-plant transfer factors for radiocaesium and radiostrontium in agricultural systems, Health Physics **78** (3) (2000) 279-288.

[5.9] EWERS, L.W., HAM, G.J., WILKINS, B.T., Review of the Transfer of Naturally Occurring Radionuclides to Terrestrial Plants and Domestic Animals, NRPB-W49. Chilton. Didcot, UK (2003) 64.

[5.10] INTERNATIONAL ATOMIC ENERGY AGENCY, Classification of soil systems on the basis of transfer factors of radionuclides from soil to reference plants, IAEA-TECDOC-1497, IAEA, Vienna (2006).

[5.11] SANZHAROVA, N.I., FESENKO, S.V., ALEXAKHIN, R.M., ANISIMOV, V.S, KUZNETSOV, V.K., CHERNYAYEVA, L.G., Changes in the forms of ^{137}Cs and its availability for plants as dependent on properties of fallout after the Chernobyl nuclear power plant accident, Science of the Total Environment **154** (1994) 9-22.

[5.12] KASHPAROV, V.A., OUGHTON, D.H., PROTSAK, V.P., ZVARISCH, S.I., PROTSAK, V.P., LEVCHUK, S.E., Kinetics of fuel particle weathering and ^{90}Sr mobility in the Chernobyl 30 km exclusion zone, Health Physics **76** (1999) 251-259.

[5.13] FESENKO S.V., SANZHAROVA N.I., SPIRIDONOV S.I., ALEXAKHIN R.M., Dynamics of ^{137}Cs bioavailability in a soil-plant system in areas of the Chernobyl nuclear power plant accident zone with a different physico-chemical composition of radioactive fallout, Journal of Environmental. Radioactivity **34**(3) (1996) 287-313.

[5.14] KROUGLOV, S.V., FILIPAS, A.S., ALEXAKHIN, R.M., ARKHIPOV, N.P., Long-Term Study on the Transfer of ^{137}Cs and ^{90}Sr from Chernobyl-Contaminated Soils to Grain Crops, Journal of Environmental Radioactivity **34(3)** (1997) 267-286.

[5.15] FESENKO, S.V., COLGAN, P.A., LISSIANSKI, K.B., VAZQUEZ, C., GUARDANS, R., The dynamics of the transfer of caesium-137 to animal fodder in areas of Russia affected by the Chernobyl accident and doses resulting from the consumption of milk and milk products, Radiation Protection Dosimetry 69/4 (1997) 289-299.

[5.16] EVANS, E.J., DEKKER, A.J., Plant uptake of ^{137}Cs from nine Canadian soils, Journal of Soil Science **46** (1966) 167-176.

[5.17] MOISEEV, I.T., TIKHOMIROV, F.A., ALEXAKHIN, R.M., RERICH, L.F., Influence of soil properties and time on ^{137}Cs forms dynamic and availability for plants, Agrohimiya **8** (1982) 109-113 (in Russian).

[5.18] MENZEL, R.G., Competitive uptake by plants of potassium, rubidium, caesium, calcium, strontium and barium from soils. Soil Science, **77** (6), (1954) 419-425.

[5.19] KUZNETSOV, V.K, SANZHAROVA, N.I., Influence of specific and variety features of the in plant yield on ^{137}Cs accumulation from sod-podzolic and chernozem soils, Agricultural Biology **1** (2000) 374-383 (in Russian).

[5.20] INTERNATIONAL ATOMIC ENERGY AGENCY. Environmental consequences of the Chernobyl accident and their remediation: twenty years of experience. Report of the UN Chernobyl Forum Expert Group “Environment” (EGE). Vienna, IAEA 2006 166.

[5.21] HOVE, K. AND STRAND, P., “Prediction for the duration of the Chernobyl radiocaesium problem in non-cultivated areas based on reassessment of the behaviour of fallout from the nuclear weapons tests”, Environmental Contamination following a Major Nuclear Accident (Proc. International Conf, Vienna, 1989) Vol. II., International Atomic Energy Agency, Vienna (1990) pp. 215-223.

[5.22] FRISSEL, M. J., “An update of the Reference soil-to-plant transfer factors of ^{90}Sr, ^{137}Cs and transuranics”, 8th Report of the Working Group Meeting on Soil-to-Plant Transfer Factors, IUR Madrid (1992) 16-25.

[5.23] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, Technical Report Series No.364, IAEA, Vienna (1994).

[5.24] KASHPAROV, V., COLLE, C., ZVARICH, S., YOSCHENKO, V., LEVCHUK, S., LUNDIN, S., Studies of soil-to-plant transfer of halogens. 2. Root uptake of radiochlorine by plants, Journal of Environmental Radioactivity **79**(3) (2005). 233-253.

[5.25] KASHPAROV, V., C. COLLE, et al., Transfer of chlorine from the environment to agricultural foodstuffs, Journal of Environmental Radioactivity **94** (2007) 1-15

[5.26] CARINI, F., Radionuclide transfer from soil to fruit, Journal of Environmental Radioactivity **52** (2001) 237-279.

[5.27] INTERNATIONAL ATOMIC ENERGY AGENCY, Modelling the Transfer of Radionuclides to Fruit, "Report of the Fruits Working Group of BIOMASS Theme 3, BIOsphere Modelling and ASSessment Programme, IAEA-BIOMASS-5" Vienna (2003).

[5.28] GREEN, N., WILKINS, B. T., HAMMOND, D. J., Transfer of radionuclides to fruit, Journal of Radioanalytical and Nuclear Chemistry **226** (1-2) (1997) 195.

[5.29] MAYALL, A., "FARMLAND: transfer of radionuclides to fruit", Rep. NRPB-M545, National Radiological Protection Board, Didcot (1995).

[5.30] FRISSEL, M. J., "A report of the IAEA-IUR joint project Transfer of radionuclides from air, soil, and freshwater to the foodchain of man in tropical and subtropical environments", Proc. of the XXVII annual meeting of ESNA, WG 3, (GERZABEK, M H, Ed.), Vienna (1997) 189.

[5.31] INTERNATIONAL UNION OF RADIOECOLOGY, Assessing the Radiological impact of Releases of Radionuclides to the Environment: Radioecology. Radioactivity and Ecosystems (VAN DER STRICHT, E., KIRCHMAN, R., EDS), Fortems, Liege (2001) 1-30

[5.32] UCHIDA, S., Radionuclides in tropical and subtropical ecosystems, Radioactivity in the Environment **10 (**2007) 193-209.

[5.33] SIMON, S.L., GRAHAM, J.C., AND TERP, S.D., Uptake of ^{40}K and ^{137}Cs in native plants of the Marshall Islands. Journal of Environmental Radioactivity **59** (2002) 223-243.

[5.34] UCHIDA, S., TAGAMI, K., HIRAI, I., Soil-to-plant transfer factors of stable elements and naturally occurring radionuclides: (2) Rice collected in Japan, Journal of Nuclear Science and Technology **44** (2007) 779-790.

[5.35] TSUKADA, H., HASEGAEA, H., HISAMATSU, S., YAMASAKI, S., Transfer of ^{137}Cs and stable Cs from paddy soil to polished rice in Aomori, Japan, Journal of Environmental Radioactivity **59** (2002) 351-363.

[5.36] WANG, J.J., WANG, C.J., HUANG, C.C., LIN, Y.M., Transfer factors of ^{90}Sr and ^{137}Cs from paddy soil to the rice plant in Taiwan, Journal of Environmental Radioactivity **39** (1998) 23-34.

[5.37] CHOI, Y.H., LEE, C.W., KIM, S.R., LEE, J.H., JO, J.S., Effect of application time of radionuclides on their root uptake by Chinese cabbage and radish, Journal of Environmental Radioactivity **39** (1998) 183-198.

[5.38] CHOI, Y.H., Lim, K.M., PARK, H.G., PARK, D.W., KANG, H.S., LEE, H.S., Transfer of ^{137}Cs to rice plants from various paddy soils contaminated under flooded conditions at different growth stages. Journal of Environmental Radioactivity **80** (2005) 45-58.

[5.39] LEE, C.W., CHOI, Y.H., HWANG, W.T., LEE, J.H., Nuclides transport analysis and calculation using dynamic model for rice ingestion pathway, Journal of Korean Association for Radiation Protection **17** (1992) 15-23 (in Korean).

[5.40] CHOI, Y.H., KIM, S.B., LIM, K.M., PARK, H.K., LEE, W.Y., Incorporation into organically bound tritium and the underground distribution of HTO applied to a simulated rice field, Journal of Environmental Radioactivity **47** (2000) 279-290.

[5.41] KOMAMURA, M., TSUMURA, A., YAMAGUCHI, N., KIHOU, N., KODAIRA, K., Monitoring ^{90}Sr and ^{137}Cs in Rice, Wheat, and Soil in Japan from 1959 to 2000. Miscellaneous publication of National Institute for Agro-Environmental Sciences **28** Tsukuba (2006).

[5.42] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Sources and Biological Effects. United Nations, New York (1988).

[5.43] SMITH, J.T., FESENKO S.V., HOWARD, B.J., HORRIL, A.D., SANZHAROVA, N.I., ALEXAKHIN, R.M., ELDER, D.G., NAYLOR, C. Temporal Change in Fallout ^{137}Cs in Terrestrial and Aquatic Systems: A Whole Ecosystem Approach. Environmental Science and Technology, 1999, 33, pp. 49-54.

6. AGRICULTURAL ECOSYSTEMS – TRANSFER TO ANIMALS

Animals can be contaminated by three different routes: through the skin, by inhalation and by ingestion. The most important transfer pathway to animals is the 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 of animals.

The most commonly applied transfer parameter for agricultural animal products is the transfer coefficient, which incorporates all the processes between ingestion of a radionuclide in herbage or soil and incorporation in a specific tissue. In addition, values for gastrointestinal fractional absorption are also given, due 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 (GI) tract is a key factor in determining the extent of radionuclide contamination of animal tissues and milk. Absorption is reported, where possible, as the true absorption coefficient (A_t) [6.1]. 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

Gastrointestinal fractional absorption values for ruminants given in Table 6.1 were derived from either a database compiled for this purpose or from authoritative animal nutrition reviews [6.2, 6.3]. Agricultural review sources were used for radionuclides which are isotopes of essential nutrient elements. The data source is specified for each element in the Table.

Values in Table 6.1 were derived from data for ruminants aged over 100 d because there is some evidence of enhanced absorption in young animals [6.4]. The Table excludes data where (i) there may have been effects on absorption of high stable element intakes (e.g. Cd); (ii) reduced absorption occurs for radiocaesium sources of low bioavailability and (iii) absorption may be underestimated due to unquantified losses in excreta and milk. Detailed discussion of the derivation of the values and literature used can be found in Howard et al [6.5].

The fractional absorption of the three major dose forming radionuclides, I, Sr and Cs, varies, it is complete for radioiodine, and higher for radiocaesium than radiostrontium. Fractional absorption of radiocaesium varies with 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 [6.2, 6.3, 6.6]. The absorption of essential elements is relatively high compared with 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 Pu, is low compared to that of many elements.

TABLE 6.1. GASTROINTESTINAL FRACTIONAL ABSORPTION VALUES[a] FOR ADULT RUMINANTS TAKEN FROM THE DATABASE AND AGRICULTURAL REVIEWS

Element	N	Mean	GSD	Min	Max
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	$>1.4 \times 10^{-3}$			
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	$>5.2 \times 10^{-4}$			
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	$>1.6 \times 10^{-1}$			
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 see [6.5]

6.1.2. Absorption in Monogastrics

Gastrointestinal fractional absorption values have been reported for use for in human assessments by the ICRP [6.7] and provide relevant values for monogastric animals. The ICRP values are shown for selected radionuclides in Table 6.2. For most radionuclides, the Reference values recommended for humans from ICRP are similar to those in Table 6.1 for ruminants. However, direct comparisons with Table 6.1 are difficult because (i) the Reference ICRP values are sometimes based on data for both ruminants and non-ruminants and (ii) the procedures for deriving the values differ.

TABLE 6.2 GASTROINTESTINAL FRACTIONAL ABSORPTION VALUES RECOMMENDED FOR ADULT HUMANS [6.7]

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

Recently, data for the fractional absorption of a few radionuclides in pigs and hens has become available from Russian language publications [6.4]. These are generally in agreement with the ICRP value with the exception of a Sr fractional absorption value in laying hens of 0.6 (probably as the consequence of a high requirement for Ca).

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 used since the nineteen sixties. The second concentration ratio approach is an alternative which has potential advantages, but for which there are currently less relevant data.

6.2.1. Transfer coefficients

The transfer coefficient was first proposed as a measure of the transfer of radionuclides to animal-derived food products by Ward et al. [6.8] to describe the transfer of radiocaesium from the diet to the milk of dairy cattle. They defined the transfer coefficient as the ratio between the radiocaesium activity concentration in milk and the daily dietary radionuclide intake. Ward et al. [6.8] reported that this parameter exhibited less variability between individual animals within the experimental herd than expressing transfer as the total amount of Cs excreted in milk expressed as a percentage of intake. The same authors 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 [6.9]. The transfer coefficient has been widely adopted as the basis for quantifying transfer to both milk (F_m, d l^{-1} or d kg^{-1}) and meat (F_f, d kg^{-1}) for all radionuclides now defined as the equilibrium ratio of the activity concentration in milk/meat to the daily dietary radionuclide intake [6.10].

To estimate transfer coefficients the dietary composition of the animal must be quantified. For agricultural animals this varies according to feeding strategies (including if animals are indoors or grazing), maintenance requirements, agricultural practices and diet composition and characteristics such as dry matter digestibility. Typical dietary constituents for agricultural animals vary between and within countries, and with 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 transfer coefficient values were derived can be found in the accompanying TECDOC [6.11], and Howard et al [6.18] provides more detailed discussion of the values in the tables.

6.2.1.1. Factors affecting transfer values: duration of intake

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

By definition, for a transfer coefficient to be valid the radionuclide activity concentration in tissues or milk needs to be at 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 (the product for which Ward et al. [6.8] originally suggest transfer coefficients) an approximate equilibrium is reached rapidly for many radionuclides.

However, experimental observations, from which transfer coefficients are derived, are often not conducted long enough for equilibrium to have been reached in tissues or milk. The requirement of equilibrium conditions is often not met for radionuclides with short physical half lives or for those radionuclides with long radioactive and biological half lives in tissues (e.g. Pu) 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 radionuclides activity concentrations in different tissues following continuous, single or varying intakes [6.13-6.17].

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 [6.18].

Transfer coefficients of radionuclides are generally higher to animals with a lower body mass and dietary intake rate so 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 to milk declines as calcium intake increases [6.19-6.23].

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 [6.24, 6.25]. There are relatively few estimates of the bioavailability of particle associated radionuclides in animals, and the 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. This also applies to different soil types which may bind radionuclides to different extents and can 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 assumed that much of this difference is because transfer coefficients incorporate dry matter intake which increases with animal size.

An alternate method to quantify transfer from herbage to animal product is the concentration ratio (CR) which is the equilibrium ratio of the radionuclide activity concentration in food product (fresh weight) divided by radionuclide concentration in 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 the CR for a given element may, unlike transfer coefficients, be generally consistent across species [6.26].

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

6.2.3. Transfer values

6.2.3.1. Transfer to milk

Tables 6.3 - 6.5 gives the F_m for cow, sheep and goat milk. All data for F_m values below are in units of d L^{-1}. The data source is specified for each element in the Table; more detailed information is available in Howard et al. [6.18].

In addition to the values derived from experiments with radionuclides, the agricultural/animal nutrition literature contains a wealth of data on many stable elements in milk and herbage which can be used to derive transfer parameters. Where appropriate, we have used a number of key reviews (6.2, 6.3, 6.6, 6.27 – 6.32) to identify typical concentrations of elements within milk and herbage. These have been used to derive transfer coefficients for milk by assuming dry matter intake rates of 16 kg d^{-1} DM for lactating cows and 1.5 kg d^{-1} DM 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 (DMI), 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 transfer will therefore not be linear with intake rate. However, given the large databases we have based these values on, 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 value of F_m it is identified in the tables below (as RS).

For cow milk there were adequate data in the database to derive values for most of the elements whereas for sheep and goat milk the stable element compilation was used more often. Where reference values are derived from the database, summary statistics are provided in the tables; if derived from stable element review data only a best estimate is presented as the reference value.

TABLE 6.3. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO COW MILK, d L^{-1}

Element	N	Mean	GSD	Min	Max
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	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[b]		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}

[b] source is a recent review paper [6.33]

TABLE 6.4. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO GOAT MILK, d L^{-1}

Element	N	Mean	GSD	Min	Max
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		5.2×10^{-2}			
I	24	2.2×10^{-1}	2.9	2.7×10^{-2}	7.7×10^{-1}
Mn		1.0×10^{-3}			

TABLE 6.4. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO GOAT MILK, d L^{-1} (Cont.)

Element	N	Mean	GSD	Min	Max
Mo	4	8.2×10^{-3}	1.4	5.0×10^{-3}	1.1×10^{-2}
Na		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[1]		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		6.4×10^{-2}			
Zr	1	5.5×10^{-6}			

TABLE 6.5. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO SHEEP MILK d L^{-1}

Element	N	Mean	GSD	Min	Max
Ba	1	4.1×10^{-2}			
Ca		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		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		3.1×10^{-1}			
Pb		3.5×10^{-2}			
Pu	1	1.0×10^{-4}			
S		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		8.1×10^{-2}			

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 then the stable element review values have been used, from which it was also possible to estimate *CR* values for horse milk. Table 6.6 compares the *CR* values for the four animal species as CR values for a given element are broadly similar across species [6.21].

TABLE 6.6. CONCENTRATION RATIOS FOR THE MILK OF DIFFERENT ANIMALS, kg L^{-1}

Element	Cow					Goat					Sheep					Horse	Mean	Ratio
	CR	SD	Min	Max	N	*CR*	SD	Min	Max	N	*CR*	SD	Min	Max	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}

Shaded values estimated from stable element review

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: (i) no additional stable element review of animal nutrition literature was conducted although the database includes some stable element values; (ii) single dose studies were not used unless sufficient time series data were available.

In summarizing F_f values, only results used reported for pigs, sheep and goats of six months or older (where this information was given) were used. For cattle, only data from animals aged 1 year or older were included whereas for poultry only data for animals older than 40 d were used. However, if data for animals above these ages were not available for an element, data for younger animals were used (on only two occasions).

Data from experiments of less than 20 d duration were not used for sheep, goats, pigs or poultry whilst for cattle experiments of less than 60 d duration were not used. Few single dose data were used, typical experiments that were included were those reported by Beresford et al. [6.34, 6.35] where models were fitted to data for consecutive slaughter dates over *circa* one year after a single administration. Subsequent predictions of F_f were made for differing periods of continuous administration; values incorporated into the database were the equilibrium or 1000 d predictions. In some experiments, data are available for a series of different sample times after continuous feeding (see 6.36). 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 6.7-6.11. All data for F_f values are in units of d kg^{-1} fresh weight. If required to convert reported dry weight values to fresh weight, it was assumed that the dry matter content of meat for all animal types was 25%.The data source is specified for each element in the Table; more detailed information is available in Howard et al [6.18]. Data for poultry meat is largely for chickens but also includes some data for duck.

The F_f values for egg contents (data is largely for chickens but some duck values are included), which excludes the shell, are presented in Table 6.12. Data for most radionuclides is relatively sparse. The values in Table 6.13 are generally similar to those proposed in TRS 364 [6.37] because many of the TRS 364 values were based upon Ng et al. [6.38] which continues to be a major source of data.

TABLE 6.7. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO COW MEAT, d kg^{-1}

Element	N	Mean	GSD	Min	Max
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}

TABLE 6.7. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO COW MEAT, d kg^{-1} (Cont.)

Element	N	Mean	GSD	Min	Max
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[1]	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}			

[1] young animals (5-6 month old)

TABLE 6.8. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO SHEEP MEAT, d kg^{-1}

Element	N	Mean	GSD	Min	Max
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}

TABLE 6.9. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO GOAT MEAT, d kg^{-1}

Element	N	Mean	GSD	Min	Max
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}			

TABLE 6.10. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO PIG MEAT, d kg^{-1}

Element	N	Mean	GSD	Min	Max
Cs	22	2.0×10^{-1}	1.5	1.2×10^{-1}	4.0×10^{-1}
Fe[1]	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}

[1]young animals (2 month old)

TABLE 6.11. TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO POULTRY MEAT, d kg^{-1}

Element	N	Mean	GSD	Min	Max
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[1]	2	1.7		1.7	1.8
Co[1]	2	9.7×10^{-1}		3.0×10^{-2}	1.9
Cs[1]	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[1]	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[1]	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}			

[1]includes values for duck

TABLE 6.12 TRANSFER COEFFICIENTS FOR RADIONUCLIDE TRANSFER TO EGG CONTENTS, d kg^{-1}

Element	N	Mean	GSD	Min	Max
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[1]	2	3.3×10^{-2}		2.6×10^{-2}	4.0×10^{-2}
Cs[1]	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[1]	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[1]	9	4.9×10^{-1}	2.5	2.5×10^{-1}	4.8
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}			

[1]includes values for duck

Values for *CR* for meat for a number of species are given in Table 6.13. 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 Fe and 5.3×10^{-1} for Zn can be derived using stable data from the agricultural sources described above. These are in reasonable agreement with values for other species in Table 6.13.

6.3. APPLICATION OF DATA

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

We have proposed that the CR would be a more robust and generic parameter than the transfer coefficient. For most radionuclides, the concentration ratio data compiled varies little between the species considered (sheep, goats, cattle, horses and poultry). Therefore, concentration ratios derived for one species could be applied to another. However, unfortunately many authors who currently report transfer coefficients do not provide the information required to estimate concentration ratios.

TABLE 6.13. CONCENTRATION RATIOS FOR THE MEAT OF DIFFERENT ANIMALS[1]

Element	Beef					Sheep					Pork					Generic	Ratio
	CR	SD	Min	Max	N	CR	SD	Min	Max	N	CR	SD	Min	Max	N		Min/ Max
Ag						$4.3x10^{-4}$				1						$4.3x10^{-4}$	
Am						$1.1x10^{-4}$				1						$1.1x10^{-4}$	
Ca	$2.3x10^{-2}$		$2.1x10^{-2}$	$2.6x10^{-2}$	2	$1.4x10^{-2}$										$1.9x10^{-2}$	$6.0x10^{-1}$
Cd	$1.7x10^{-1}$	$1.5x10^{-1}$	$2.3x10^{-3}$	$3.5x10^{-1}$	7	$1.2x10^{-2}$		$1.3x10^{-3}$	$2.3x10^{-2}$	2	$1.3x10^{-1}$				1	$9.2x10^{-2}$	$6.9x10^{-2}$
Ce						$2.2x10^{-4}$				1						$2.2x10^{-4}$	
Cl	$2.4x10^{-1}$		$4.8x10^{-2}$	$4.3x10^{-1}$	2											$2.4x10^{-1}$	
Co	$3.9x10^{-1}$		$7.2x10^{-3}$	$7.8x10^{-1}$	2	$2.3x10^{-1}$										$3.1x10^{-1}$	$5.9x10^{-1}$
Cs	$2.3x10^{-1}$	$1.7x10^{-1}$	$2.2x10^{-2}$	$7.3x10^{-1}$	17	$6.4x10^{-1}$	1.0	$5.3x10^{-2}$	7.5	51	$9.2x10^{-2}$	$1.0x10^{-1}$	$8.3x10^{-3}$	$2.4x10^{-1}$	4	$3.9x10^{-1}$*	$1.4x10^{-1}$
Fe	$2.2x10^{-1}$	$2.5x10^{-1}$	$6.0x10^{-2}$	$7.2x10^{-1}$	6	$2.7x10^{-1}$				1						$2.5x10^{-1}$	$8.2x10^{-1}$
I	$9.5x10^{-2}$	$8.2 x10^{-2}$	$3.2x10^{-2}$	$1.9x10^{-1}$	3					1	$9.3x10^{-2}$		$3.5x10^{-2}$	$1.5x10^{-1}$	2	$9.4x10^{-2}$	$9.8x10^{-1}$
La	$1.6x10^{-3}$	$2.4 x10^{-4}$	$1.3x10^{-3}$	$1.8x10^{-3}$	3											$1.6x10^{-3}$	
Mg	$1.4x10^{-1}$		$9.4x10^{-2}$	$1.9x10^{-1}$	2											$1.4x10^{-1}$	
Mn	$8.0x10^{-3}$		$4.6x10^{-3}$	$1.1x10^{-2}$	2											$8.0x10^{-3}$	
Mo	$9.6x10^{-2}$		$2.5x10^{-2}$	$1.7x10^{-1}$	2											$9.6x10^{-2}$	
Na	$9.7x10^{-1}$				1											$9.7x10^{-1}$	
Nb	$6.5x10^{-6}$				1											$6.5x10^{-6}$	
Ni	$8.0x10^{-2}$				1											$8.0x10^{-2}$	
P	1.3[2]															1.3	
Pb	$7.7x10^{-2}$	$1.8x10^{-1}$	$1.0x10^{-3}$	$6.2x10^{-1}$	11	$1.2x10^{-2}$	$4.0x10^{-3}$	$9.2x10^{-3}$	$1.6x10^{-2}$	3	$6.6x10^{-1}$		$2.3x10^{-1}$	1.1	2	$2.5x10^{-1}$	$1.8x10^{-2}$
Po	$1.4x10^{-1}$	$1.3x10^{-1}$	$3.7x10^{-2}$	$4.1x10^{-1}$	7											$1.4x10^{-1}$	
Pu						$3.9x10^{-5}$	$2.4x10^{-5}$	$1.5x10^{-5}$	$6.3x10^{-5}$	3						$3.9x10^{-5}$	
Ra	$1.8x10^{-1}$	$3.8x10^{-1}$	$1.3x10^{-3}$	1.3	11											$1.8x10^{-1}$	
Rb	$3.0x10^{-1}$				1											$3.0x10^{-1}$	
Ru						$5.7x10^{-4}$				1						$5.7x10^{-4}$	
S						$5.0x10^{-1}$										$5.0x10^{-1}$	
Sb	$2.7x10^{-1}$				1											$2.7x10^{-1}$	
Se											1.1				1	1.1	
Te	$1.8x10^{-1}$				1											$1.8x10^{-1}$	
Th	$6.2x10^{-3}$	$5.0x10^{-3}$	$1.7x10^{-3}$	$1.2x10^{-2}$	3											$6.2x10^{-3}$	
U	$3.3x10^{-1}$	$6.1x10^{-1}$	$3.0x10^{-3}$	1.7	8											$3.3x10^{-1}$	
Zn	1.7	1.1	$4.7x10^{-1}$	3.2	9	2.1		1.3	2.9	2						1.9	$8.2x10^{-1}$

[1]Goat value of 6.2×10^{-1} for Cs (n=4) is included in the generic value; [2]Shaded cells denote CR values estimated from the stable element review

REFERENCES

[6.1] MAYES, R.W., BERESFORD, N.A., HOWARD, B.J., VANDECASTEELE, C.M., STAKELUM, G., Use of the true absorption-coefficient as a measure of bioavailability of radiocaesium in ruminants, Radiation and Environmental Biophysics **35** (1996), 101-109.

[6.2] NATIONAL RESEARCH COUNCIL (NRC), Nutrient requirements of dairy cattle, 7th Edition, National Academic press, Washington DC. (2001) pp. 381.

[6.3] AGRICULTURAL RESEARCH COUNCIL (ARC), The nutrient requirements of ruminant livestock, C.A.B. International, Wallingford (1980) 351 pp.

[6.4] FESENKO, S., ISAMOV, N., HOWARD, B.J., VOIGT, G., BERESFORD, N.A., SANZHAROVA, N. Review of Russian language studies on radionuclide behaviour in agricultural animals: part 1. Gut absorption, Journal of Environmental Radioactivity **98** (2007a), 85-103.

[6.5] HOWARD, B.J., BERESFORD, N.A., BARNETT, C.L, FESENKO, S. Revision of TRS 364: Gastrointestinal fractional absorption of radionuclides in adult ruminants. Journal of Environmental Radioactivity (submitted).

[6.6] MCDONALD, P., EDWARDS, R.A., GREENHALGH, J.F.D., MORGAN, C.A., Animal nutrition, 5th Edition, Longman Scientific and Technical, Harlow (1995) 607 pp.

[6.7] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION (ICRP), Human alimentary tract model for radiological protection, Annals of the ICRP: Publication **100** (2006), 250.

[6.8] WARD, G.M., JOHNSON, J.E., STEWART, H.F., "Cesium-137 passage from precipitation to milk", Proceedings of the second conference on radioactive fallout from nuclear weapons tests, (Klement, A.W., Ed.). National Technical Information Service, Springfield (1965) 703-710.

[6.9] WARD, G.M., JOHNSON, J.E., The caesium-137 content of beef from dairy and feed lot cattle, Health Physics 11 (1965), 95-100.

[6.10] NG, Y.C., A review of transfer factors for assessing the dose from radionuclides in agricultural products, Nuclear Safety 23 (1982), 57-71.

[6.11] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments, TECDOC No. xxx, IAEA, Vienna (2008)

[6.12] WARD, G.M., JOHNSON, J.E., WILSON, D.W., Deposition of fallout Cs-137 on forage and transfer to milk, Public Health Reports **81** (1966), 639-645.

[6.13] MÜLLER, H., PRÖHL, G., Ecosys-87 - a dynamic-model for assessing radiological consequences of nuclear accidents, Health Physics **64** (1993), 232-252.

[6.14] CROUT, N.M.J., VOIGT, G., Modelling the dynamics of radioiodine in dairy cows, Journal of Dairy Science **79** (1996), 254-259.

[6.15] CROUT, N.M.J., BERESFORD, N.A., HOWARD, B.J., MAYES, R.W.M., HANSEN ,H.S. A model of radiostrontium transfer in dairy goats based on calcium metabolism, Journal of Dairy Science **81** (1998a), 92-99.

[6.16] CROUT, N.M.J., MAYES, R.W., BERESFORD, N.A., LAMB, C.S., HOWARD, B.J., A metabolic approach to simulating the dynamics of C-14, H-3 and S-35 in sheep tissues, Radiation and Environmental Biophysics **36** (1998b), 243-250.

[6.17] THORNE, M.C., Parameterisation of Animal Models. Mike Thorne and Associates, Halifax (2003).

[6.18] HOWARD, B.J., BERESFORD, N.A., BARNETT, C.L, FESENKO, S. Radionuclide transfer to animal products: revised recommended transfer coefficient values. Journal of Environmental Radioactivity (In press).

[6.19] ANNENKOV, B.N., DIBOBES, I.K., ALEKSAKHIN, R.M., Radiobiology and radioecology of farm animals, (1973) 220 pp

[6.20] SIROTKIN, A.N., Radionuclide uptake to animal stuffs, Sel'skohozyaistvenaya radioecologiya, (Alexakhin, R.M., Korneyev, N.A., Eds.), Ecologiya, Moscow (1991) 106-115 (In Russian).

[6.21] HOWARD, B.J., BERESFORD, N.A., MAYES, R.W., HANSEN, H.S., CROUT, N.M.J., HOVE, K. The use of dietary calcium intake of dairy ruminants to predict the transfer coefficient of radiostrontium to milk, Radiation and Environmental Biophysics **36** (1997), 39-43.

[6.22] BERESFORD, N.A., MAYES, R.W., HANSEN, H.S., CROUT, N.M.J., HOVE, K., HOWARD, B.J., Generic relationship between calcium intake and radiostrontium transfer to the milk of dairy ruminants, Radiation and Environmental Biophysics **37** (1998a), 129-131.

[6.23] FESENKO, S., HOWARD, B.J., ISAMOV, N., VOIGT, G., BERESFORD, N.A., SANZHAROVA, N., BARNETT, C.L., Review of Russian language studies on radionuclide behaviour in agricultural animals: part 2. Transfer to milk, Journal of Environmental Radioactivity **98** (2007b) 104-136.

[6.24] HOWARD, B.J., MAYES, R.W., BERESFORD, N.A., LAMB, C.S., Transfer of radiocaesium from different environmental sources to ewes and suckling lambs, Health Physics **57** (1989), 579-586.

[6.25] BERESFORD, N.A., MAYES, R.W., BARNETT, C.L., HOWARD, B.J., The transfer of radiocaesium to ewes through a breeding cycle - an illustration of the pitfalls of the transfer coefficient, Journal of Environmental Radioactivity **98** (2007), 24-35.

[6.26] BERESFORD, N.A., MAYES, R.W., HOWARD, B.J., EAYRES, H.E., LAMB, C.S., BARNETT, C.L., SEGAL, M.G., The bioavailability of different forms of radiocaesium for transfer across the gut of ruminants, Radiation Protection Dosimetry **41** (1992), 87-91.

[6.27] MINISTRY OF AGRICULTURE FISHERIES AND FOOD (MAFF) - STANDING COMMITTEE ON TABLES OF FEED COMPOSITION, UK tables of nutritive value and chemical composition of feedingstuffs, Rowett Research Services Ltd., Aberdeen (1990) 420 pp.

[6.28] NATIONAL RESEARCH COUNCIL (NRC), Nutrient requirements of beef cattle, update 2000, 7th Revised Edition, National Academy Press, Washington DC. (1996) 232 pp.

[6.29] NATIONAL RESEARCH COUNCIL (NRC), Mineral tolerance of animals, 2nd Revised Edition, National Academy Press, Washington D.C (2005) 496 pp.

[6.30] NATIONAL RESEARCH COUNCIL (NRC), Nutrient requirements of small ruminants: sheep; goats; cervids and new world camelids, National Academy Press, Washington, D.C. (2007) 362 pp.

[6.31] UNDERWOOD, E.J., Trace elements in human and animal nutrition, 4th Edition, Academic Press, New York (1977) 545 pp.

[6.32] CHURCH, D.C., "Digestive physiology and nutrition of ruminants - Practical nutrition", Volume 3 (1980) pp 416.

[6.33] HOWARD, B.J., BERESFORD, N.A., GASHCHAK, S., ARKHIPOV, A., MAYES, R.W., CABORN, J., STRØMANN, G., WACKER, L., The transfer of $^{239/240}$Pu to cow milk. Journal of Environmental Radioactivity **98** (1998b), 191-204.

[6.34] BERESFORD, N.A., CROUT, N.M.J., MAYES, R.W., Interpretation of the results of a three year study to examine the dynamics of radionuclides in sheep tissue, RP0424, Institute of Terrestrial Ecology, Grange-over-Sands (1996) 59 pp.

[6.35] BERESFORD, N.A., CROUT, N.M.J., MAYES, R.W., HOWARD, B.J., LAMB, C.S., Dynamic distribution of radioisotopes of cerium, ruthenium and silver in sheep tissues Journal of Environmental Radioactivity **38** (1998b), 317-338.

[6.36] FESENKO, S., ISAMOV, N., HOWARD, B.J., BERESFORD, N.A., BARNETT, C.L., SANZHAROVA, N., VOIGT, G., Review of Russian language studies on radionuclide behaviour in agricultural animals: part 2. Transfer to meat, Journal of Environmental Radioactivity (in press).

[6.37] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments, Technical Report No 364, IAEA, Vienna (1994).
[6.38] NG, Y.C., COLSHER, C.S., THOMPSON, S.E., Transfer coefficients for assessing the dose from radionuclides in meat and eggs, NUREG/CR-2976 UCID-19464, Lawrence Livermore National Laboratory, (1982) 118 pp.

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 to 100 years between planting and harvesting, or 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 which, 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 animals, which, after the Chernobyl accident, have all shown a tendency for relatively high levels of radiocaesium contamination in comparison with agricultural food products.

During deposition of atmospheric radioactive fallout to forests, the tree canopy is contaminated directly by dry or wet interception of aerosol-derived radionuclides (Table 7.1). 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 due to weathering of intercepted radioactive materials by wind and rain, and the natural loss of leaf litter. These canopy processes are followed by, or accompanied by, root uptake which is the predominant route of tree contamination over the longer term. Two stages in 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 the tree and the soil, and
2. A "steady state" phase characterized by slow changes in biological availability, with root uptake determining the degree of contamination of the trees.

TABLE 7.1. CANOPY INTERCEPTION FRACTIONS FOR DIFFERENT TYPES OF FORESTS [7.1].

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

Over the first few days of radioactive discharges from the Chernobyl NPP, about 70 - 80% of all the radioactive fallout was retained by the aboveground parts of trees. Over this period, coniferous trees trapped radioactivity 2 - 3 times as effectively as did deciduous forests and 7-10 times more than other types of natural or semi-natural ecosystems (meadow, mire) [7.2].

Ecological half-lives in the course of active growth of trees vary from 3 - 4 weeks to 3 months depending on the type and age of trees. In the phase of physiological dormancy (autumn and winter), the half-lives are in a range of 4 - 6 months [7.2].

7.1.2. Aggregated transfer factors for soil-tree transfer

The relationship between radionuclide activity concentrations in forest soils and trees is influenced by many factors, hence T_{ag} values are highly variable. 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:

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

Table 7.2 and 7.3 provide available data on the T_{ag} values for radiocaesium and radiostrontium in foliage and wood as recorded in different ecological conditions with varying age and species of trees. More details including the related information sources are given in the accompanying TECDOC [7.3].

TABLE 7.2. RADIOCAESIUM AGGREGATED TRANSFER FACTORS (T_{ag} in m^2 kg^{-1}, DW) TO FOREST TREES, MEASURED IN APPARENT STEADY STATE CONDITIONS

Species	Wood		Needles/Leaves		Number of observations
	GM	Range	GM	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 7.3. T_{ag} VALUES (m^2 kg^{-1}, DW) FOR RADIOSTRONTIUM TRANSFER TO FOLIAGE AND WOOD OF DIFFERENT FOREST TREE SPECIES. MEASURED FOLLOWING THE CHERNOBYL (1991-1992) AND KYSHTYM (1966-1972) ACCIDENTS (main reference: [7.6])

Species	Wood		Needles/Leaves		Number of observations
	GM	Range	GM	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 aggregated Transfer coefficient (T_{ag}), because of the difficulty to know exactly the location within the soil, both vertically and horizontally, from which radionuclides are being absorbed. The transfer coefficients to mushrooms are widely variable (3 to 4 orders of magnitude). This variability arises for several reasons:

- the intensity of caesium transfer is highly dependent on the species,
- the mycelium depth determines the contamination chronology,
- the nutritional type of mushroom species can affect the degree of caesium transfer.

Saprophytic mushrooms develop on decomposing materials in the surface layers of a soil, so these kinds of mushrooms will be first contaminated following 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 ones and can be the most contaminated in the medium and long terms after deposition. **Parasitic** mushrooms develop at the expense of the trees. Very few are edible and their radionuclide concentration is dependent on the degree of host tree contamination, and they tend to be characterized by low transfer coefficients.

The majority of available information is addressed to ^{137}Cs (Table 7.4), however, although in a less extent, such data are also available for some other long-lived radionuclides (Tables 7.5, 7.6). In these tables, 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 species and weather conditions [7.7].

Aggregated transfer factors are presented here for edible species of mushrooms which contribute directly to human radiation doses. Data for 'non-edible' mushroom species, details of the relevant studies and full set of references, containing data presented here are given in [7.3].

TABLE 7.4. AGGREGATED TRANSFER FACTORS TO EDIBLE MUSHROOMS FOR ^{137}Cs, $m^2 \cdot kg^{-1}$, DW

Mushroom species	Type of mushrooms	Transfer coefficient ($m^2.kg^{-1}$ dry weight) GM(*)	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

TABLE 7.5. MEAN AGGREGATED TRANSFER FACTORS TO MUSHROOMS FOR ^{90}Sr, m^2 kg^{-1}, DW [7.8]

Mushroom species	Life mode of mushrooms	^{90}Sr transfer coefficient [7.8]
Boletus edulis	Symbiotic	6×10^{-3}
Boletus appendiculatus	Symbiotic	5×10^{-3}
Cantharellus cibarius	Symbiotic	6×10^{-3}

TABLE 7.6. AGGREGATED TRANSFER FACTORS TO MUSHROOMS FOR Pu, m^2 kg^{-1}, DW [7.9]

Mushroom species	Life mode of mushrooms	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

Some authors have used the conventional soil-plant transfer factor to quantify radionuclide absorption by mushrooms, especially for natural radionuclides. These data are presented in the TECDOC [7.3].

Changes with time in the contamination of mushrooms reflect the bioavailability of radionuclides in the various relevant nutrient sources used by different species and Fig 7.1 indicates the tendency for a slow decrease of ^{137}Cs in mushroom contamination during the 1990s.

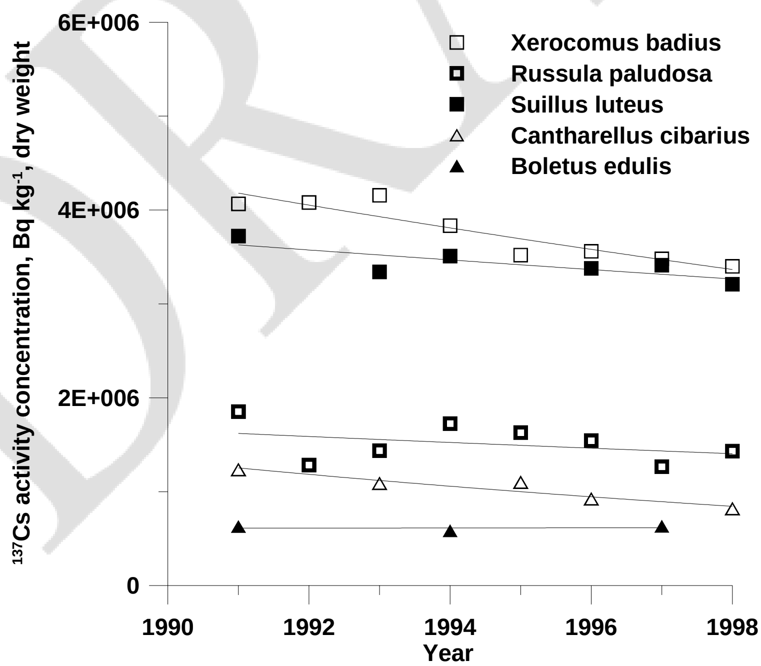

FIG. 7.1. Cs-137 activity concentrations (Bq/kg DW) in selected mushroom species. Cs-137 soil deposition at the site in 1986 was 555 kBq m^{-2} [7.10]

7.3. RADIONUCLIDE TRANSFER TO BERRIES

Uptake of radiocaesium by forest berries is high in comparison with foodstuffs grown in agricultural systems. T_{ag} values for radiocaesium in different berry species are presented in Table 7.7.

TABLE 7.7. AGGREGATED TRANSFER FACTORS FOR CAESIUM IN BERRIES, m^2 kg^{-1}, DW [7.11]

Berries	N	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

* Arithmetic means.

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 given for 1992-1993, 1999 with reported T_{ag} values of (7.1±4.1) 10^{-3} m^2 kg^{-1} and (9.2±3.0) 10^{-2} m^2 kg^{-1} to bilberry and wild strawberry respectively [7.12].

After the Chernobyl accident, the evolution of the ^{137}Cs content in all plant organs of all berry species shows a clear decreasing trend. Mean effective half-life ($T_{1/2}^{eff}$) for ^{137}Cs in berries calculated for the period from 1991 to 2006 is close to 10 years for most of the berry species [7.13].

7.4. RADIONUCLIDE TRANSFER TO GAME

7.4.1. Factors affecting transfer values

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

- heterogeneous deposition of radionuclides to forests and associated terrain;
- different dietary composition and feeding behaviour between game species different dietary composition and feeding behaviour of game species, for example some species can utilise produce from neighbouring cultivated areas or be reared with additional feed (eg brown hare, moose and pheasants);
- seasonal variations in diet and/or feeding behaviour (e.g. for roe deer, wild boar, reindeer, moose).

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

The consumption of meat of game from natural and semi-natural areas by the general population is low, but groups such as hunters may consume relatively large quantities which can sum up to critical dose levels. Early reports described relationships between radionuclide concentrations or amounts in precipitation, soil and animals and their intake by humans [7.14, 7.15]. 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 [7.16]. A general review of the parameter values for radionuclide transfers from soil to game is given in [7.17]. In Table 7.8 the actual collection of aggregated transfer factors in game is presented. The range of the mean values of T_{ag}, 3 x 10^{-4} – 0.10 m^2 kg^{-1} FW represent typical game animals hunted for human food, and the variability in the composition of feed. Data for game species, details of the relevant studies and full set of references, containing data presented here are given in the accompanying TECDOC [7.3].

Roe deer *(Capreolus capreolus)* consume a wide variety of herbs, grasses and also 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} of roe deer from Austria, Czech Republic and Germany are given in Table 7.8. 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 10-35 days [7.3]). All mammals exhibit fast and slow components of retention. A typical value for the fast component is 1 day for all mammalian species, but typically relates to only about 10 percent of the retained activity. It was found that the inter-species variation in the half-life of the long term component of retention is determined by body mass, as discussed, for example, in [7.18]. Ecological half-lives of roe deer meat vary between 6 and 13 years. Soil properties provide a significant influence (e.g. organic matter fraction in peat or spruce forest).

Red deer (*Cervus elaphus*) in central Europe are mostly managed game and live in deciduous or mixed forests. Few data exist concerning the time-dependence of the aggregated transfer coefficient T_{ag} with respect to ^{137}Cs in red deer (Table 7.8). Ecological half-lives of ^{137}Cs in red deer range from 5 to 18 years, for ^{90}Sr in antlers about 22 years are reported. Geometric mean values of T_{ag} of red deer from Austria, Czech Republic and Germany are given in Table 7.8.

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

Wild boar *(Sus scrofa)* is characterized by a very large feeding area. Omnivorous, the wild boar changes its diet with the seasons. Nearly totally herbivorous in spring and summer, it behaves mainly as a burrower when grass is rare in winter and feeds on roots, tubers, larvae and earthworms for which the transfers for caesium are higher than in green plants. Hence increased levels of contamination (on the order of 50%) are usually observed from October to March (Table 7.8). Decades after a contamination event with radiocaesium the activity concentration in wild boar can be very high and it can even show no decline with time because of the special feeding habits of wild boar. Geometric mean values of T_{ag} of wild boar from Austria, Czech Republic and Germany are given in Table 7.8, minimum values are valid for beech forest, 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 mostly determine the intake of ^{137}Cs in a few months preceding hunting. Regional soil types are reflected in values of T_{ag}, and the post-Chernobyl decrease in these values has been almost negligible in Northern areas (Table 7.8) while a somewhat decreasing trend has been observed in a 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 concnetnrations with time other than those due to the physical half-life which therefore determines the effective half-life [7.23]. However, data for moose, or elk, from Poland show a gradual decline in ^{137}Cs activity concentrations during 1986 - 1991, thus implying processes that reduce the bioavailability of ^{137}Cs in soil in regions south of the boreal forest zone [7.24].

TABLE 7.8. AGGREGATED TRANSFER COEFFICIENT T_{ag} (m² kg^{-1} fw) for ^{137}Cs FROM ACCUMULATED DEPOSITION TO MEAT OF GAME AND SEMI-DOMESTICATED REINDEER. *Based on post-Chernobyl data, and for game, meat samples representing hunting season*

Species or group of game animals	Range of geometric mean values		Number of ref.
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	GSD	
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	

Among the species or groups of small game the values of T_{ag} for ^{137}Cs were highest for arctic hare *(Lepus timidus),* hunted also in winter when bark and branches of trees are its main feed. Brown hare *(Lepus europaeus),* and particularly pheasant *(Phasianus colchicus)* visit cultivated land for feed, reflected by the low values of T_{ag}. A mixture of species form the group of forest birds characterised by constancy of long term values of T_{ag}. For the group waterfowl from freshwater ecosystems the T_{ag}'s for ^{137}Cs follow exponential decrease with time, corresponding to an ecological half-life of 1.1 year during the first few years after contaminating deposition. Biological half-life of ^{137}Cs in red grouse *(Lagopus lagopus)*, 10-11 d, was obtained for captive birds.

The seasonal composition of the feed of reindeer explains why the ^{137}Cs concentration in reindeer meat during summer and early autumn is only 10 or 20 % of the winter concentration, or less. After the Chernobyl accident the ecological half-life of ^{137}Cs in reindeer meat has ranged from 3 to 17 years, and where short and long components have been estimated, their ranges were 1 to 3 years and 16 to 18 years. Estimates for ecological half-lives reveal a significant dependence on the type and condition of pastures, and the need to consider seasons with their specific T_{ag} values. Values for 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

Transfer of radionuclides to game and the rate of activity reduction, given as 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 muscle activity concentration of deer animals often occurs in temperate zone.

The parameter most widely used to quantify radionuclide transfers to wild foodstuffs in forests is the aggregated transfer coefficient (T_{ag}). This simplistic approach is adopted because of the complexity of transfer pathways in forests. Unlike domestic animals, game animals have diets which are difficult to identify because they vary between locations and between seasons. Edible fungi are an ecologically complex group of organisms which obtain their nutrition from widely different locations and with highly variable rates. Similarly, understorey plants producing edible berries can have complex root distributions which make 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, i.e. 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 with time. Finally, in all cases T_{ag} values should be considered as a means of carrying out screening calculations, rather than providing a definitive method of 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.

REFERENCES

[7.1] ALEXAKHIN, R.M., NARYSHKIN M.A., Radionuclide migration in forest biogeocenoses, Nauka, Moscow (1977) (in Russian).

[7.2] TIKHOMIROV, F.A., SHCHEGLOV A.I., Main investigation results on the forest radioecology in the Kyshtym and Chernobyl accident zones, Science of the Total Environment **157** (1994) 45-57.

[7.3] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments, TECDOC No. XXX, IAEA, Vienna (2008)

[7.4] BELLI, M. (Ed.). SEMINAT. Long term dynamics of radionuclides in semi-natural environments: derivation of parameters and modelling. Agenzia Nazionale per la Protezione dell'Ambiente. (2000) 105 pp.

[7.5] FESENKO S.V., SOUKHOVA N.V., SANZHAROVA N. I., AVILA R., SPIRIDONOV S.I., KLEIN D., LUCOT E. AND BADOT P.M., Identification of processes governing long-term accumulation of ^{137}Cs in forest trees following the Chernobyl accident. Radiat. Environ. Biophys. **40** (2001) 105-113.

[7.6] SHCHEGLOV, A.I. Biogeochemistry of anthropogenic radionuclides in forest ecosystems of central part of South-European plain, Doctor of Science Thesis, Moscow State University. Moscow, Moscow, 1997 (in Russian).

[7.7] KRASNOV V.P., ORLOV A.A., BUZUN V.A., LANDIN V.P., SHELEST Z.M. Applied Radioecology of forest. (KRASNOV V.P. Ed.), Zhytomyr, POLISSYA, 2007. 679 pages.

[7.8] ASLANOGLOU X., ASSIMAKOPOULOS P.A., AVERIN V., HOWARD B.J., HOWARD D.C., KARAMANIS D.T., STAMOULIS K. Impact of the Chernobyl accident on a rural population in Belarus. In: Karaoglou A., Desmet G., Kelly G.N., Menzel H.G. (Eds), The Radiological Consequences of the Chernobyl Accident, (1996) pp. 363-378. European Commission, Brussels.

[7.9] MIETELSKI J.W., BAEZA A.S., GUILLEN J., BUZINNY M., TSIGANKOV N., GACA P., JASINSKA M., TOMANKIEWICZ E. Plutonium and other alpha emitters in mushrooms from Poland, Spain and Ukraine. Applied Radiation and Isotopes; **56**, (2002) 717-729.

[7.10] INTERNATIONAL ATOMIC ENERGY AGENCY, Modelling the migration and accumulation of radionuclides in forest ecosystems. IAEA-BIOMASS-1, IAEA, Vienna (2002).

[7.11] BERESFORD N.A., VOIGT G., WRIGHT S.M., HOWARD B.J., BARNETT C.L., PRISTER B., BALONOV M., RATNIKOV A., TRAVNIKOVA I., GILLETT A.G., et al. Self-help countermeasure strategies for populations living within contaminated areas of Belarus, Russia and the Ukraine. J. Environ. Radioact. **56**, (2001) 215-239.

[7.12] IPATYEV, V., BULAVIK, I., BAGINSKY, V., GONCHARENKO, G. AND DVORNIK, A., Forest and Chernobyl: Forest ecosystems after the Chernobyl nuclear power plant accident: 1986-1994, Journal of Environmental Radioactivity 42 (1999) 9-38.

[7.13] KRASNOV V., ORLOV A. Multiyear monitoring of radiocontamination of wild berry plants from the Ericaceae family in Ukraine, Botanica Lithuanica 10(3) (2004) 209-215.

[7.14] HVINDEN, T., LILLEGRAVEN, A., ^{137}Cs and ^{90}Sr in precipitation, soil and animals in Norway, Nature **192** (1962) 1144-1146.

[7.15] WHICKER, F.W., FARRIS, G.C., DAHL, A.H., “Wild deer as a source of radionuclide intake by humans and as indicators of fallout hazards”, Radiation Protection, Part 2. (SNYDER,.W., ABEE, H. H., BURTON, L. K., MAUSHART, R., BENCO, A., DUHAMEL, F., WHEATLEY, B. M., Eds), Oxford, Pergamon Press (1967) 1105-1110.

[7.16] HOWARD, B.J., BERESFORD, N.A., HOVE, K., Transfer of radiocaesium to ruminants in natural and semi-natural ecosystems and appropriate countermeasures, Health Physics **61** (1991) 715-725.

[7.17] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments. Technical Report Series N°364, Vienna (1994).

[7.18] COUGHTREY, P. J. and THORNE, M.C. Radionuclide distribution and transport in terrestrial and aquatic ecosystems. A critical review of data. Vol. 1, A.A. Balkema Publishers (1983) 495.

8. ARCTIC AND ALPINE ECOSYSTEMS

8.1. DEFINITIONS AND PROCESSES

Arctic (or Polar) and Alpine (Upland) areas typically are extensive with little, if any, fertilization by humans and includes forests, upland areas, polar regions and unimproved pastures (eg semi-arid steppe) Due to the poor nutrient status of the soils, these is little agriculture involving crop production other than of herbage for animals. The main foodstuffs from these areas are either wild products collected by humans, such as mushrooms and berries, a variety of game and semi-domesticated animals including reindeer and other ruminants [8.1-8.3].

8.1.1. Polar regions

Due to specific environmental conditions, arctic ecosystems are very vulnerable to radioactive contamination. The high utilisation of semi-natural ecosystems for local production of foodstuffs and local dietary habits may lead to cumulative doses due to radiocaesium and polonium with significant contributions persisting for a long time after the initial environmental contamination [8.4]. These landscapes are characterised by a pronounced diversity in environmental conditions, types of land use and dietary habits, which lead to a high variability of contamination levels in products and transfer parameters.

Like in other semi-natural environments, the transfer to food products of radiocaesium is higher than in intensively cultivated land and persistence for a long time after deposition. The reason is that due to low temperatures soil building processes and litter decomposition in arctic ecosystems is slower, leading to low pH values and nutrient deficiency in soils. In general, biogeochemical processes are slower, and contaminants remain available for biota species for a longer period than in temperate environments [8.1-8.4].

The food chain *lichen–reindeer–man* has been the main object of study within terrestrial arctic radioecological research. The high interception by lichen of radionuclides, particularly radiocaesium and polonium, is one of the key factors contributing to probably the most vulnerable 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 three cm of lichen which is consumed by reindeer [8.5].

8.1.2. Upland regions

In upland ecosystems, radiocesium is efficiently stored in superficial soil layers and plant litter, in some areas caused by the presence of high amounts of fungal biomass (in acid soils) [8.3, 8.6]. Deposited radiocaesium remains available for root uptake by meadow vegetation and can enter the grass-ruminant-human foodchain. Upland regions can have a high socio-economic value and serve as basis for extensive agriculture. In summer, upland grass pastures are used as free ranging cows, sheep and goats (milk and meat production) and, to a limited extent, for the production of winter feed for animals [8.3]. In this chapter data from Alpine areas are taken to represent main features and parameters for radionuclide transfer in Uplands.

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 (sheep are stabled in the winter and fed upon stored feed) and assumes an exclusive consumption of locally-produced feed. However, the slaughter of reindeer and sheep typically occurs during the autumn/winter in a given year. These temporal variations make it difficult to compare T_{ag} values between sites in different years [8.7-8.8]. To predict changes with 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 [8.3]:

a) Variation with time

b) Seasonal variability

c) Spatial variability and dietary variability of grazing animals (as already discussed)

The reduction of concentration of radionuclides in both arctic and alpine ecosystems system is commonly described as an exponential decay with an effective half life as discussed is Chapter 2. For the transfer of radionuclides from feed to milk or 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 related to the daily dietary radionuclide intake (see also Chapter 6).

8.2. RADIONUCLIDE TRANSFERS IN POLAR REGIONS

8.2.1. Transfer to lichens

Lichens are a major component of reindeer diet. They don't have a rooting system and take up nutrients and associated pollutants from air and 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 or leaching. Depending on the physical and chemical properties radionuclides may also be translocated to fresh growth. Sr-90 is more mobile than ^{137}Cs in lichens, and is washed out from lichens more rapidly than ^{137}Cs [8.3]. Table 8.1 gives examples of mass interception fractions (f_l) estimated for lichens at the Kola Peninsula for 1961-1999 [8.9].

TABLE 8.1. ^{137}Cs AND ^{90}Sr LICHEN MASS INTERCEPTION FRACTIONS (f_L,, DRY WEIGHT) FOR THE KOLA PENINSULA AND ECOLOGICAL HALF LIVES (T_1, T_2) FOR THE LICHEN

Radionuclide	f_l, m^2 kg^{-1}	a_1[1]	T_{eff1}, y	T_{eff2}, y
^{137}Cs	1.4	0.80	2.0	20
^{90}Sr	0.7	0.72	1.0	20

[1] a_1 gives the fraction of the initial concentration in lichen declining with the short half-life T_1

In a situation with deposition onto snow (in winter), lichen will only become contaminated during snowmelt, with some of the deposited radioactivity lost via runoff and effectively decreasing the lichen interception fraction. In contrast, if radionuclide deposition occurs as a single pulse dry deposition then the 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 [8.3].

8.2.2. Transfer to reindeer

The reindeer diet change 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 2-3 fold increase in biological half-life of radiocaesium from about 7 to about 20 days [8.10-8.11]. All three factors contribute significantly to increasing 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 to those during winter [8.12]. A review of radionuclide contamination levels in reindeer and caribou due to the nuclear weapons tests fallout is presented in the accompanying TECDOC [8.3] while some representative values from Golikov et al. [8.9] who analysed ^{137}Cs transfer to reindeer during winter at the Kola Peninsula (Russia) and northern Norway from the 1960s are given in Table 8.2.

TABLE 8.2. INITIAL ^{137}Cs AGGREGATED TRANSFER FACTORS FOR REINDEER MEAT ($T_{ag}(0)$ m^2 kg^{-1}, FRESH WEIGHT), ECOLOGICAL (T_1, T_2) and EFFECTIVE (T_{eff1}, T_{eff2}) HALF-LIVES IN MUSCLES OF REINDEER, years [8.9]

Area	$T_{ag}(0)$,	a_1 [1]	T_1	T_2	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

[1] The factor a_1 gives the fraction of the initial concentration in lichen declining with the short half-life T_1.

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 [8.3], as suggested by a double exponential model. As an alternative approach Åhman [8.10] divided the time period after the accident into the first 10 years and the second 10 years (year 10 – 20). Analysis of data from all herds together showed that the effective half life during the first period was considerably shorter than in the latter period (Table 8.3).

TABLE 8.3. Cs-137 AGGREGATED TRANSFER FACTORS TO REINDEER MEAT IN THE FIRST YEAR AFTER FALLOUT (T_{agi}) AND EFFECTIVE HALF-LIVES (T_{eff}) FOR DIFFERENT PERIODS AFTER THE CHERNOBYL ACCIDENT (after Åhman [8.10] and Skuterud (unpublished data)).

Country and herd	Season	T_{ag} 1986-1987	T_{eff} 1-10, y	T_{eff} 10-20, y	T_{eff} 1-20, y
Sweden: Vilhelmina norra, Ubmeje, Ran	September	0.11-0.24	2.5-3.1	7.6- no decline	4.5-6.7
	October	0.27-0.39	2.1-2.5	11.4-20.6	5.8-7.9
	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: Østre Namdal, Vågå	September		4.1-4.9	No decline	9.2-12.4
	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 year for both sites, with standard errors of 0.8 and 1.5 year.

More detailed data on aggregated transfer factors and ecological half-lives for ^{137}Cs and ^{90}Sr in reindeer are given in the accompanying TECDOC which also includes references to studies of ^{210}Po, ^{210}Pb, ^{226}Ra in reindeer and caribou in Alaska [8.3].

8.2.3. Transfer to ruminants

For animal products in the Arctic other than reindeer meat radiocaesium activity concentratios decrease rapidly in the first year after deposition and then more slowly. Seasonal variations occur with higher ^{137}Cs and ^{90}Sr activity concentrations in the summer, when cows are put out to pasture or fed fresh grass. Tables 8.4 and 8.5 give available data on T_{ag} values (for early and late periods after deposition) and appropriate information on variability of the effective ecological half lives in milk. A compilation of T_{ag} values for lamb meat is given in Table 8.4.

TABLE 8.4: SUMMARY OF T_{ag} VALUES FOR COW MILK, $m^2\ kg^{-1}$ FW

Phase	Region	Year(s)	T_{ag}
Early period ($T_{ag}(0)$)			
	Fennoscandia and NW Russia		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[3]	1965	7.6×10^{-3}
Late period			
	Lovozero (Russia)	1998-1999	0.24×10^{-3}
	Kola region (Russia)	1998-1999	0.15×10^{-3}
	Kola region (Russia)	1974-1978	0.14×10^{-3}
	Nenets AO (Russia)	1974-1978	0.12×10^{-3}
	Kola region (Russia)	1978-1985	0.082×10^{-3}
	Nenets AO (Russia)	1978-1985	0.062×10^{-3}

TABLE 8.5. EFFECTIVE HALF-LIVE VALUES FOR ^{137}Cs, ^{90}Sr ACTIVITY CONCENTRATIONS IN MILK FROM VARIOUS ARCTIC AREAS ([8.2; 8.14]), years

Area	^{137}Cs - Chernobyl fallout	^{137}Cs - Global fallout	
	T_{eff}	T_{eff1}	T_{eff2}
Faroe	1.3 – 1.8	1.0 – 1.8	6.5 – 8.8
Finland	0.7 - 3.4	1.0	4.5
Norway	-	1.1 – 1.9	4.5 – 6.1
Sweden	-	1.4 – 1.8	6.2 – 9.1
		^{90}Sr - Chernobyl fallout	
		T_{eff1}	T_{eff2}
Faroe		1.0 – 1.4	4.0 – 5.5
Finland		1.0 – 1.3	8.4 – 12.0
Norway		1.5 – 1.8	4.0 – 4.6
Sweden		1.4 – 3.0	8.5 - .0

[3] Average value for 8 regions; range is 3.5-14.6 x $10^{-3}\ m^2$ kg ; Palsson, unpublished

TABLE 8.7: SUMMARY OF INITIAL AND LATE PHASE T_{ag} VALUES FOR LAMB (SHEEP) MEAT, m^2 kg^{-1} FW

Phase	Region	Years	T_{ag}
Early	Fennoscandia and Northwest Russia		3.8×10^{-1}
($T_{ag}(0)$)	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	Northern Sweden	1990-1997	4.7×10^{-2}
	Faroe Islands	1990-1997	$(5.5\text{-}2.5) \times 10^{-3}$
	Finland	1990-1993	0.83×10^{-3}
	Iceland	1990-1993	1.5×10^{-2}
	Norway	1990-1993	3.9×10^{-2}

8.3. RADIONUCLIDE TRANSFERS IN ALPINE ECOSYSTEMS

8.3.1. Soil-plant transfer in Alpine ecosystems

Similar like for other semi-natural systems the use of aggregated transfer factors is quite effective for assessments of radionuclide transfer in alpine ecosystems. This is due to the fact that variability of conventional transfer factors is extremely high [8.15]. Influencing factors are e.g. high variability of microclimatic conditions, small-scale variability of soil properties, and changing hydrological conditions [8.15-8.16]. Available peer-reviewed data are given in Table 8.9.

TABLE 8.9. AGGREGATED TRANSFER FACTORS (T_{ag}; m^2 kg^{-1}) FOR ^{137}Cs AND ^{90}Sr FROM SOIL TO GRASSLAND VEGETATION IN ALPINE ECOSYSTEMS

Soil type	N	GM	GSD	AM	SD	Min	Max
			^{137}Cs				
Sandy	8	0.014	3.1	0.021	0.015	0.002	0.043
Loamy	4	0.003	2.9	0.004	0.006	0.001	0.013
Unspec.	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

8.3.2. Transfer to ruminants in Alpine ecosystems

Feed transfer coefficient were determined in milk from alpine regions with calcareous and silicate bedrock [8.15-8.17] and in one intensively productive lowland region for comparison [8.16].

TABLE 8.10: TRANSFER COEFFICIENTS F_m [d l^{-1}] FOR ^{137}Cs AND ^{90}Sr IN UPLAND ALPINE AREAS

Site	AM	SD	Min	Max
		^{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

The feed transfer coefficients for ^{137}Cs in lowland region is significantly lower than on alpine production sites, however for ^{90}Sr no difference could be found. Also no significant differences for both radionuclides could be determined between milk feed transfer factors on silicate and calcareous bedrock.

Considerably longer ecological (or effective) half-lives have been observed cow milk from Alpine pastures in comparison to lowland production sites. For the period 1988–2006 Lettner et al. [8.18] derived ecological half-lives of 0.7-1.4 years for the fast initial period and 9.3-12.7 years for the long-term decay component of ^{137}Cs concentrations in cow 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

Transfer of radiocaesium to game animals and the ecological half-lives reflect the soil and pasture conditions in semi-natural environments. The data for both parameters show a considerable variability, due to seasonal effects, small-scale heterogeneity in soil and climate parameters, and 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 simplistic approach of using Tag values is 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 semi-natural systems in which radionuclide fluxes have stabilized, namely 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 with time. Finally, in all cases T_{ag} values should be considered as a means of carrying out screening calculations, rather than providing a definitive method of calculating transfer. Detailed, site-specific dose assessments will require more consideration of local transfer processes, pathways and rates than T_{ag} values can provide.

REFERENCES

[8.1] ARCTIC MONITORING AND ASSESSMENT PROGRAMME, AMAP Assessment Report: Arctic Pollution Issues, Arctic council, Oslo (1998) 859 pp.

[8.2] ARCTIC MONITORING AND ASSESSMENT PROGRAMME, AMAP Assessment 2002: Radioactivity in Arctic, Arctic council, Oslo (2004) 100 pp.

[8.3] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments, TECDOC No. XXX, IAEA, Vienna (2008)

[8.4] BORGHUIS, A.M., LILAND, A., STRAND, P. (Eds.), Arctic Vulnerability to Radioactive Contamination), Final Report (Contract number: IC15-CT98-0201), Norwegian Radiation Protection Authority, Oslo, 2002.

[8.5] LIDÉN, K., GUSTAFSSON, M., "Relationship and seasonal variation of ^{137}Cs in lichen, reindeer and man in northern Sweden 1961 to 1965", Radioecological Concentration Processes, Pergamon Press, Oxford (1967) p.193.

[8.6] STEMMER, M., HROMATKA, A., LETTNER, H., STREBL F., Radiocaesium storage in soil microbial biomass of undisturbed alpine meadow soils and its relation to ^{137}Cs soil–plant transfer, Journal of Environmental Radioactivity, **79**(2) (2005) 107-118

[8.7] BERGAN, T. (Ed.), Ecological Half-Lives of Radioactive Elements in Semi-Natural Systems. NKS, Risø National Laboratory NKS(97)FR5, Roskilde (2000) 218 pp.

[8.8] HOVE, K., LÖNSJÖ, H., ANDERSSON, I., SORMUNEN-CRISTIAN, R., SOLHEIM H., et al., "Radiocaesium transfer to grazing sheep in Nordic environments", Nordic Radioecology: The Transfer of Radionuclides through Nordic Ecosystems to Man (DAHLGAARD, H., Ed.), Elsevier Science B.V. Studies in Environmental Science **62**, Amsterdam (1994) 211-227.

[8.9] GOLIKOV, V., LOGACHEVA, I., BRUK, G., SHUTOV, V., BALONOV, M. et al., Modelling of long-term behaviour of caesium and strontium radionuclides in the Arctic environment and human exposure, Journal of Environmental Radioactivity, **73**(1-3) (2004) 159-169.

[8.10] ÅHMAN, B., Modelling radiocaesium transfer and long-term changes in reindeer, Journal of Environmental Radioactivity **98**(1-2) (2007) 153-165.

[8.11] HOLLEMAN, D.F., LUICK, J.R., et al., Transfer of Radiocesium Form Lichen to Reindeer, Health Physics **21**(5) (1971) 657.

[8.12] SKUTERUD, L., E. GAARE, et al., Chernobyl radioactivity persists in reindeer, Journal of Environmental Radioactivity **83**(2) (2005) 231-252.

[8.13] HOVE, K., PEDERSEN, Ø., GARMO, T.H., HANSEN, H.S., STAALAND, H., Fungi: A major source of radiocaesium contamination of grazing ruminants in Norway, Health Physics **59**(2) (1990).189-192.

[8.14] THØRRING, H., "Radioactive contamination of milk from the Nordic countries", Impact Assessment within the IAEA Arctic Assessment Project (IASAP), (Ilus E. Ed.), Proceedings of the Summary Seminar within the NKS-B Programme 2002-2005. 24-25 October 2005, Tartu, Estonia, NKS, Risø. NKS-143 (2006) 152-158.

[8.15] ALBERS, B.P., STEINDL, H., SCHIMMACK, W., BUNZL, K., Soil to plant and plant-to-cow's milk transfer of radiocaesium in alpine pastures: significance of seasonal variability, Chemosphere **41** (2000) 717 – 723.

[8.16] MACHART, P., HOFMANN, W., TÜRK, R., STEGER, F., Ecological half-life of ^{137}Cs in lichens in an alpine region, Journal of Environmental Radioactivity, **97** (2007) 70-75.

[8.17] GASTBERGER, M., STEINHÄUSLER, F., GERZABEK, M.H., HUBMER, A., Fallout strontium and caesium transfer from vegetation to cow milk at two lowland and two Alpine pastures, Journal of Environmental Radioactivity **54**(2) (2001) 267-273.

[8.18] LETTNER, H., HUBMER, A., BOSSEW, P., STREBL, F., Cs-137 and ^{90}Sr transfer to milk in Austrian alpine agriculture, Journal of Environmental Radioactivity **98(**1-2) (2007) Pages 69-84.

9. RADIONUCLIDE TRANSFERS IN FRESHWATER ECOSYSTEMS

Radionuclides dispersed in the environment can be deposited into water surface or on the surface of the catchment (watershed). Wash-off of radionuclides from the catchment can represent a long-term source of radionuclides for freshwater ecosystems. Once in the water, some radioactivity is typically adsorbed by solid particles: this partitioning between the solid and water affects both transport and biological uptake. Solid particles can settle out 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 remobilised, becoming available again for uptake by freshwater biota. Detailed information on the physical processes listed above as well as transfer parameters are provided in the accompanying TECDOC [9.1]. In this document, information is confined to parameters relating to availability of radionuclides sorbed to sediments and on 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 interactions with suspended particulate matter (SPM) and settlement in sedimentation zones of a water system. Besides, the uptake of radionuclides by aquatic organisms depends on the concentration and on the speciation of 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 between the particulate phase and the dissolved phase under equilibrium conditions (in $Bq.kg^{-1}$ of SPM per Bq L^{-1}).

Sorption of radioactive on natural particles resulted from several kinetic processes, involving rapid, but also slow processes (e.g. oxidation processes, inner sphere complexation and migration of cation in the clay structure) [9.1-9.12]. Kinetics in the interactions of radionuclides at the interface water-SPM depends on the element of concern, but also on other environmental co-factors, such as: SPM concentration. [9.1, 9.4, 9.7]; the ionic strength and age of the contamination (termed as ageing effect) [9.1-9.3].

Desorption kinetics may be highly governed by the inner speciation of bound radionuclides (i.e. distribution among easily and less accessible binding sites respectively) [9.5].

For sorption of some radionuclides in freshwater ecosystems the seasonality effect (and the associated biological activity in the river) is important. So, for Co or Mn, oxidation processes, are partly microbially mediated, govern their slow uptake onto SPM. Seasonal differences may then reflect strong seasonal variation in the abundance of oxidizing bacteria [9.5, 9.11].

Based on availability of the data, all radionuclides were divided into four groups [9.12]: radionuclides for which large databases are accessible; K_d values for radionuclides with moderate databases, K_d values for radionuclides for which only single values are available and for radionuclides with K_d values which are mainly product of expert estimates mainly given in the review published in 1991 [9.13]. The latter values were also quoted in TRS 364 [9.14] without clear referencing. The database contains K_d values for natural freshwaters (rivers and lakes) from suspended particulate matter (SPM) or superficial sediment (top 0-5 cm).

In addition, information on potential co-factors and on criteria allowing estimating the quality of each referenced data was collected, especially about: 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), redox conditions (especially for I). The methodology for data processing in the first case i.e. if large databases were accessible (Ag, Am, Co, Cs, I, Mn, Pu and Sr) was as follows: (i) a construction of the database with available K_d data and information on corresponding environmental co-factors; (ii) application of quality criteria; (iii) determination of non- conditional (iii) and conditional (iv) Probability Density Functions (PDFs) by a bootstrap statistical procedure to account for parametric uncertainty [9.12]. For the second group of radionuclides (Be, Ba, Ce, Ra, Ru, Sb, and Th), similar approach (steps (i)-(iii)) was used, but only non-conditional PDFs were defined (the step (iv) was omitted) for reducing the uncertainty over a given range of values for any parameter. Simple statistical data processing was applied for radionuclides of the third group and the data for radionuclides of the fourth group (Cr, Fe, Zn, Zr, Tc, Pm, Eu, U, Np, Cm) were taken as they were reproduced in [9.13 and 9.14].

Reference K_d values with the associated GSD are given in Table 9.1. The data were obtained from field measurements ("Field") and laboratory adsorption ("Ads") or desorption ("Des") experiments. Where appropriate, separate K_d values are presented for these three types of measurement.

TABLE 9.1. K_d VALUES IN FRESHWATER ECOSYSTEMS, L kg^{-1}

Element	N	GM	GSD	Min	Max	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	$2.5 x 10^{2}$	$1.6 x 10^{4}$	Various
Be	29	4.2×10^{4}	3.6	$5.1 x 10^{3}$	$3.4 x 10^{5}$	Various
Ce	15	2.2×10^{5}	2.9	$4.2 x 10^{4}$	$1.2 x 10^{6}$	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	$4.4 x 10^{3}$	14	$5.9 x 10^{1}$	$3.4 x 10^{5}$	Ads[1]
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

TABLE 9.1. K_d VALUES IN FRESHWATER ECOSYSTEMS, L kg^{-1} (Cont.)

Element	N	GM	GSD	Min	Max	Data origin
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	$4.4 \text{ x } 10^3$	14	$5.9 \text{ x } 10^1$	$3.4 \text{ x } 10^5$	Ads[1]
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	$1.1 \text{ x } 10^3$	$5.2 \text{ x } 10^4$	Various
Ru	74	3.2×10^4	1.9	$1.1 \text{ x } 10^4$	$9.3 \text{ x } 10^4$	Various
Sb	23	5.0×10^3	3.9	$5.5 \text{ x } 10^2$	$4.6 \text{ x } 10^4$	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	$1.2 \text{ x } 10^3$	$2.7 \text{ x } 10^7$	Various

[1]only oxic systems

Information related to additional elements is given in Table 9.2 (i.e. Cr, Fe, Zn, Zr, Tc, Pm, Eu, U, Np, Cm) and reported in TRS 364 [9.14]. As it was mentioned earlier these values are based on only on one publication [9.13] and must be used with caution.

TABLE 9.2. GROSS AVERAGE K_d VALUES IN AQUEOUS SYSTEMS, L kg^{-1} [9.14]

Element	Expected value	Min	Max
Cr	Low[1]	-	-
Fe	$5.0 \text{ x } 10^3$	$1.0 \text{ x } 10^3$	$1.0 \text{ x } 10^4$
Zn	$5.0 \text{ x } 10^2$	$1.0 \text{ x } 10^2$	$1.0 \text{ x } 10^3$
Zr	$1.0 \text{ x } 10^3$	$1.0 \text{ x } 10^3$	$1.0 \text{ x } 10^4$
Tc	$5.0 \; 10^0$	nd[2]	$1.0 \text{ x } 10^2$
Pm	$5.0 \text{ x } 10^3$	$1.0 \text{ x } 10^3$	$1.0 \text{ x } 10^4$
Eu	$5.0 \text{ x } 10^2$	$2.0 \text{ x } 10^2$	$9.0 \text{ x } 10^2$
U	$5.0 \text{ x } 10^1$	$2.0 \text{ x } 10^1$	$1.0 \text{ x } 10^3$
Np	$1.0 \text{ x } 10^1$	$2.0 \text{ x } 10^{-1}$	$1.0 \text{ x } 10^2$
Cm	$5.0 \text{ x } 10^3$	$1.0 \text{ x } 10^1$	$7.0 \text{ x } 10^4$

[1] reproduced according to [9.14]; [2]nd – not detectable

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 into aquatic biota is often represented by simplified ratios that relate radionuclide concentrations in biotic tissues to concentrations in the reference media [9.12, 9.15, 9.16].

The steady state models can be sub-divided into two categories based on the chemical behaviour of a given radionuclide and its associated transfer processes to edible biotic tissues. These include: i) models that are based on simple radionuclide partitioning between organisms and reference phases (such as surface water or sediments); and ii) specific activity models, which assess partitioning of radionuclides relative to stable analogues in the body [9.12].

9.2.1. Concentration Ratios

Depending upon the radionuclide uptake pathway being considered, a number of representations of partitioning can be defined. These include: i) concentration ratio (*CR)*), which is the ratio of the contaminant concentration in biota (C_b) from all exposure pathways (including water, sediment and ingestion/dietary pathways) on a per unit tissue fresh weight basis relative to that of water (C_w) and (ii) the biota sediment concentration ratio (CR_s), which is the ratio of the concentration of a radionuclide in an organism (C_b) on a per unit tissue fresh weight basis relative to the value measured in the sediment (C_{sed}) on a per unit fresh sediment basis. Fresh weights to dry weights ratios for selected aquatic organisms are included in Appendix 1.

The *CRs* 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 bioaccumulation factor, *BAF*s). Water-to-biota *CR* values from the literature have been compiled for radionuclides and their stable analogues in Tables 9.3 to 9.6, whereas sediment-to-biota concentration ratios (CR_s) are provided in Tables from 9.7 to 9.8 (largely based on the data from Vanderploeg and Yankovich [9.15 and 9.16]). Additional information on tissue-specific radionuclide transfer factors can be found in the accompanying TECDOC [9.12].

TABLE 9.3. SUMMARY OF CONCENTRATION RATIOS (*CR)* FOR EDIBLE AQUATIC PLANTS[1], L kg^{-1}, FW

Element	N	Mean[2]	GSD	Min	Max
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	-	na[3]	Na
Co	19	7.1×10^2	5.1×10^0	5.0×10^1	2.0×10^4

TABLE 9.3. SUMMARY OF CONCENTRATION RATIOS (*CR)* FOR EDIBLE AQUATIC PLANTS[1], L kg^{-1}, FW (Cont.)

Element	N	Mean[2]	GSD	Min	Max
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}

[1]All types of aquatic plants are included in the assessments, [2] For N=2 the mean is Arithmetic mean; [3] na – not available.

TABLE 9.4. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR FRESHWATER INVERTEBRATES, L kg^{-1}, FW

Element	N	Mean[1]	GSD	Min	Max
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}
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}

TABLE 9.4. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR FRESHWATER INVERTEBRATES, L kg^{-1}, FW

Element	N	Mean[2]	GSD	Min	Max
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}

[1]For N=2 the mean is Arithmetic mean

TABLE 9.5. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR FRESHWATER FISH TISSUES, L kg^{-1}, FW.

Element			Whole			Data		Muscle		
	N	Mean	GSD	Min	Max	N	Mean	GSD	Min	Max
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	na	na	na	na	na	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	na	na	na	na	na	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}	9.0e-01	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}	1.1e-01	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 x 102	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	na	na	na	na	na	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	na	na	na	na	na	5	3.6×10^{1}	4.3×10^{0}	6.0×10^{0}	1.7×10^{2}

[1]For N=2 the mean is Arithmetic mean; [2]na=not available

TABLE 9.5. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR FRESHWATER FISH TISSUES, $L\ kg^{-1}$, FW (Cont.)

Elem.	Whole					Muscle				
	N	Mean[1]	GSD	Min	Max	N	Mean[1]	GSD	Min	Max
Pu	na	na	na	na	na	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	na	na	na	na	na	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 x 101	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}
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}

[1]For N=2 the mean is Arithmetic mean; [2]na= not available

TABLE 9.6. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR EDIBLE HERPETOFAUNA [9.18], L kg^{-1}, FW

Element	Biota Type (tissue)	N	Mean[1]	GSD	Min	Max
Al	Tadpole (whole)	3	1.0×10^{4}	1.3×10^{0}	7.5×10^{3}	1.3×10^{4}
Al	Frog (muscle)	2	1.3×10^{2}		1.2×10^{2}	1.3×10^{2}
Al	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}
As	Frog (muscle)	2	5.2×10^{1}		2.4×10^{1}	9.0×10^{1}
As	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}
Ca	Frog (muscle)	2	3.5×10^{0}		3.4×10^{0}	3.5×10^{0}
Ca	Frog (carcass)	2	2.9×10^{2}		2.9×10^{2}	2.9×10^{2}
Ca	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}
Cd	Frog (muscle)	2	1.2×10^{2}		1.1×10^{2}	1.2×10^{2}
Cd	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}
Co	Frog (muscle)	2	5.5×10^{2}		1.9×10^{2}	9.0×10^{2}
Co	Frog (carcass)	2	2.4×10^{3}		1.9×10^{3}	3.0×10^{3}
Co	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}
Cr	Frog (muscle)	2	9.2×10^{1}		9.2×10^{1}	9.3×10^{1}
Cr	Frog (carcass)	2	2.6×10^{3}		1.9×10^{2}	4.9×10^{3}
Cs	Tadpole (whole)	3	3.0×10^{3}	1.3×10^{0}	2.5×10^{3}	4.0×10^{3}
Cs	Frog (muscle)	2	2.6×10^{2}		1.7×10^{2}	3.4×10^{2}
Cs	Frog (carcass)	2	2.1×10^{2}		1.6×10^{2}	2.5×10^{2}
Cs	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}
Cu	Frog (muscle)	2	1.1×10^{2}		1.1×10^{2}	1.1×10^{2}
Cu	Frog (carcass)	2	4.4×10^{2}	2.3×10^{0}	2.9×10^{2}	6.0×10^{2}

[1] For N=2 the mean is Arithmetic mean

TABLE 9.6. SUMMARY OF CONCENTRATION RATIOS (*CR*) FOR EDIBLE HERPETOFAUNA [9.18], $L\ kg^{-1}$,FW (Cont.)

Element	Biota Type (tissue)	N	Mean	GSD	Min	Max
Fe	Tadpole (whole)	3	2.4×10^{3}	1.2×10^{0}	1.9×10^{3}	2.9×10^{3}
Fe	Frog (muscle)	2	3.5×10^{1}		1.9×10^{1}	5.0×10^{1}
Fe	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}
K	Frog (muscle)	2	1.5×10^{3}		1.4×10^{3}	1.5×10^{3}
K	Frog (carcass)	2	1.6×10^{3}		1.5×10^{3}	1.6×10^{3}
K	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}
Mg	Frog (muscle)	2	1.5×10^{1}		9.4×10^{0}	2.1×10^{1}
Mg	Frog (carcass)	2	2.4×10^{1}		2.3×10^{1}	2.4×10^{1}
Mg	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}
Mn	Frog (muscle)	2	2.0×10^{0}		9.3×10^{-1}	3.1×10^{0}
Mn	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}
Na	Frog (muscle)	2	1.4×10^{2}		9.9×10^{1}	1.9×10^{2}
Na	Frog (carcass)	2	7.7×10^{1}		7.5×10^{1}	7.9×10^{1}
Na	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}
Ni	Frog (muscle)	2	2.4×10^{1}		2.1×10^{1}	2.7×10^{1}
Ni	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}
Pb	Frog (muscle)	2	5.5×10^{0}		2.1×10^{0}	9.9×10^{0}
Pb	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}
Zn	Frog (muscle)	2	9.0×10^{2}		2.0×10^{2}	1.5×10^{3}
Zn	Frog (carcass)	2	1.0×10^{4}		9.5×10^{3}	1.1×10^{4}

[1]For N=2 the mean is the arithmetic mean

TABLE 9.7. SUMMARY OF SEDIMENT-TO-BIOTA CONCENTRATION RATIOS (CR_S) FOR WHOLE FRESHWATER INVERTEBRATES [9.17, 9.19]

Element	N	Mean	GSD	Min	Max
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}

TABLE 9.8: SUMMARY OF SEDIMENT-TO-BIOTA CONCENTRATION RATIOS (CR_S) FOR EDIBLE TISSUES OF FRESHWATER FISH [9.6, 9.8]

Elem.	Whole fish					Fish muscle					Fish liver				
	N	Mean	GSD	Min	Max	N	Mean	GSD	Min	Max	N	Mean	GSD	Min	Max
Ag	9	6.9×10^{-1}	3.5×10^{0}	1.2×10^{-1}	4.9×10^{0}	na[2]	na	na	na	na	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}	na	na	na	na	na	1	1.4×10^{-1}	na	na	na
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}	na	na	na	na	na
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}	na	na	na	na	na
Mo	Na	na	na	na	na	na	na	na	na	na	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}	na	na	na	na	na	na	na	na
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	na	na	na	na	na	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}	na	na	na	na	na	na	na	na	na	na
Sr	35	1.4×10^{-2}	1.5×10^{1}	1.9×10^{-4}	9.5×10^{-1}	na	na	na	na	na	71	4.7×10^{-4}	2.2×10^{0}	9.9×10^{-5}	2.6×10^{-3}
Ti	1	1.6×10^{-2}				na	na	na	na	na	na	na	na	na	na
Tl	13	2.9×10^{2}	5.6×10^{0}	6.9×10^{0}	2.9×10^{3}	1	7.5×10^{1}	na	na	na	na	na	na	na	na
V	29	2.1×10^{-3}	2.4×10^{0}	4.2×10^{-4}	1.3×10^{-2}	na	na	na	na	na	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}

[1]For N=2 the mean is Arithmetic mean; [2] na= not available

In general, CR and CR_s 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 [9.20]. To account for this, CR and CR_s values can be multiplied by a factor, K, that accounts for the radionuclide-specific half-lives, as described by:

$$K = \frac{\lambda b}{\lambda r + \lambda b} \tag{9.1}$$

where λ_b is the biological decay constant = 0.693 t_b^{-1} (day^{-1}); λ_r = radioactive decay constant = 0.693 t_r^{-1} (day^{-1}); t_b = biological half-life (day); t_r = radiological half-life (day). For screening purposes, a t_b of 30 days (or a λ_b of 0.023 day^{-1}) can be assumed [9.20].

Details outlining how transfer factors were defined can be found in the accompanying TECDOC [9.12].

9.3. RADIONUCLIDE PARTITIONING INTO EDIBLE BIOTIC TISSUES

9.3.1. Application of specific activity model approach for 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:

$$SA_{m,r} = \frac{C_{m,r}}{C_{m,a}} \cdot C_{b,a} \tag{9.2}$$

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 radioisotope-to-all isotope ratio in the biota tissue being considered.

Notable examples of radionuclides for which a specific activity models should be used include tritium, ^{14}C and ^{36}Cl, which are discussed in Chapter 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 exchange for calcium in bones and other hard tissues [9.21- 9.23].

Fish-to-water CR for radiocesium 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 [9.24-9.26].

For radiocesium in predatory/omnivorous fishes, the *CR* can be estimated using the following equation [9.26]:

$$CR(predatory / omnivorous) = \frac{4880}{[K^+]} \qquad (9.3)$$

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

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

$$CR(non - predatory) = \frac{2390}{[K^+]} \qquad (9.4)$$

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 [9.15 and 9.24]:

$$CR(\text{muscle}) = exp(5.2 – 1.2\ ln[Ca]) \qquad (9.5)$$

$$CR(\text{bone}) = exp(9.7 – 1.2\ ln[Ca]) \qquad (9.6)$$

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 [9.16]:

$$CR(\text{whole fish}) = exp(9.13 – 1.2\ ln[Ca]) \qquad (9.7)$$

An important consideration in the application of specific activity models is the choice of environmental medium, *m*. Indeed, in some instances, organisms may obtain their supplies of an element from multiple sources, e.g. 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 upon the species, radionuclide and tissue under consideration, it may be necessary to estimate the percent 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 [9.27- 9.29].

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

$$\text{Percent Loading in Tissue} = \frac{C_{tissue} \cdot m_{tissue}}{C_{whole} \cdot m_{whole}} \cdot 100\% = \frac{CR_{tissue} \cdot C_{\text{Reference Tissue}} \cdot m_{tissue}}{C_{whole} \cdot m_{whole}} \cdot 100\% \qquad (9.8)$$

where C_{tissue} is the element concentration in a given tissue (in mg/kg fresh weight or Bq/kg 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 fresh weight or Bq/kg 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 literature data); 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 [9.2].

9.4. APPLICATION OF DATA

The process of interaction of dissolved radionuclides with solids particles in suspension or deposited, is usually modelled according to the "K_d concept", where K_d is the partition coefficient "particulate form/dissolved form" 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 and the attached phases may be not instantaneously achieved and the adsorption and desorption processes are not always rapidly reversible [9.30 and 9.31].

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 into 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, fish feeding rate, size and position on the food chain. It is recommended that, where possible, estimates of radionuclides in water are used to predict accumulation in fish (i.e. that the *CR* is used) as these 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, though for sediment-dwelling organisms and benthic (bottom dwelling) fish, the sediments may of course play an important role.

REFERENCES

[9.1] BENES, P. and POLIAK, R., Factors affecting interaction of radiostrontium with river sediments, Journal of Radioanalytical and Nuclear Chemistry **141**(1) (1990) 75-90.

[9.2] BENES, P., CERNIK, M., RAMOS, P.L., Factors affecting interaction of radiocaesium with freshwater solids. II. Contact time, concentration of the solid and temperature, Journal of Radioanalytical and Nuclear Chemistry **159**(2) (1992) 201-218.

[9.3] BENES, P., RAMOS, P. L., POLIAK, R., Factors affecting interaction of radiocaesium with freshwater solids. I. pH and composition of water, and contact time, Journal of Radioanalytical and Nuclear Chemistry **133**(2) (1989) 359-376.

[9.4] BUNKER, D. J., SMITH, J. T., LIVENS, F. R., HILTON, J., Determination of radionuclide exchangeability in freshwater systems, Science of the Total Environment **263**(1-3) (2000) 171-183.

[9.5] CIFFROY, P., GARNIER, J.-M., BENYAHYA, L., Kinetic partitioning of Co, Mn, Cs, Fe, Ag, Zn and Cd in freshwaters (Loire) mixed with brackish waters (Loire estuary) : experimental and modelling approaches, Marine Pollution Bulletin **46**(5), (2003) 626-641

[9.6] COMANS, R.N.J., HILTON, J., VOITSEKHOVITCH, O., LAPTEV, G., POPOV, V., MADRUGA, M. J., BULGAKOV, A., SMITH, J. T., MOVCHAN, N., KONOPLEV, A., A comparative study of radiocaesium mobility measurements in soils and sediments from the catchment of a small upland oligotrophic lake (Devoke Water, U.K.), Water Research **32**(9) (1998) 2846-2855.

[9.7] EYROLLE, F., CHARMASSON, S., Importance of colloids in the transport within the dissolved phase (<450 nm) of artificial radionuclides from the Rhône river towards the Gulf of Lions (Mediterranean Sea), Journal of Environmental Radioactivity **72** (3) (2004) 273-286.

[9.8] HÅKANSON, L., MIKRENSKA, M., PETROV, K., FOSTER, I., Suspended particulate matter (SPM) in rivers: empirical data and models, Ecological Modelling **183**(2-3) (2005) 251-267.

[9.9] McKINLEY, J.P., JENNE, E.A., Experimental investigation and review of the “solids concentration” effects in adsorption Studies, Environmental Science and Technology **25**(12) (1991) 2082-2087.

[9.10] SMITH, J.T., COMANS, R.N.J., Modelling the diffusive transport and remobilisation of ^{137}Cs in sediments: the effects of sorption kinetics and reversibility, Geochimica and Cosmochimica Acta **60**(6) (1996) 995-1004.

[9.11] MOFFETT, J. W., A radiotracer study of cerium and manganese uptake onto suspended particles in Chesapeake Bay, Geochimica et Cosmochimica Acta **58**(2) (1994) 695-703.

[9.12] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments, TECDOC No. xxx, IAEA, Vienna (2009).

[9.13] ONISHI, Y., SERNE, R.J., ARNOLD, E.M., COWEN, C.E. THOMPSON, F.L., Critical review: radionuclide transport, sediment transport, and water quality mathematical modelling and radionuclide adsorption/desorption mechanisms, Rep. NUREG/CR-1322, PNL-2901, Pacific Nortwest Lab., Richmond, WA (1991).

[9.14] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of parameter values for the prediction of the radionuclide transfer in temperate environments. IAEA, Technical Report Series N° 364, (1994).

[9.15] VANDERPLOEG, H.A., et al., Bioaccumulation factors for radionuclides in freshwater biota, Environmental sciences division, Publication No. 793 (1975)

[9.16] YANKOVICH, T.L., CORNETT, R.J.J., Temporal changes in radionuclide transfer to biota in Canadian shield lakes receiving chronic inputs: reconstruction of radionuclide exposure to non-human biota in perch lake over a 40 year period, Proceedings of the ECORAD conference, Aix-En-Provence, France (2004).

[9.17] YANKOVICH, T.L., et al., Preliminary screening of aquatic macrophytes as biomonitors in environmental risk assessment of nuclear facilities: an ecosystem approach. Proceedings of the 2nd International symposium on ionizing radiation: environmental protection approaches for nuclear facilities (2001).

[9.18] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, National sediment quality survey, EPA-923-C-01-001 (2001).

[9.19] YANKOVICH, T.L., unpublished data.

[9.20] NATIONAL COUNCIL ON RADIOLOGICAL PROTECTION, Screening models for releases of radionuclides to atmosphere, surface water, and ground: Recommendations of the National Council on Radiological Protection and Measurements, (1996).

[9.21] STEMBERGER, R.S., CHEN, C.Y., Fish tissue metals and zooplankton assemblages of northeastern U.S. lakes, Canadian Journal of Fisheries and Aquatic Sciences **55(2)** (1999) 339.

[9.22] OPHEL, I.L., The fate of radiostrontium in a freshwater community, Radioecology, Reinhold Publishing Corporation, New York, (1976) 213-216.

[9.23] OPHEL, I.M., JUDD, J.M., Sr–Ca relationships in aquatic food chains, proceedings of the second national symposium on radioecology, US AEC tech. Inf. Cent., Oak Ridge National Lab., Oak Ridge, TN. CONF-670503 (1967) 221–225.

[9.24] BLAYLOCK, B.G., Radionuclide data base available for bioaccumulation factors for freshwater biota, Nuclear Safety **23** (1992) 427.

[9.25] ROWAN, D.J., RASMUSSEN, J.B., Bioaccumulation of radiocaesium by fish: the influence of physicochemical factors and trophic structure, Canadian Journal of Fisheries and Aquatic Sciences **51** (1994) 2399–2410.

[9.26] SMITH, J.T., et al., Radiocaesium concentration factors of Chernobyl-contaminated fish: a study of the influence of potassium, and "blind" testing of a previously developed model, Journal of Environmental Radioactivity **49** (2000) 359.

[9.27] YANKOVICH, T.L., BEATON, D., Concentration ratios of stable elements measured in organs of terrestrial, freshwater and marine non-human biota for input into internal dose assessment for PSL-2: a literature review, COG-99-106-I (2000).

[9.28] YANKOVICH, T.L., Conceptual development of reference plant, fish and amphibian with recommendations on the establishment of approaches to improve estimates of internal dose to non-human biota, COG-00-129 (2001).

[9.29] CANLI, M., KARGIN, F., A comparative study on heavy metals (Cd, Cr, Pb and Ni) accumulation in the tissue of the carp *Cyprinus Carpio* and the Nile fish *Tilapia Nilotica*, Turkish Journal of Zoology **19** (1995) 165.

[9.30] COMANS, R.N.J., HOCKLEY, D.E., Kinetics of caesium sorption on illite. Geochimica et Cosmochimica Acta **56** (1992) 1157-1164.

[9.31] SMITH, J.T., COMANS, R.N.J, BERESFORD, N.A., WRIGHT, S.M., HOWARD, B.J. CAMPLIN, W.C., Chernobyl's legacy in food and water, Nature **405** (2000) 141.

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

The data for parameter values described in the previous chapters 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. Specific activity (SA) for a given radionuclide is defined as the activity per unit mass of the corresponding stable element. SA 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 SA 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 SA 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 SA 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, 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 SA 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

$$C_{sw} = CR_s\, C_{air} / H_a \qquad (10.1)$$

where C_{air} (Bq m^{-3}) is the concentration in air (assumed known through measurement or modelling), CR_s is an empirical constant and H_a is the absolute humidity (L m^{-3}). Equation (10.1) 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 descended to the ground.

CR_s is difficult to estimate and depends on a number of local factors. The geometric mean (GM) of the available data [10.1-10.2] is 0.23 but a slightly larger value (0.3) is Reference 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 values of CR_s. Values based on local measurements should be used wherever possible.

The Reference value of CR_s is shown in Table 10.1, 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 (FW) plant material (C_{pfw}^{HTO}, Bq kg^{-1} FW) is calculated using a model [10.3] that explicitly considers contributions to the plant from air moisture (via diffusion through the stomates) and soil water (via the transpiration stream):

$$C_{pfw}^{HTO} = WC_p [RH \; \frac{C_{air}}{H_a} + (1 - RH)\; C_{sw}] / \gamma \,. \qquad (10.2)$$

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

TABLE 10.1. MODEL PARAMETERS FOR WHICH FIXED VALUES ARE SUGGESTED

Parameter	Symbol	Equation	Value	Units
Soil water/air moisture ratio for HTO	CR_s	10.1	0.3 [1]	unitless
Partition factor for plants	R_p	10.3	0.54	unitless
Water content of fish	WC_f	10.6	0.78	L kg^{-1} fresh weight
Partition factor for fish	R_f	10.7	0.66	unitless
Water equivalent factor for fish	WEQ_f	10.7	0.65	L kg^{-1} dry weight
Stable carbon content of air	S_{air}	10.8	0.20	gC m^{-3}
Fraction of feed that is contaminated	f_c	10.9	1.0*	unitless
Stable carbon content of fish	S_f	10.10	117	gC kg^{-1} fresh weight

[1] nominal value; a site-specific value should be used if available

The partitioning between air and soil in Equation (10.2) in terms of the relative humidity applies specifically to plant leaves, which draw the majority of their tritium from the air. The equation is conservative for fruit, 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 preferred. Water contents for a number of broad plant categories are listed in Table 10.2.

TABLE 10.2. WATER CONTENTS (WC_p, L kg^{-1} FW) FOR TERRESTRIAL PLANTS [10.4 -10.14]

Plant category	N	GM	GSD	Min	Max
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 - sweet corn	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

These are the same categories defined in Chapter 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 considered. The dry matter contents reported in Appendix 1 for individual species have been synthesized, converted to water contents and combined with data from other sources to produce the values in Table 10.2. 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 a common form of 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} FW) is given by:

$$C_{pfw}^{OBT} = (1 - WC_p)\ WEQ_p\ R_p\ C_{pfw}^{HTO} / WC_p, \qquad (10.3)$$

where R_p is a partition factor and WEQ_p is the water equivalent factor (kg of water produced per kg dry weight (DW) combusted). Values of R_p 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 [10.15-10.17] are all less than one, with a GM of 0.54 and a GSD of 1.16 for the crops considered (maize, barley and alfalfa). In the absence of other information, the value of 0.54 is assumed to apply to all plant types (Table 10.1). Regardless of the plant in question, the plant concentration used in Equation (10.3) 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 10.3, vary little among the various plant categories.

TABLE 10.3. WATER EQUIVALENT FACTORS (WEQ_p, L water kg^{-1} DW) FOR TERRESTRIAL PLANTS (calculated from data in [10.7, 10.10, 10.14])

Plant category	N	GM	GSD	min	max
Leafy vegetables	10	0.51	1.05	0.47	0.55
Non-leafy vegetables	12	0.53	1.03	0.50	0.55
Root crops	11	0.52	1.06	0.45	0.55
All others	91	0.56	1.04	0.50	0.60

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 the 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.

Here, concentrations in animal products are based on a metabolic model [10.18], 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 plus OBT) in the animal product are given by:

$$C_{afw}^{T\_HTO} = CR_a^{HTO}\ C_f^{HTO} \qquad (10.4)$$

$$C_{afw}^{T\_OBT} = CR_a^{OBT}\ C_f^{OBT} \qquad (10.5)$$

where $C_{afw}^{T\_HTO}$ is the total tritium concentration in the animal product from HTO intake (Bq kg^{-1} FW), CR_a^{HTO} is the concentration ratio for HTO intake ((Bq kg^{-1} FW) / (Bq L^{-1})), C_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} FW), CR_a^{OBT} is the concentration ratio for OBT intake ((Bq kg^{-1} FW) / (Bq kg^{-1} DW)), and C_f^{OBT} is the average OBT concentration in feed (Bq kg^{-1} DW).

C_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. C_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 shown in Tables 10.4 and 10.5.

TABLE 10.4. CONCENTRATION RATIOS FOR HTO INTAKE (CR_a^{HTO}) [10.18]

Product	Animal mass (kg)	Intake rate (kg DW d^{-1})	Production rate (kg d^{-1} or L d^{-1})	Fraction OBT (f_{OBT})	CR_a^{HTO}, (Bq kg^{-1} FW product per Bq L^{-1} intake)	CR_a^{HTO}, (Bq kg^{-1} FW product per Bq L^{-1} intake)	
						Min	Max
Cow milk	550	14	15	0.04	0.87	0.81	0.92
Sheep milk	50	1.8	1.3	0.06	0.78	0.76	0.89
Goat milk	50	2.5	2.5	0.04	0.83	0.81	0.93
Beef meat	500	9.3	0.7	0.09	0.66	0.64	0.82
Veal meat	160	4.85	0.8	0.08	0.69	0.64	0.82
Sheep meat	50	1.22	0.08	0.12	0.74	0.67	0.78
Lamb meat	20	1.0	0.2	0.12	0.78	0.60	0.81
Goat meat	50	1.2	0.08	0.10	0.67	0.64	0.81
Pork meat	100	2.7	0.8	0.15	0.67	0.61	0.77
Hen meat	2.5	0.12	0.01	0.10	0.76	0.70	0.80
Broiler meat	1.7	0.11	0.03	0.10	0.76	0.70	0.90
Egg	2.5	0.15	0.05	0.08	0.66	0.64	0.81

TABLE 10.5 CONCENTRATION RATIOS FOR OBT INTAKE (CR_a^{OBT}) [10.18]

Product	Animal mass (kg)	Intake rate (kg DW d^{-1})	Production rate (kg d^{-1} or L d^{-1})	Fraction OBT (f_{OBT})	CR_a^{OBT} (Bq kg^{-1} FW product per Bq kg^{-1} DW intake)	CR_a^{OBT} , (Bq kg^{-1} FW product per Bq kg^{-1} DW intake)	
						Min	Max
Cow milk	550	14	15	0.47	0.24	0.17	0.30
Sheep milk	50	1.8	1.3	0.57	0.32	0.23	0.39
Goat milk	50	2.5	2.5	0.40	0.32	0.25	0.38
Beef meat	500	9.3	0.7	0.80	0.40	0.35	0.53
Veal meat	160	4.85	0.8	0.72	0.35	0.31	0.45
Sheep meat	50	1.22	0.08	0.75	0.40	0.35	0.56
Lamb meat	20	1.0	0.2	0.78	0.55	0.41	0.67
Goat meat	50	1.2	0.08	0.60	0.43	0.36	0.45
Pork meat	100	2.7	0.8	0.74	0.64	0.45	0.75
Hen meat	2.5	0.12	0.01	0.55	0.50	0.42	0.60
Broiler meat	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	0.68

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 contents in their products.

The OBT concentration in the animal product can be split out by multiplying the total concentration by f_{OBT} from Tables 10.4 and 10.5, 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}).

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 SA equilibrium is a good approximation for HTO concentrations in most aquatic compartments [10.19, 10.20]. The water pools to which freshwater fish are exposed, including lake water and water derived from foods at different trophic levels, all similar HTO concentration. This implies that the *HTO* concentration in the fresh weight fish (C_{ffw}^{HTO} , Bq kg^{-1} FW) is given by:

$$C_{ffw}^{HTO} = WC_f \cdot C_w \qquad (10.6)$$

where C_w (Bq L^{-1}) is the HTO concentration in the water column (assumed known through measurement or modelling) and WC_f is the fractional water content of the fish (L kg^{-1} FW). The water content is roughly constant at 0.78 for most fish that form part of the human diet [10.7] (Table 10.1).

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 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:

$$C_{ffw}^{OBT} = (1 - WC_f) \cdot WEQ_f \cdot R_f \cdot C_w , \qquad (10.7)$$

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 has a GM of 0.66, which is the Reference value for all fish, and a GSD of 1.5 [10.19-10.24]. 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 [10.7] show a small GSD of 1.06, and the GM of 0.65 is Reference for generic assessments (Table 10.1).

10.2. CARBON-14

10.2.1. Release of ^{14}C to air

The assumption of full SA 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 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} FW) is given by

$$C_{pfw} = \frac{C_{air} \cdot S_p}{S_{air}} , \qquad (10.8)$$

where S_p is the concentration of stable carbon in the plant (gC kg^{-1} FW), C_{air} is the concentration of ^{14}C in air (Bq m^{-3}) (assumed known through measurement or modelling), and S_{air} is the concentration of stable carbon in air (gC 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 presently about 0.20 g/m^3 (Table 10.1). Measured values of the carbon contents for the various plant categories are shown in Table 10.6. 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 [10.7].

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

$$C_{afw} = \frac{f_c \cdot C_{pfw} \cdot S_a}{S_p} \qquad (10.9)$$

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 (gC kg^{-1} FW).

TABLE 10.6. CONCENTRATION OF STABLE CARBON IN TERRESTRIAL PLANTS (S_p) (from [10.7, 10.10, 10.14, 10.25-10.27])

Plant category	Stable carbon content, (g C kg^{-1} FW)				
	N	GM	GSD	Min	Max
Leafy and non-leafy vegetables	49	3.0 x 10^1	1.40	1.8 x 10^1	6.5 x 10^1
Leguminous vegetables - seed	7	4.1 x 10^2	1.08	3.8 x 10^2	4.7 x 10^2
-vegetative mass	5	5.9 x10^1	1.46	4.1 x 10^1	1.1 x 10^2
Root crops	23	4.6 x10^1	1.46	2.2 x 10^1	9.5 x 10^1
Tubers	6	10.3 x 10^2	1.20	8.6 x 10^1	1.3 x 10^2
Fruit	48	6.2 x10^1	1.27	3.1 x 10^1	1.0 x 10^2
Grass, Fodder, Pasture	25	1.0 x 10^2	1.31	4.0 x 10^1	1.6 x 10^2
Cereals (including rice)	29	3.9 x 10^2	1.05	3.6 x 10^2	4.3 x 10^2
Maize - sweet corn	3	1.2 x 10^2	1.00	1.2 x 10^2	1.2 x 10^2
- feed corn	1	3.8 x 10^2	-	-	-
Silage	13	1.3 x 10^2	1.42	6.5 x 10^1	1.8 x 10^2

The factor f_c is introduced to allow for the fact that animals may be fed supplementary concentrates or feed from remote sources that is uncontaminated. The value of f_c should be set from a consideration of local farming practices; if a site-specific value is not available, f_c should be conservatively set to 1 (Table 10.1).

Carbon contents of various animal products are shown in Table 10.7. A few of these values were directly measured [10.25, 10.27] but most were calculated from the carbon contents of protein, fat and carbohydrate and the fractions of protein, fat and carbohydrate in the product [10.7].

TABLE 10.7. CONCENTRATION OF STABLE CARBON IN TERRESTRIAL ANIMAL PRODUCTS (S_a)

Animal product	Stable carbon content (g C kg^{-1} FW)				
	N	GM	GSD	Min	Max
Cow milk	8	6.5 x 10^1	1.03	6.2 x 10^1	6.9 x 10^1
Sheep milk	1	1.1 x 10^2	-	-	
Goat milk	1	7.1 x 10^1	-	-	
Beef meat	14	2.0 x 10^2	1.19	1.6 x 10^2	2.9 x 10^2
Veal meat	3	1.6 x 10^2	1.21	1.3 x 10^2	1.9 x 10^2
Sheep meat	1	2.9 x 10^2	-	-	
Lamb meat	2	2.8 x 10^2	1.26	2.3 x 10^2	3.2 x 10^2
Goat meat	1	1.7 x 10^2	-	-	
Pork meat	12	3.0 x 10^2	1.39	1.7 x 10^2	5.5 x 10^2
Hen meat	1	2.4 x 10^2	-	-	
Broiler meat	5	1.5 x 10^2	1.23	1.1 x 10^2	2.0 x 10^2
Egg	2	1.6 x 10^2	1.01	1. 6 x 10^2	1.6 x 10^2

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 SA equilibrium with dissolved inorganic carbon (DIC):

$$C_{ffw} = C_{DIC} \cdot S_f \qquad (10.10)$$

where C_{ffw} is the ^{14}C concentration in fresh weight fish (Bq kg^{-1} FW), C_{DIC} is the ^{14}C concentration in DIC in the water column (Bq/gC) (assumed known through measurement or modelling), and S_f (gC kg^{-1} FW) 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 [10.7]. The calculated values have a relatively low GSD of 1.18, and the GM of 117 gC kg^{-1} FW is Reference for use with all species (Table 10.1).

10.3. CHLORINE-36

As in the case of ^3H and ^{14}C, SA modelling for ^{36}Cl takes advantage of stable element contents in the environment and isotopic equilibrium between compartments to generate reliable estimates for ^{36}Cl concentrations. SA is especially important for ^{36}Cl due 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 cow meat and milk have shown that the isotopic ratio in animal products is the same as that in their foodstuffs [10.28]. The average equilibrium chlorine isotopic ratio in the dietary daily 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

$$\frac{C_{animal}}{S_{animal}} = \frac{q_{water} \cdot C_{water} + q_{foodstuff} \cdot C_{foodstuff}}{q_{water} \cdot S_{water} + q_{foodstuff} \cdot S_{foodstuff}} \qquad (10.11)$$

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

Table 10.8 lists stable chlorine concentrations for various environmental compartments for use in SA modelling. These correspond to the means of literature data. They should be used with caution and only when site-specific data are not available.

10.4. APPLICATION OF DATA

The specific activity concepts upon which the tritium, ^{14}C and ^{36}Cl models are based are theoretically sound for long-term safety assessments with constant release rates. However, the models do not apply to short-term 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.

TABLE 10.8. STABLE INORGANIC CHLORINE CONTENTS IN ENVIRONMENTAL MEDIA [10.29-10.33] as summarized in [10.34]

Environmental media	Content	Unit	Environmental media	Content	Unit
Air[1]			Root vegetable	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[1]	0.010	g/L	Potatoes	1.00	g/kg
Groundwater[2]	0.016	g/L	Red beet	0.60	g/kg
River[3]	0.007	g/L	Carrot	0.50	g/kg
Rain[4]	0.011	g/L	Celery	0.50	g/kg
Soil	0.2	g/kg (DW)	Turnip	0.55	g/kg
Terrestrial plants			Onion	0.25	g/kg
Cereals (grains)	0.50	g/kg (FW)	Radish	0.30	g/kg
Oat	0.50	g/kg	Horse radish	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 seeds)	0.19	g/kg	Leafy vegetable	0.50	g/kg
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
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	Woman	0.40	g/L
Pickle	0.27	g/kg	Cow	1.00	g/L
Courgette	0.18	g/kg	Ewe	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	Mare	0.30	g/L

TABLE 10.8. STABLE INORGANIC CHLORINE CONTENTS IN ENVIRONMENTAL MEDIA [10.29-10.33] as summarized in [10.34] (Cont.)

Environmental media	Content	Unit	Environmental media	Content	Unit
Guava	0.45	g/kg	Egg	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	Sheep	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 fishes	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	Fresh water invertebrates	1.00	g/kg

[1]Dependent on distance from the sea; [2] variation: 0.001-0.070; [3] variation: 0.001-0.035; [4] variation: 0.001-0.020

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.

REFERENCES

[10.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Modelling the environmental transport of tritium in the vicinity of long-term atmospheric and sub-surface sources, IAEA-BIOMASS-3, IAEA, Vienna (2003).

[10.2] DAVIS, P.A., KOTZER, T.G., WORKMAN, W.J.G., Environmental tritium concentrations due to continuous atmospheric sources, Fusion Science and Technology 41 (2002) 453-457.

[10.3] MURPHY, C.E. Jr., The relationship between tritiated water activities in air, vegetation and soil under steady-state conditions, Health Physics **47** (1984) 635-639.

[10.4] BROWN, R.M., OGRAM, G.L., SPENCER, F.S., Field studies of HT oxidation and dispersion in the environment, II The 1987 June experiment at Chalk River, Canadian Fusion Fuels Technology Project Report CFFTP-G-88007 (1989).

[10.5] BROWN, R.M., The measurement of tritium in Canadian food items, Prepared for the AECB under Contract 87055-9-4070.01-SS (1994).

[10.6] FRISSEL, M.J., HEISTERKAMP, S., Geometric mean transfer factor values calculated with multilinear regression analyses. Sixth Report of the IUR Working Group on soil-to-plant transfer factors. RIVM, Bilthoven (1989).

[10.7] GEIGY, Geigy scientific tables, Vol. 1, 8th edition, Units of measurement, body fluids, composition of the body, nutrition. Ciba-Geigy Ltd., Basel, Switzerland (1981).

[10.8] KÖNIG, L.A., FARK, S., HEMPELMANN, S., LANGGUTH, K.G., PAPADOPOULOS, D., STRACK, S., Untersuchungen zum Transport von Tritium in der Umwelt, Kernforschungszentrum Karlsruhe Report KfK 4131 (1987).

[10.9] NG, Y.C., COLSHER, C.S., THOMPSON, S.E., Soil-to-plant concentration factors for radiological assessments, Report NUREG/CR-2975 UCID-19463, Lawrence Livermore National Laboratory (1982).

[10.10] NATIONAL RESEARCH COUNCIL, Nutrient requirements of dairy cattle, Committee on Animal Nutrition, Board on Agriculture and Natural Resources, 7th revised edition, National Academy Press, Washington, D.C. (2001).

[10.11] PAUNESCU, N., COTARLEA, M., GALERIU, D., MARGINEANU, R., MOCANU, N., Evaluation of environmental tritium level in preoperational period of Cernavoda CANDU nuclear power plant, Journal of Radioanalytical and Nuclear Chemistry **239** (1999) 465-470.

[10.12] SCHEIER, N.W., KIM, S.B., Evaluation of a model of OBT formation at night in edible parts of non-leafy vegetables. AECL Report 153-121241-440-011 (2006).

[10.13] SIMPSON, OGORZALY, Cited in http://www.thefruitpages.com/ contents.shtml. Information collected from USDA Nutrient Database for standard reference, (1995).

[10.14] Animal Nutrition and Feeding, (STOICA. I. Ed) Coral-Sanivet, Bucharest (1997) (In Romanian).

[10.15] McFARLANE, J.C., Tritium fractionation in plants, Environmental and Experimental Botany **16** (1976) 9-14.

[10.16] GARLAND, J.A., AMEEN, M., Incorporation of tritium in grain plants, Health Physics **36** (1979) 35-38.

[10.17] KIM, M-A, BAUMGÄRTNER, F., Equilibrium and non-equilibrium partition of tritium between organics and tissue water of different biological systems, Applied Radiation and Isotopes **45** (1994) 353-360.

[10.18] GALERIU, D. et al., Modelling ^{3}H and ^{14}C transfer to farm animals and their products under steady state conditions, Journal of Environmental Radioactivity, doi:10.1016/j.jenvrad.2006.11.010 (in press) (2007).

[10.19] KIM, S.B., WORKMAN, W.J.G., DAVIS, P.A., YANKOVICH, T., Tritium concentrations in the Perch Lake ecosystem, AECL document CTD-03700-ENA-003, Chalk River Laboratories, Chalk River, Ontario (2004).

[10.20] EATON, D., MURPHY C.E. Jr., Tritium uptake by fish in a small stream, Westinghouse Savannah River Company Report WRSC-TR-92-193-Rev 1, Aiken SC. (1992).

[10.21] ELWOOD, J.W., Tritium behaviour in fish from a chronically contaminated lake, Proc. of the 3rd National Symposium on Radioecology, Oak Ridge, May 10-12 (1971) 435-439.

[10.22] BLAYLOCK, B.G., FRANK, M.L., "Distribution of tritium in a chronically contaminated lake", Behaviour of Tritium in the Environment, Proc. of a Symposium, San Francisco, 16-20 October 1978. IAEA-SM-232/74, IAEA, Vienna (1979) 711.

[10.23] PATZER, R.G., MOGHISSI A.A., McNELIS, D.N., "Accumulation of tritium in various species of fish reared in tritiated water" Proc. of a Symposium on Environmental Behaviour of Radionuclides Released in the Nuclear Industry, Aix-en-Provence. IAEA, Vienna (1973) 403.

[10.24] STRAND, J.A., TEMPLETON W.L., OLSON, P.A., "Fixation and long-term accumulation of tritium from tritiated water in an experimental aquatic environment", Radiation effects and tritium technology for fusion reactors, Proc. of an international conference held at Gatlinburg, TN, October 1-3, 1975. (WATSON, J.S., WIFFEN, F.W. Eds.) (1976) III-77-95.

[10.25] GARNIER-LAPLACE, J., ROUSSEL-DEBET, S., CALMON P., Modélisation des transferts du carbone 14, émis par les réacteurs à eau pressurisée en fonctionnement normal dans l'environnement proche du site, Rapport IPSN/DPRE/SERE 98/007 (1998).

[10.26] UCHIDA, S., TAGAMI, K., HIRAI, I., Soil-to-plant transfer factors for stable elements and naturally-occurring radionuclides. I. Upland field crops collected in Japan, Journal of Nuclear Science and Technology **44** (2007) 628-640.

[10.27] HOLTUM, J.A.M. LATZKO, E., Carbon and Carbon Metabolism in the Environment, Institüt für Strahlen-Hygiene, Bundesgesundheitsamt. Neuherberg, Germany, ISH-Heft-92 (1986).

[10.28] KASHPAROV, V., C. COLLE, et al., Transfer of chlorine from the environment to agricultural foodstuffs, Journal of Environmental Radioactivity **94** (2007) 1-15.

[10.29] COUGHTREY, P. J., JACKSON, D., et al., Radionuclide distribution and Transport in Terrestrial and Aquatic Ecosystems, (A.A. BALKEMA Ed.) Rotterdam (1983).

[10.30] RANDOUIN, L., P. LE GALLIC, et al., Tables de composition des aliments. Malakoff (France) (1988).

[10.31] GRAEDEL, T.E. KEENE, W.C., The tropospheric budget of reactive chlorine, Global Biogeochemistry Cycles **9** (1995) 47-78.

[10.32] GRAEDEL, T. E. AND W. C. KEENE The budget and cycle of Earth' natural chlorine, Pure and Applied Chemistry **68**(9) (1996) 1689-1696.

[10.33] OBERG, G., The biogeochemistry of Chlorine in soil, The handbook of Environmental Chemistry. **3** (2003) 43-62.

[10.34] TAMPONNET, C., Modélisation des transferts environnementaux du chlore 36, Rapport IRSN/DEI/SECRE n°2006-19 (2006).

11. FOOD PROCESSING

11.1. DEFINITIONS AND PROCESSES

The concentration of radionuclides in food can be affected by food processing actions such as radionuclide extraction during boiling, removal of certain parts of the raw food (eg. bran, peel, shell, bone) and drying or dilution [11.1, 11.2]. Neglecting of 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. It 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 can often be considered as the most effective countermeasure for reducing the radioactive contamination of the foodstuff to permissible levels or below and can be applied both domestically and in industrial processing of food [11.2 - 11.7].

In reporting the quantitative results of food processing, the following food processing transfer parameters are applied: food processing retention factor (F_r) is the fraction of activity of radionuclides that is retained in the food after processing; processing efficiency (P_e) which is the ratio of the fresh weight of processed food divided to weight of original raw material;

processing factors[4] (P_f) for a foodstuff which is the ratio of the radionuclide activity concentrations (analogous to *CR* - concentration ratio).

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

$$F_r = P_f \cdot P_e \qquad (11.1)$$

Application of these various factors is illustrated 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 (Table 11.6). In the case of dairy products (Table 11.7), 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 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 milk. Therefore, the processing factor (P_f) is 5 [11.1].

F_r values for animal food products are all based on contamination *in vivo*. All data on plants refer to the 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 (for example, 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 whether 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 when 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.

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 over the consequences of radionuclide transfer from nuclear weapons testing into the human food chain. Following the accident at the Chernobyl NPP, new measurements have become available. Noordijk and Quinault [11.4] reviewed the existing literature with in the framework of the CEC and VAMP programmes. These results were mainly reported in TRS 364 [11.1]. This updated account includes the more recent results and information from various reviews [11.5-11.7], 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) [11.8] and from the database created within the framework of the Franco-German Initiative FGI [11.2, 11.3]. The main results obtained, focusing on the most effective methods, are shown in Tables 11.1-11.12.

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[1] In the ICRU report 65 this value is called the Food processing retention factor.

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 [11.5]. 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 Chernobyl accident into long-stored foodstuffs (such as butter, cheese and dried milk) ensured significant decreases of ^{131}I concentrations in these foodstuffs due to the radioactive decay before their delayed consumption. For that reason, storage and processing times for the main foodstuffs are also reported here (see Table 11.13). 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 [11.9].

TABLE 11.1. FOOD PROCESSING RETENTION FACTOR F_r AND THE PROCESSING EFFICIENCY P_e FOR VEGETABLES AND FRUIT (DATA ARE BASED ON TOTAL CONTAMINATION OF THE PLANT)

Method of processing	Food processing retention factor (F_r)		P_e
	Element	Value	
Washing of vegetables, berry and	Cs	0.6-1.0	1.0
Fruits	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
Producing of sugar from beetroot	Cs	0.001-0.01	0.12
Producing of starch from potato	Cs	0.02-0.03	0.18
Olive press: - oil	Cs	0.13	0.2
- cake	Cs	0.43	0.5
Processing rapeseed to oil	Cs	P_f=0.004[(1)]	
	Sr	P_f=0.002[(1)]	

[1] Value is given for food processing

TABLE 11.2. FOOD PROCESSING RETENTION FACTOR F_r AND THE PROCESSING EFFICIENCY P_e FOR VEGETABLES AND FRUIT (DATA ARE BASED ON EXTERNAL CONTAMINATION ONLY)

Method of processing	Food processing retention factor, 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 11.3. FOOD PROCESSING RETENTION FACTOR F_r AND THE PROCESSING EFFICIENCY P_e FOR CEREALS

Raw material	Method of processing	Food processing retention factor		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[(1)]	

[1] Value given for processing food (P_f)

TABLE 11.4. FOOD PROCESSING RETENTION FACTOR F_r AND THE PROCESSING EFFICIENCY P_e FOR DRINKS

Raw material	Method of processing	Food processing retention factor, F_r		P_e
		Element	Value	
Surface waste	Conventional	Co	0.4	1.0
water	Treatment	Cs	0.7	1.0
	To tap water	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	
Herb tea	Brewing	Cs	0.4-0.6	
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 11.5. FOOD PROCESSING FACTORS F_r FOR TRITIUM

Raw material	Method of processing	Food processing retention factor		Processing efficiency P_e
		HTO	OBT	
Blackberries	Washed and stewed	0.55	0.56	0.59
Broad beans	Boiled	0.28[1]	0.69[2]	0.91
Cabbage	Washed and steamed	0.28[1]	-	0.98
Carrots	Washed and boiled	0.28[1]	0.43[2]	0.85
New potatoes	Scrubbed and boiled	0.55[2]	-	0.92
	Peeled and roasted	0.22[2]	-	0.62
Old potatoes	Peeled and boiled	0.55	0.74	0.92
	Peeled and roasted	0.21	-	0.65
Hulled rice	Boiled	0.84	-	-
Soybean	Boiled	0.77	-	-
Rice flour	Boiled	0.69	-	-
Soybean flour	Boiled	0.74	-	-

[1]some data are below the detection limit; [2]not significant at the 5% level

TABLE 11.6. FOOD PROCESSING FACTORS FOR ^{14}C

Raw material	Method of processing	Food processing retention factor F_r	Processing efficiency, P_e
New potatoes	Scrubbed and boiled	0.69	0.92
Hulled wheat	Boiled	0.82	-
Hulled rice	Boiled	0.98	-
Soybean	Boiled	0.86	-
Wheat flour	Boiled	0.92	-

TABLE 11.7. FOOD PROCESSING RETENTION FACTOR F_r AND THE PROCESSING EFFICIENCY P_e FOR DAIRY PRODUCTS (**bold** denote Reference values)

Product	Food processing retention factor F_r			P_e	
	Element	Reference value	Range		
	Ca,Cl, K, Na, Mg		0.03	**0.08**	0.03-0.24
Cream	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
Skim 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

TABLE 11.7. FOOD PROCESSING RETENTION FACTOR F_r AND THE PROCESSING EFFICIENCY P_e FOR DAIRY PRODUCTS (**bold** denote Reference values) (Cont.)

Product	Food processing retention factor F_r			P_e	
	Element	Reference value	Range		
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[1]					
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
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[1]					
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
acid	Cs		0.75-0.90		0.82
	I		0.60-0.73		0.82
	Sr		0.70-0.90		0.82
Casein[1]					
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
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

TABLE 11.7. FOOD PROCESSING RETENTION FACTOR F_r AND THE PROCESSING EFFICIENCY P_e FOR DAIRY PRODUCTS (**bold** denote Reference values) (Cont.)

Product	Food processing retention factor F_r			P_e	
	Element	Reference value	Range		
Casein whey[1]					
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
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[2]					
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

[1]Separate values are given for the rennet and acid coagulation procedures; [2]Decontamination of milk by ion exchange on a commercial scale.

TABLE 11.8. FOOD PROCESSING RETENTION FACTOR F_r AND THE PROCESSING EFFICIENCY P_e FOR MEAT (**bold** data denote Reference values)

Raw material	Method of processing	Food processing retention factor F_r			P_e
		Element	F_r (reference)	F_r	
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	

TABLE 11.8. FOOD PROCESSING RETENTION FACTOR F_r AND THE PROCESSING EFFICIENCY P_e FOR MEAT (**bold** data denote Reference values)

Raw material	Method of processing	Food processing retention factor F_r			P_e
		Element	F_r (reference)	F_r	
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 [(1)]	

[1] Value given for food processing

TABLE 11.9. FOOD PROCESSING RETENTION FACTOR F_r FOR ^{137}Cs, ^{90}Sr AND THE 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 of berries	^{137}Cs	1	0.1
	Soaking in water of dried berries	^{137}Cs	0.8	0.1
Mushrooms	Washing	^{137}Cs	0.4	1
	Drying of mushrooms	^{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	

TABLE 11.10. FOOD PROCESSING RETENTION FACTOR F_r AND THE PROCESSING EFFICIENCY P_e FOR ^{137}Cs in SOME EDIBLE MUSHROOM SPECIES

Mushroom species	Type of culinary processing	F_r	P_e
Boletus edulis (*dry weight*)	*Consecutive processing*		
	Washing by flowing water for 10 min.	0.90-0.95	1.1
	Soaking in 0.85 % salt solution for10 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 by flowing water for10 min.	0.50-0.55	1.3
	Boiling for 20 min. and washing by 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 by flowing water for10 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 72 h	0.003-0.005	1.0

TABLE 11.11. Cs-137 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	Food processing retention factor F_r							
		^{137}Cs				^{90}Sr			
		AM	SD	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, 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

TABLE 11.12 FOOD PROCESSING RETENTION FACTOR F_r AND THE PROCESSING EFFICIENCY *Pe* FOR LOWER SEA ORGANISMS

Raw mat.	Method of processing	Element	F_r values	*Pe*
Shrimp	Wash with tap water	Ca	0.9	1.0
		^{90}Sr	0.7	1.0
	Wash 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	Wash 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	Wash with tap water	Ca	0.8	1.0
		^{90}Sr	0.7	1.0
	Wash 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 11.13. DELAY TIMES (STORAGE AND PROCESSING TIMES) BETWEEN HARVESTING AND CONSUMPTION OF FOOD PRODUCTS

Raw material	Typical value	Min	Max
Cereals and cereal products	6 months	45 days	1 year
Potatoes and beet	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
Pasteurized skim milk	2 days	1 day	6 days

TABLE 11.13. DELAY TIMES (STORAGE AND PROCESSING TIMES) BETWEEN HARVESTING AND CONSUMPTION OF FOOD PRODUCTS (Cont.)

Raw material	Typical value	Min	Max
Cheese (rennet coagulation)	1.5 months	30 days	3 months
Cheese (acid coagulation)	1 month	7 days	2 months
Fresh* beef	20 days	14 days	28 days
Fresh* pork, veal	4 days	2 days	7 days
Fresh* chicken	4 days	2 days	7 days
Fresh* lamb	10days	7 days	14 days
Fresh* game	10 days	2 days	20 days
Eggs	14 days	2 days	28 days

* refers to fresh meat, frozen meats would have longer delay times of up to 6 months

11.3. APPLICATION OF DATA

Food processing retention factor (F_r) is mainly applied for assessment of the total losses of radionuclides during processing (removal of a radionuclide from the food chain and/or estimation of discharges to waste streams) and calculations of collective dose [11.1]. Also 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, rapeseed and wine from grapes, the parameter P_f is more appropriate [11.5].

Milk products may require careful consideration, due 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 for collective dose assessment an F_r value of 1.0 for all milk. However, such 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 the chapter 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, it is reference that, in the absence of specific information, the food-processing factor for ^{14}C and T radionuclides should be 1 (i.e., concentrations in food products should not be reduced when the food is processed).

REFERENCES

[11.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of parameter values for the prediction of the radionuclide transfer in temperate environments. IAEA, Technical Report Series N° 364, (1994) 74.

[11.2] BOGDEVITCH, I., SANZHAROVA, N., PRISTER, B., TARASIUK, S., “Countermeasures on natural and agricultural areas after Chernobyl accident”, Role of GIS in Lifting the Cloud off Chernobyl, (J. KOLEJKA Ed.), Kluwer Academic Publishers (2002) 147-158.

[11.3] DEVILLE-CAVELIN, G., ALEXAKHIN, R.M., BOGDEVITCH, I.M., PRISTER, B.S., BIESOLD, H., PEREPELYATNIKOVA, L.V., SANZHAROVA, N.I., TARASIUK, S.V., "Countermeasures in agriculture: assessment of efficiency", Proc. of the International Conference "Fifteen Years after the Chernobyl Accident. Lessons Learned", Kiev (2001) 118-128.

[11.4] NOORDIJK, H., QUINAULT, J.M., The influence of food processing and culinary preparation on the radionuclide content of foodstuffs: A review of available data, Modelling of Resuspension, Seasonality and Losses during Food Processing, First report of the VAMP Terrestrial Working Group, IAEA-TECDOC-647, Vienna (1992) 35-59.

[11.5] GREEN, N., The effect of storage and processing on radionuclide content of fruit, Journal of Environmental Radioactivity **52** (2001) 281-290.

[11.6] GREEN, N., WILKINS, B.T., Effects of processing on radionuclide content of foods: derivation of parameter values for use in radiological assessments. NRPB-M587, National Radiological Protection Board, Chilton (1995).

[11.7] LONG, S., POLLARD, D., CUNNINGHAM, J.L., ASTASHEVA, N.P., DONSKAYA, G.A., LABETSKY, E.V., The effects of food processing and direct decontamination techniques on the radionuclide content of foodstuffs: A literature review. Part 2: Meat, fruit, cereals and drinks, Journal of Radioecology **3**(2) (1995) 15-38.

[11.8] FOOD STANDARDS AGENCY, McCance Widdowson's The Composition of Foods, Sixth summary edition. Cambridge: Royal Society of Chemistry, ISBN 0-85404-428-0, (2002), 537,

[11.9] WATTERSON J., NICHOLSON K. W. Change in radionuclide content of crops as a result of food preparation Journal of Radiological Protection **16**(3) (1996) 191–200.

[11.10] RANTAVAARA, A.H., Transfer of radionuclides during processing and preparation of foods; Finnish studies since 1986, Radioactivity Transfer during Food Processing and Culinary Preparation (Proc. Seminar Cadarache), CEC, Luxembourg (1989) 69-94.

[11.11] HISAMATSU, S., TAKIZAWA, Y., ABE, T., Reduction of ^{131}I content in leafy vegetables and seaweed by cooking, Journal of Radiation Research. **28** (1987) 135-140.

[11.12] WILKINS, B.T., BRADLEY, E.J., DODD, N.J., The effects of culinary preparation on radionuclide levels in vegetable foodstuffs, Radiation Protection Dosimetry. **20** (1987) 187-190.

[11.13] ANNENKOV, B., Radiobiology and radioecology of farm animals, Radiobiol. Radioekol. Sel'skokhoz. Zhivotn. (1973) (in Russian).

12. USE OF ANALOGUES

In cases where there is no data or relatively few data for environmental transfers of a radionuclide, 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 may be used in screening models if little or no other data are available. Relevant knowledge such as time scales of processes, physical, chemical and biological properties of the environment and relevant media is required to derive parameter values from stable isotopes [12.1].

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

– *Analogue Isotopes*. Use of a parameter value for a related or similar isotope[5];
– *Analogue elements*. Use of a parameter value for a related or similar element and
– *Analogue species* Use of a parameter value for a related or similar species

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 on the well-studied ^{134}Cs or ^{137}Cs for the 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 12.1].

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 macro-elements for plants occurring in soil, the uptake and transfer of a chemically similar element will be influenced by any lack or excess of the essential one. 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 [12.1].

The most commonly used analogue element pairs are K and Cs, Ca and Sr, Ba and Ra. Ba, Ca and K are regarded as elements indicating the influence of metabolic processes. Transition elements in the same period (row) of the periodic table also tend to be chemically similar to each another [12.1]. Lanthanides are oxidation state analogues for actinides, so their distribution can give an indication of the long-term behaviour of the radioactive transuranic elements, though 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.

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[5] This approach was in a wide use in the current document.

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 between 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 Chapter 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, though 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, e.g. between chicken meat 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) arises only when the animal is 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 larger than concentrations in meat.

12.4. OTHER ANALOGUE APPROACHES

Soil K_d values can vary significantly with soil type (see Chapter 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 maximise 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 to consider the characteristics of each individual case, a general order of preferences for data sources is as follows:

- Data for the specific parameter for the specific radionuclide.
- Data for the specific parameter of interest 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).
- Data for the specific parameter for an analogue element.

- 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.
- 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-recognised element analogue and a cross-species animal product analogue; on the other hand, the order would be reversed if choosing 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 could only be proven to be valid by comparing its behaviour in the conditions of interest with that of the thing 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, amongst the lanthanides it could be samarium and europium. However, in practice, by far the most extensive data amongst 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 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 stations, 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 of ^{131}I are limited by radioactive decay to a period of a few months at most, and so could be of little value for identifying and characterising long-term behaviour, because the time scale 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 observations of the long-lived species have been made on short enough time scales. 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 recognised that although isotopes of an element have the 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, due 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 ^{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 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 can be reflected in trends in environmental behaviour. A problem of element analogue 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 then it will behave in the same way as the radionuclide of interest would.

REFERENCES

INTERNATIONAL ATOMIC ENERGY AGENCY, QUANTIFICATION OF RADIONUCLIDE TRANSFER IN TERRESTRIAL AND FRESHWATER ENVIRONMENTS FOR RADIOLOGICAL ASSESSMENTS, TECDOC No. XXX, IAEA, Vienna (2009)

APPENDIX I. REFERENCE INFORMATION ON TERRESTRIAL PLANTS AND ANIMALS

TABLE A1.1. DRY MATTER CONTENTS IN PLANTS, % [A1.1, A1.2]

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	
Broadbeans	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 ryegrass		20	
Millet		23	88
Alfalfa		26	
Sickle alfalfa		33	
Bastard Lucerne,		23	
Red clover		22	
Ladino clover		26	
Sainfoin		23	
White sweetclover,		22	
Yellow sweetclover,		22	
Fussian brome grass,		21	

TABLE A1.1. DRY MATTER CONTENTS IN PLANTS, % [A1.1, A1.2] (Cont.)

Crop	Seeds	Vegetative mass	Grain
Slender wheat grass		34	
Couch grass		37	
Standard crested grass		39	
Timothy grass		26	
Meadow fescue		20	
Cock’s foot grass		22	
Meadow grass		22	
Cabbage		12	
Lettuce		8.0	
Leek		11	
Onion (aboveground 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	
Zuchini		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	
Water-melon		7.0	

TABLE A1.2. DRY MATTER CONTENTS IN FEEDS, % [A1.3]

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 A1.3. DRY MATTER CONTENT OF WILD BERRIES [A1.4, A1.6], %

English name	Latin name	N	AM	SD	Min	Max
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 A1.4. CARCASS WEIGHT AND MEAT FRACTION FOR GAME ANIMALS, kg [A1.4-A1.6]

Species of animal	Carcass weight, kg	Fraction of meat in carcass weight
Moose, adult	1.9 x10^{2}	0.80
Moose, calf	8.3 x10^{1}	0.78
White-tailed deer	5.0 x10^{1}	0.78
Fallow deer	3.3 x10^{1}	0.78
Roe deer	1.8 x10^{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 x10^{-1}	0.90
Hazel grouse	2.4 x10^{-1}	0.90
Willow grouse	3.6 x10^{-1}	0.90
Partridge	2.4 x10^{-1}	0.90
Pheasant	6.9 x10^{-1}	0.90
Goose	2.3	0.90
Eider	1.3	0.90

TABLE A1.4. CARCASS WEIGHT AND MEAT FRACTION FOR GAME ANIMALS, kg (Cont.)

Species of animal	Carcass weight, kg	Fraction of meat in carcass weight
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 gains more weight in Northern than in Central Europe.

TABLE A.1.4. WATER CONTENTS IN FRESHWATER AND RIPARIAN DIETARY ITEMS AND TISSUES CONSUMED BY HUMANS, % [A1.9-A1.10]

Food Type	AM	SD	Min	Max
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

TABLE A.1.4. WATER CONTENTS IN FRESHWATER DIETARY ITEMS AND TISSUES CONSUMED BY HUMANS, % [A1.9-A1.10]

Food Type	AM	SD	Min	Max
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 A1.5. CARBON AND PERCENT HYDROGEN CONTENTS IN FRESHWATER AND RIPARIAN DIETARY ITEMS AND TISSUES CONSUMED BY HUMANS (ON A PER UNIT DRY WEIGHT BASIS) [A1.11-A1.14].

Type of Organism	Tissue Type	% C (per unit DW)					% H (per unit DW)				
		N	AM	SD	Min	Max	N	AM	SD	Min	Max
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	na	na	na	na	na
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	na	na	na	1	6.0	na	na	na

na – not available

REFERENCES

[A1.1] HANDBOOK OF PARAMETER VALUES FOR THE PREDICTION OF RADIONUCLIDE TRANSFER IN TEMPERATE ENVIRONMENTS. Technical Report Series, No. 364, International Atomic Energy Agency, Vienna, 1994

[A1.2] Fodder crops. Handbook. Moscow, 1999

[A1.3] www.agriknowledge.co.uk

[A1.4] RANTAVAARA, A., unpublished data.

[A1.5] SAMPLE, B., et al., Methods and tools for estimation of the exposure of terrestrial wildlife to contaminants, Oak Ridge National Laboratory. ORNL/TM-13391 (1997).

[A1.6] RANTAVAARA, A., NYGRÉN, T., NYGRÉN, K., HYVÖNEN, T., Radioactivity of game meat in Finland after the Chernobyl accident in 1986, Report STUK-A62. Radiation and Nuclear Safety Authority (Previous name: Finnish Centre for Radiation and Nuclear Safety), Helsinki (1987).

[A1.7] HUNTERS ASSOCIATION, FINLAND, www. riista.fi (2006).

[A1.8] JOKELAINEN, A., PEKKARINEN, M., ROINE, P., MIETTINEN, J. K., The diet of Finnish Lapps, Zeitschrift für Ernährungswissenschaft **3** (1962)110-117.

[A1.9] YANKOVICH, T.L., unpublished data.

[A1.10] JORGENSEN, S.E., et al., Handbook of Environmental Data and Ecological Parameters, Pergamon Press, New York (1979).

[A1.11] ADAMS, L.W., et al., "Tritium behaviour in aquatic plants and animals in a freshwater marsh ecosystem", Behaviour of Tritium in the Environment, IAEA-SM-232/74 (1979) 231-245.

[A1.12] KOTZER, T., KRAMER-TREMBLAY, S., Behaviour of radiocarbon in the freshwater environment around CANDU Nuclear Power Generating Stations, COG Report, COG-01-080 (2002).

[A1.13] KOTZER, T., YANKOVICH, T.L., Concentrations of tritium (OBT, FWT) in fish and associated media, TK-01-01 (2001).

[A1.14] KOTZER, T., et al., Natural concentrations of tritium (OBT, FWT) in fish and associated media, COG report (2001).

APPENDIX II. PLANT GROUPS AND ASSOCIATED CROPS

TABLE A2.1. PLANT GROUPS, WITH COMMON AND LATIN NAMES OF ASSOCIATED CROPS

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.) Henelt).*
	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 A2.1. PLANT GROUPS, WITH COMMON AND LATIN NAMES OF ASSOCIATED CROPS

Plant group	Common name	Latin name
Non-Leafy vegetables	Tomato	*Lycopersicon esculentum Mill.*
	Lady's finger (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 (Cherra??)	*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.*
	Zuchini	*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, etc.)	*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*
Plant group	Common name	Latin name
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 A2.1. PLANT GROUPS, WITH COMMON AND LATIN NAMES OF ASSOCIATED CROPS

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 ^{x}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.*
	Water-melon	*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 A2.1. PLANT GROUPS, WITH COMMON AND LATIN NAMES OF ASSOCIATED CROPS

Crasses	Red fescue	*Festuca rubra L.*
	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.*
Fodder	Spring vetch (common vetch)	*Vicia sativa L.*
Leguminous (cultivated species)	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 (faba-bean; broad-bean)	*Vicia faba L.*
	Clover (crimson clover)	*Trifolium incarnatum L..*
	Alfalfa ***	*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.*
Plant group	Common name	Latin name
Pasture (species mixture)	Grass-leguminous mixture (festuca+ timothy-clover, oats-clover….)	
	Natural grasses mixture	
	Undefined mixture	
	Canadian thistle	*Cirsium arvense (L.) Scop.*
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*

TABLE A2.1. PLANT GROUPS, WITH COMMON AND LATIN NAMES OF ASSOCIATED CROPS

Plant group	Common name	Latin name
	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.*

REFERENCES

[A.2.1] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of radionuclide transfer in terrestrial and freshwater environments for radiological assessments, TECDOC No. XXX, IAEA, Vienna (2009).

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