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Nagra Biosphere Modelling: Review of Generic Data

August 2013

R. Walke, M. Thorne, L. Limer

**Nationale Genossenschaft
für die Lagerung
radioaktiver Abfälle**

Hardstrasse 73
CH-5430 Wettingen
Telefon 056-437 11 11

www.nagra.ch

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Summary

Nagra uses a compartment model for representing the distribution of radionuclides in the biosphere following release from a deep geological repository and for calculating potential effective radiation doses to persons. The current model, which builds on Nagra's previous biosphere model TAME, is implemented in a software application and is referred to as the Swiss Biosphere Assessment Code, SwiBAC.

Parameter values for representing important radionuclides in the biosphere model were last reviewed and updated for Stage 1 of the ongoing siting procedure for deep geological repositories in Switzerland in 2008. This report presents a review of element-dependent data within SwiBAC with the aim of updating Nagra's biosphere data to be consistent with the latest international consensus, for example, as reflected in the latest recommendations of the International Atomic Energy Agency. The review also takes note of more recent sources to ensure that the data are fully up-to-date, for example, discussions and recommendations arising from the BIOPROTA international collaborative project.

The current review relates to the following 32 elements, which are included in the reference data set for SwiBAC: Be, C, Cl, K, Ca, Co, Ni, Se, Sr, Zr, Nb, Mo, Tc, Pd, Ag, Sn, I, Cs, Sm, Eu, Ho, Pb, Po, Ra, Ac, Th, Pa, U, Np, Pu, Am and Cm. It further focuses on the following element-specific parameters:

- the soil to crop transfer factor;
- the weathering loss term for externally intercepted contaminants;
- the translocation rate from external intercepted contamination to edible crop;
- the food processing factor;
- the transfer factor from feed to meat;
- the transfer factor from feed to milk;
- the transfer factor from feed to eggs; and
- the surface water to fish transfer factor.

SwiBAC calculations undertaken with the changes described in this report and with the new parameter recommendations show that, in most cases, steady-state biosphere dose conversion factors (BDCFs) remain within a factor two of the previous values used by Nagra. In other cases, the new BCDF values are much lower than before, with the exception of Ca-41, for which an increase in the BDCF by almost a factor of ten is observed.

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1 Introduction

Nagra has contracted Quintessa to review and update generic element-specific input data used in support of its biosphere modelling code SwiBAC. The models supporting the latest version SwiBAC 1.2 are described in a 'Model Definition' report (Walke and Keesmann 2013). The reviewed data are from Nagra (2003), Brennwald and van Dorp (2008), as well as from Nagra (2010).

The initial SwiBAC models and data reflect the TAME model, which was originally described in Klos et al. (1996). A description of the biosphere modelling concepts and data was given in Nagra (2003), including a full description and justification of the supporting data. Parameter values for important radionuclides were reviewed and updated for stage 1 of the ongoing siting procedure for repositories in Switzerland in Brennwald and van Dorp (2008).

The current review relates to the following 32 elements, which are included in the reference data set for SwiBAC:

Be, C, Cl, K, Ca, Co, Ni, Se, Sr, Zr, Nb, Mo, Tc, Pd, Ag, Sn, I, Cs, Sm, Eu, Ho, Pb, Po, Ra, Ac, Th, Pa, U, Np, Pu, Am and Cm.

The review focuses on element-specific parameters excluding sorption coefficients.

The review aims to update Nagra's biosphere data consistent with the latest international consensus, for example, as reflected in the International Atomic Energy Agency Technical Report Series 472 (IAEA 2010) and its supporting report IAEA (2009). However, the review also takes note of more recent sources to ensure that the data are up-to-date, for example, discussion and recommendations arising from the BIOPROTA project (www.bioprota.org). A full review of primary literature was beyond the scope of the study.

The updated parameter recommendations are presented in Section 2, with the following parameters being described within sub-sections:

- the soil to crop transfer factor (Section 2.1);
- the weathering loss term for externally intercepted contaminants (Section 2.2);
- the translocation rate from external intercepted contamination to edible crop (Section 2.3);
- the food processing factor (Section 2.4);
- the transfer factor from feed to meat (Section 2.5);
- the transfer factor from feed to milk (Section 2.6);
- the transfer factor from feed to eggs (Section 2.7); and
- the surface water to fish transfer factor (Section 2.8).

Based on these recommendations, the library files of the precursor of the model described in Walke & Keesmann (2013), namely SwiBAC 1.1[1], have been updated. Section 3 presents biosphere dose conversion factors (BDCFs) using SwiBAC 1.1 and the updated input parameter recommendations, including comparison against the previous BDCFs in Nagra (2010) and an associated analysis.

The effects of some of the key changes to the modelling approach resulting from the present review and which have led to the latest version SwiBAC 1.2 are also explored in Section 3.

Conclusions are presented in Section 4, whilst references are presented at the end of the report.

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[1] SwiBAC Version 1.1 is documented in unpublished internal technical notes.

2 Parameter Recommendations

The generic element-dependent parameter recommendations are presented in the following subsections. Each includes an introductory discussion describing the parameter and its key considerations together with a table presenting the previous and new parameter recommendations. Justification for parameter values and associated distributions is provided as footnotes to the tables, along with associated references.

The study has focused on providing recommended best-estimate parameter values. However, ranges are included in the discussion to help support sensitivity analyses, which may be considered in the future.

For transfer factors, the new recommendations are made to one significant figure. A greater level of precision is inappropriate, given the degree of uncertainty surrounding the parameter values, and is not necessary for the type of calculation being undertaken with SwiBAC.

2.1 Soil to Crop Transfer Factor

The soil to crop transfer factor[2] represents equilibrium concentrations within edible plant tissues as a result of radionuclide uptake from the soil based on fresh weight (fw) of plant tissue and dry weight (dw) of soil; it therefore has units of (Bq/kg fw crop) per (Bq/kg dw soil).

Extensive data are provided in Tables 17, 18 and 19 of IAEA (2010). These values are given on a dry weight plant and dry weight soil basis in IAEA (2010), and have therefore been scaled by the ratio of dry weight plant to fresh weight plant for use in SwiBAC. This information is given in Tables 82 to 85 in Appendix I of IAEA (2010); the values assumed here are summarised in Tab. 1.

Tab. 1: Crop Dependent Values for the Ratio Dry Weight:Fresh Weight.

Crop	**Dry weight:fresh weight ratio assumed [%]**	**Notes**
Pasture	20	See Table 84 of IAEA (2010), which also gives dry matter content values of 26% for grass silage and 86% for grass hay.[3]
Grain	88	Value based upon wheat in Table 82 of IAEA (2010).
Green vegetables	10	Based on an average of cabbage, lettuce, leek, onion, spinach and cauliflower in Table 82 of IAEA (2010).
Root vegetables	20	Based on consideration of beetroot, carrot, potato and turnip in Table 82 of IAEA (2010), with additional weight given to potatoes as a staple of the diet.
Fruit	15	Based on an average of apple, pear, grape and strawberry in Table 83 of IAEA (2010).

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[2] The mathematical representation of the SwiBAC model refers to this parameter by K_{crop}.

[3] Note that fresh weight refers in this context to the feed when consumed by the animal, not to the standing biomass before harvest. This is particularly relevant for grass hay, for which water content is substantially reduced at harvesting.

IAEA (2010) has been used in preference to other sources, particularly where the values are supported by several samples or more. Where available, the fruit is based upon herbaceous fruit data provided in IAEA (2010). For many of the elements where data were not available in IAEA (2010), the recommended values are based on Walke et al. (2013).

Where the available data suggest very similar values for different types of plants and where distinctions between those values are not supported by a large number of samples, then there is a preference to adopt the same value for different plant types, given that the typical level of uncertainty surrounding soil-to-plant transfer factors spans several orders of magnitude (e.g. Sheppard 2005).

The values used previously by Nagra, and the new recommendations are given in Tab. 2. To aid comparison of the old and new values, they are compared graphically in Fig. 1.

From this it is clear that, for the vast majority of elements, there is limited change in the recommended values. For Ag, there is a consistent decrease in the recommended values across all crops. The previous values had been taken from the SKB database (Karlsson and Bergström 2002; Karlsson et al. 2002), whereas the new values are taken from IAEA (2010), or derived from IAEA (2010) in Walke et al. (2013).

For the elements Sm, Eu and Ho the new values are consistently higher than the old ones. The new values, taken from Walke et al. (2013), are based upon values for Pm reported in IAEA (2010), accounting for the conversion between dry and fresh weight. The basis for the original values defined in Nagra (2003) is not clear.

Tab. 2: Soil to Crop Transfer Factor, [(Bq/kg fw crop) per (Bq/kg dw soil)].

Element	**Pasture**		**Grain**		**Green Vegetables**		**Root Vegetables**		**Fruit**		**Notes**
	Previous	New	Previous	New	Previous	New	Previous	New	Previous	New	
Be	2.40E-3	3E-3	4.70E-4	3E-3	4.70E-4	3E-3	4.70E-4	3E-3	4.70E-4	3E-3	1
C	3.5E+0	3.5E+0	1.7E+1	1.7E+1	1.6E+0	1.6E+0	3.6E+0	3.6E+0	1.7E+0	1.7E+0	2
Cl	1.30E+1	3E+1	4.50E+1	3E+1	5.00E+0	3E+1	7.50E+0	3E+1	7.50E+0	3E+1	3
K	2.00E-2	1E-1	1.30E-2	1E-1	1.30E-2	1E-1	8.00E-3	1E-1	5.00E-2	1E-1	4
Ca	5.80E-1	1E+0	1.20E-1	1E+0	1.50E-1	1E+0	1.40E-1	1E+0	1.40E-1	1E+0	5
Co	9.00E-2	1E-2	1.30E-2	1E-2	7.40E-3	1E-2	8.20E-2	1E-2	8.20E-2	1E-2	6
Ni	5.00E-2	2E-2	4.20E-2	2E-2	1.70E-2	2E-2	1.60E-2	2E-2	1.60E-2	2E-2	7
Se	2.50E-1	7E-3	3.60E-2	6E-2	3.50E-2	4E-3	3.80E-2	5E-3	5.00E-1	3E-3	8
Sr	5.80E-1	3E-1	1.20E-1	1E-1	1.50E-1	1E-1	1.40E-1	1E-1	1.40E-1	1E-1	9
Zr	2.00E-2	2E-3	2.70E-2	9E-4	3.40E-3	6E-4	2.10E-3	6E-4	2.10E-3	6E-4	10
Nb	4.70E-2	4E-2	9.40E-3	1E-2	9.40E-3	3E-3	9.40E-3	3E-3	5.00E-3	3E-3	10
Mo	1.10E+0	7E-1	4.00E+0	7E-1	4.50E-1	6E-2	7.00E-1	6E-2	7.00E-1	6E-2	11
Tc	2.50E+0	1E+1	4.50E+0	1E+1	1.00E+0	1E+1	1.50E+0	1E+1	2.00E+1	1E+1	12
Pd	5.00E-2	4E-2	5.00E-2	4E-2	1.70E-2	4E-2	1.60E-2	4E-2	1.60E-2	4E-2	13
Ag	5.00E-2	1E-4	4.00E-1	1E-4	1.00E-1	1E-4	2.00E-1	1E-4	2.00E-1	1E-4	14
Sn	1.00E-1	1E-2	3.60E-1	1E-2	4.00E-2	1E-2	6.00E-2	1E-2	6.00E-2	1E-2	15
I	1.00E-1	3E-2	3.60E-1	3E-2	1.90E-2	3E-2	6.40E-3	3E-2	5.00E-2	3E-2	16
Cs	2.00E-2	5E-2	1.30E-2	3E-2	1.30E-2	6E-3	8.00E-3	8E-3	5.00E-2	3E-3	17
Sm	5.00E-4	2E-2	1.80E-4	2E-2	2.00E-4	2E-2	3.00E-4	2E-2	3.00E-4	2E-2	18
Eu	5.00E-4	2E-2	1.80E-4	2E-2	2.00E-4	2E-2	3.00E-4	2E-2	3.00E-4	2E-2	18
Ho	5.00E-4	2E-2	1.80E-4	2E-2	2.00E-4	2E-2	3.00E-4	2E-2	3.00E-4	2E-2	18

Tab. 2: (continued)

Element	Pasture		Grain		Green Vegetables		Root Vegetables		Fruit		Notes
Pb	4.50E-3	1E-2	1.70E-2	1E-2	1.80E-3	1E-2	2.70E-3	1E-2	1.00E-2	1E-2	19
Po	9.76E-3	2E-2	2.83E-2	1E-3	3.08E-3	1E-3	5.86E-3	1E-3	5.86E-3	1E-3	20
Ra	3.40E-3	1E-2	2.89E-2	1E-2	3.40E-3	1E-2	6.80E-3	1E-2	3.40E-3	1E-2	21
Ac	5.00E-4	3E-4	1.80E-4	3E-5	2.00E-4	3E-5	3.00E-4	3E-5	5.00E-4	3E-5	22
Th	9.50E-4	2E-2	7.10E-4	2E-3	3.80E-4	1E-4	5.70E-4	1E-4	5.00E-4	1E-4	23
Pa	9.40E-3	2E-2	1.70E-2	2E-3	2.70E-2	1E-4	6.00E-2	1E-4	4.00E-2	1E-4	24
U	7.10E-4	9E-3	6.04E-3	5E-3	7.10E-4	2E-3	1.42E-3	2E-3	7.10E-4	2E-3	25
Np	1.00E-3	1E-2	8.50E-3	3E-3	1.00E-3	3E-3	2.00E-3	3E-3	1.00E-3	3E-3	26
Pu	9.50E-5	1E-4	1.80E-3	1E-5	1.40E-4	1E-5	3.00E-4	1E-5	1.00E-4	1E-5	27
Am	5.00E-4	3E-4	2.20E-5	3E-5	2.00E-4	3E-5	3.00E-4	3E-5	1.00E-3	3E-5	28
Cm	5.00E-4	3E-4	1.10E-3	3E-5	2.00E-4	3E-5	3.00E-4	3E-5	3.00E-4	3E-5	28

Notes for Tab. 2:

1. Table 17 of IAEA (2010) give a value that equates to 8E-2 on a fresh weight plant basis, however, it is based on a single sample. Be would be expected to be highly bioexcluded relative to Ca, therefore a value of 0.003 is used for all plant types, based on Section 4.1.3.3 of Thorne (2007).
2. Based on modelling of C-14 in the soil-plant-atmosphere system, described in Nagra (2013), which is known to be conservative. Note that the recommendations for carbon are specified to two significant figures to reflect the parameter recommendations in Nagra (2013) and to ensure that the dynamic behaviour of C-14 is consistent in the two models.
3. Table 18 of IAEA (2010) includes some limited data for a wide range of plant types. A cautious value of 30 is recommended across all plant types to reflect uncertainty in the value and also to reflect that in an inland, upland area like Switzerland, the soils are likely to be chloride-deficient and higher transfer factors will apply because stable chloride levels in plants are maintained quasi-homeostatically.
4. The value will be strongly determined by the fraction of potassium in the soil that is available and therefore on agricultural practice and the use of fertilizers. A value of 0.1 is adopted across all plant types based on the limited data available in Table 17 of IAEA (2010).
5. There is limited data available for Ca, although average values of about 9 and 20 are reported on a dry weight basis in Table 17 of IAEA (2010) for stems and shoots of cereals and stems and shoots of leguminous vegetables. A geometric average of these values converted to a fresh weight basis for plant implies a value of about 1. It is noted that this is typically an order of magnitude greater than the values for Sr, with which a similarity would be expected, which implies that this is a conservative assumption.
6. Consideration of a wide range of plant types in Table 17 of IAEA (2010) supports a value of 1E-2 on a fresh weight basis across all plant types.
7. Based on consideration of Table 17 of IAEA (2010) and discussion in Section 2.5.2 of Thorne (2008).
8. IAEA (2010) does not contain recommendations for Se. However, a comprehensive peer-reviewed discussion appears in Pérez-Sánchez et al. (2012). The values recommended here are based on sources discussed therein, in particular Uchida et al. (2007a,b) and Tsukada and Nakamura (1998).
9. Table 17 of IAEA (2010) indicates that a value of 0.1 is appropriate for a range of plant types. A value of 0.3 is supported for pasture, given the large number of associated samples (172). Results for fruit presented in Table 19 of IAEA (2010) are at odds (i) with values for other plants and (ii) with an expected similarity with Ca. Given this uncertainty, a value of 0.1 is conservatively adopted for fruits.
10. Based on Table 17 of IAEA (2010). The similar nature of the values means that the same value is used for green and root vegetables, based on the average of the two. No value is available for fruit so the vegetables value is used.
11. Based on Table 17 of IAEA (2010). The similar nature of the values means that the same value is used for green and root vegetables, based on the average of the two. No value is available for fruit, so the vegetable value is used. No value is available for pasture so the grain value is conservatively used.
12. Table 18 of IAEA (2010) indicates that a value of 10 is appropriate for a range of plant types. The low value of about 1 for cereal grain on a fresh weight basis is only based on two results and is discounted.
13. Table 3-38 of Walke et al. (2012).

14. Based on Table 17 of IAEA (2010) values for leafy vegetables, non-leafy vegetables and root crops.
15. Based on Section 4.1.3.3 of Thorne (2007).
16. Based on review in Section 4.3 and recommendation in Table 4-21 of Thorne and Limer (2009), which includes consideration of IAEA (2009) and which is in agreement with the single value given for I to fruit in Table 19 of IAEA (2010). It is unclear why the data presented in Table 20 of IAEA (2009) are not summarised in Table 17 of IAEA (2010).
17. Table 17 of IAEA (2010), note that the uptake of Cs by plants is dependent on the potassium status of the soil and is therefore affected by agricultural practice. Application of fertilizers will increase the potassium status of the soil and decrease the uptake of caesium.
18. Values for lanthanides would be expected to be similar. No values for Sm, Eu or Ho are presented in IAEA (2010) so these values are based on data for Pm in Table 17 of IAEA (2010) by analogy.
19. Data in Table 17 of IAEA (2010) indicate limited distinction between plant types for Pb, which is supported by Thorne and Mitchell (2011). The recommended value is based on the data given in Table 17 of IAEA (2010).
20. Based on relatively limited data for Po in Table 17 of IAEA (2010). The data suggest that values for grain and vegetables are similar, so no distinction is made and a value of 0.001 is used for these crops and fruits. The data indicate that a higher value may be appropriate for pasture, so a value of 0.01 on a fresh weight basis is recommended, although Section 2.13.2 of Thorne (2008) notes that this higher value may be due to the confounding factor of atmospheric deposition to pasture.
21. Based on relatively extensive data in Table 17 of IAEA (2010), which indicates a value of 0.01 on a fresh weight basis across a range of plant types. No data is available in IAEA(2010) for fruit, however it is reasonable to adopt the same value used for all other plant types.
22. No data for Ac is given in IAEA (2010). Consistent with the reports of Walke et al. (2013) and Thorne (2008), transfer factors for actinium are taken to be the same as for americium and curium.
23. Based on relatively extensive data in Table 17 of IAEA (2010). The data suggest a distinction between grain and other crops, which is reflected in the recommendations. No values are provided for fruit in IAEA (2010), so the vegetable value is used. A notably higher value is given for pasture in Table 17 of IAEA (2010), which is reflected here; however, this is considered conservative and may reflect a contribution from external contamination, as noted in Section 2.17.2 of Thorne (2008).
24. IAEA (2010) provide no data for Pa. Consistent with Thorne (2008) and the report Walke et al. (2013), transfer factors for Pa are taken to be identical to those for thorium.
25. Based on extensive data in Table 17 of IAEA (2010). No data is presented for fruit, which is taken to have the same transfer factor as for green and root vegetables.
26. Based on extensive data in Table 17 of IAEA (2010), which indicates little difference between crops, but supports a higher value for pasture. No data is presented for fruit, which is taken to have the same transfer factor as for other crops.
27. Based on extensive data in Table 17 of IAEA (2010), which indicates little difference between crops and fruit, but supports a higher value for pasture.
28. Biogeochemical similarities mean that Am and Cm should be considered together (Section 2.19.2 of Thorne 2008). Relatively extensive data for both is given in Table 17 of IAEA (2010), which supports a value of about 3E-5 on a fresh weight basis for crops and fruit and

a value of about 3E-4 for pasture. In considering the value for crops and fruit, additional weight has been given to the values for grain, given the relatively large number of supporting samples.

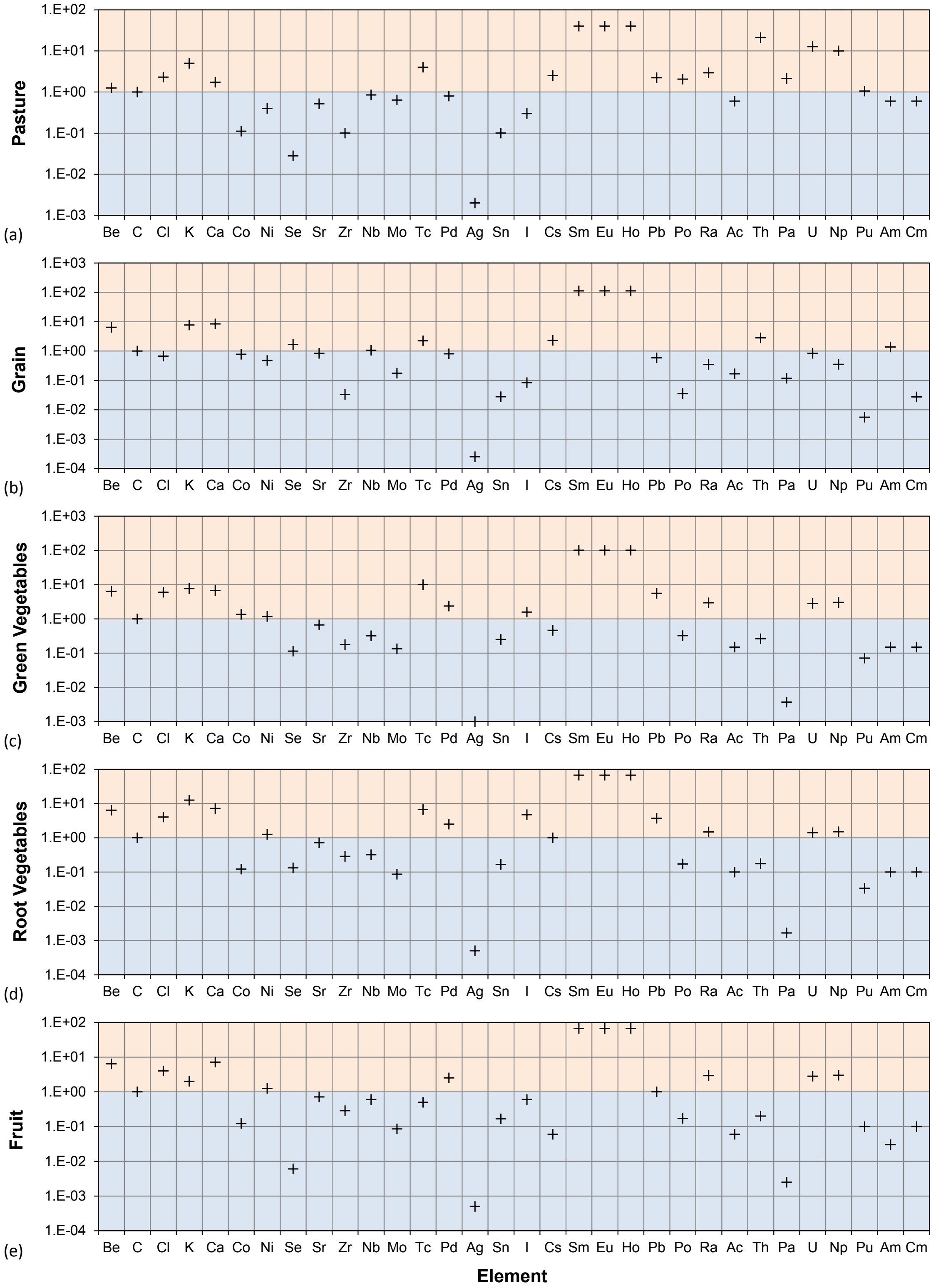

Fig. 1: Ratio New:Old of Soil to Crop Transfer Factors.

(a) Pasture; (b) Grain; (c) Green Vegetables; (d) Root Vegetables; and (e) Fruit.

2.2 Weathering Loss Term for Externally Intercepted Contaminants

The weathering loss term for externally intercepted contaminants[4] represents the loss rate to soil of radionuclides that have been intercepted from irrigation water on the external surfaces of crops. The data for the parameter is presented on a per year basis, /a.

Once deposited on vegetation, contaminants are lost from plants by leaching or cuticular abrasion. The increase of biomass during growth does not cause a loss of contaminant; however, it does lead to a decrease in concentration due to growth dilution. Although growth (and hence growth dilution) cannot be described by a simple exponential function, at least in some parts of the growth curve, the growth rates observed are equivalent to half-lives of 10 to 50 days (Thiessen et al. 1999). Growth dilution is often included within weathering loss and the rate of reduction of concentration is often expressed in terms of the weathering half-life.

The values used previously by Nagra are taken from Simmonds and Crick (1982). These gave a half-life of approximately 14 days for most element and crop combinations (Tab. 3).

IAEA (2010) provides some element-specific recommendations for weathering loss rates which include growth dilution[5], in particular for Cs, I, Pu and Sr, but only for a limited number of crop types. The chapter on weathering in IAEA (2009) features weathering loss data as a function of plant growth stage. This includes a few short weathering half-lives relating to contamination a few days before harvest. Weathering will include shorter and longer-term processes, the short half-lives in IAEA (2009) are because the associated studies will have tended to emphasise short-term losses.

It is noted that Table 6 of IAEA (2010) shows no consistent trend in values between different elements or different crop types. The most that can be said is that the arithmetic mean values range between 10 and 43 days, and that the full ranges (where given) are between 7.9 and 49 days. Thus, the data presented in IAEA (2010) are consistent with the recommendations of Walke et al. (2012), which consider that there is no strong argument for element-specific weathering loss rates.

Walke et al. (2012) note that, overall, weathering half-lives, including growth dilution, are generally in the range 5 to 50 days, though values of up to 100 days may be recorded. Walke et al. (2012) recommend a weathering half-life of 20 days, excluding growth dilution. Adjusting this value for inclusion of growth dilution, a reference weathering half-life of 15 days is therefore recommended for all elements, with the exception of C, and crop types, with a range from 5 to 50 days to be considered in sensitivity calculations. The recommended reference value corresponds to a weathering rate of 17 /a.

A rapid rate is retained for C. Given its status as an element that represents a fundamental building block of biological systems, a model specific to C-14 is used by Nagra to support its representation in SwiBAC (Nagra 2013). Interception of C-14 is of limited importance for carbon, which is predominantly taken-up by plants from the canopy atmosphere for use in photosynthesis. Interception and weathering is therefore excluded from Nagra's model for C-14, so the use of a rapid rate for weathering is appropriate in SwiBAC.

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[4] The mathematical representation of the SwiBAC model refers to this parameter by W_{crop}.

[5] Growth dilution is included in the definition of weathering on page 45 of IAEA (2009), which forms the basis of the values presented in IAEA (2010).

Tab. 3: Weathering Loss Term for Externally Intercepted Contaminants, [/a].

Element	**Pasture, Root Vegetables, Fruit**		**Grain**		**Green Vegetables**	
	Previous	New	Previous	New	Previous	New
C	500	500	500	500	500	500
Be, Cl, K, Ca, Co, Ni, Se, Sr, Zr, Nb, Mo, Tc, Pd, Ag, Sn, I, Cs, Sm, Eu, Ho, Pb, Po, Ra, Ac, Th, Pa, U, Cm	18.1	17	8.4	17	18.1	17
Np, Am, Pu	18.1	17	50.6	17	50.6	17

2.3 Translocation Rate from External Intercepted Contamination to Edible Crop

The translocation rate from external intercepted contamination to edible crop[6] represents the rate of absorption and translocation, to the edible plant tissues, of radionuclides that have been intercepted from irrigation water on the external surfaces of crops; the data for the parameter is presented on a per year basis, /a. It is only relevant for root vegetables, fruit and grain, all external contamination remaining on green vegetables and pasture is taken to be associated with edible tissues. The assumption of full availability seems appropriate for green vegetables and pasture. However, using such an approach for grain would imply that all external contamination of a cereal plant would instantly be available in the grain at harvest time. It is therefore recommended that, unlike previously, translocation rates are now included for grain as well as for root vegetables and fruit.

Tables 7 to 11 of IAEA (2010) contain data for the translocation fraction (%) for a range of elements and plant types, although the majority of the data relate to Cs and Sr. These data are also discussed in more detail in IAEA (2009), where it is noted that the scarcity of literature on this process highlights an important lack of knowledge, e.g. how translocation might change during plant growth, the effects of chronic contamination, few data for most radionuclides, and potentially inappropriate use of chemical analogues in the absence of element-specific data.

There is a review of an extensive set of data for grain in IAEA (2010). The range of translocation fractions reported for grain is 0.001 to 0.1 for various elements, plant types and stages of plant growth, with a typical value of 0.01. The range of reported values for the other crops is similar to that of grain. The limited number of values reported for the actinides are lower, which reflects their low bioavailability, whilst values for lanthanides would be expected to be similar to those for the higher actinides.

Translocation fractions, TF_{crop}, can be converted to translocation rates using the following relationship:

$$TF_{crop} = \frac{T_{crop}}{T_{crop} + W_{crop}} \tag{1}$$

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[6] The mathematical representation in TAME and earlier versions of the SwiBAC model refers to this parameter by T_{crop}.

which can be rearranged to give:

$$T_{crop} = \frac{TF_{crop} W_{crop}}{1 - TF_{crop}} \tag{2}$$

It is recommended that translocation fractions be used as the primary input to SwiBAC instead of translocation rates[7]. This ensures that the data is expressed in a format that is consistent with the way that the source data are typically expressed. It also ensures that the translocation fraction remains consistent with the source data in cases where the weathering rate is varied.

The current translocation rates are given in Tab. 4, together with the implied translocation fractions. New translocation fractions are also given in Tab. 4 based on a translocation fraction of 0.01 in most cases and a translocation fraction of 0.001 for lanthanides and actinides (excluding uranium). Uranium tends to be much more soluble in the environment than the other actinides and has biochemical similarities with calcium, so its translocation fraction is taken to be 0.01.

Tab. 4: Translocation Fraction from External Intercepted Contamination to Edible Crop.

Element*	**Previous**					**New Translocation Fraction for Root Vegetables, Fruit and Grain [-]**
	Translocation Rate [/a]		**Implied Translocation Fraction [-]**			
	Root Vegetables	Fruit	Root Vegetables	Fruit	Grain†	
Be	0.00E+0	0.00E+0	0.0	0.0	n/a	0.01
Cl	2.02E+0	2.02E+0	0.10	0.10	n/a	0.01
K	0.00E+0	0.00E+0	0.0	0.0	n/a	0.01
Ca	0.00E+0	0.00E+0	0.0	0.0	n/a	0.01
Co	9.50E-1	9.50E-1	0.050	0.050	n/a	0.01
Ni	9.50E-1	9.50E-1	0.050	0.050	n/a	0.01
Se	2.02E+0	1.20E-1	0.10	0.0066	n/a	0.01
Sr	1.80E-1	1.80E-1	0.0098	0.0098	n/a	0.01
Zr	1.80E-1	1.80E-1	0.0098	0.0098	n/a	0.01
Nb	1.80E-1	6.20E-1	0.0098	0.033	n/a	0.01
Mo	0.00E+0	0.00E+0	0.0	0.0	n/a	0.01
Tc	2.02E+0	1.20E-1	0.10	0.0066	n/a	0.01
Pd	0.00E+0	0.00E+0	0.0	0.0	n/a	0.01
Ag	9.50E-1	9.50E-1	0.050	0.050	n/a	0.01
Sn	9.50E-1	9.50E-1	0.050	0.050	n/a	0.01
I	2.02E+0	3.30E-1	0.10	0.018	n/a	0.01
Cs	2.02E+0	9.80E-2	0.10	0.0054	n/a	0.01
Sm	3.80E-1	3.80E-1	0.021	0.021	n/a	0.001
Eu	3.80E-1	3.80E-1	0.021	0.021	n/a	0.001
Ho	0.00E+0	0.00E+0	0.0	0.0	n/a	0.001

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[7] This recommendation has been implemented in SwiBAC 1.2 (Walke & Keesmann 2013).

Tab. 4: (continued)

Element*	Previous					New Translocation Fraction for Root Vegetables, Fruit and Grain [-]
	Translocation Rate [/a]		Implied Translocation Fraction [-]			
	Root Vegetables	Fruit	Root Vegetables	Fruit	Grain†	
Pb	0.00E+0	1.10E-1	0.0	0.0060	n/a	0.01
Po	1.80E-1	1.10E-1	0.0098	0.0060	n/a	0.01
Ra	1.80E-1	7.30E-2	0.0098	0.0040	n/a	0.01
Ac	1.80E-1	2.10E-1	0.0098	0.011	n/a	0.001
Th	1.80E-1	1.30E-1	0.0098	0.0071	n/a	0.001
Pa	0.00E+0	2.10E-1	0.0	0.011	n/a	0.001
U	1.80E-1	1.90E-1	0.0098	0.010	n/a	0.01
Np	0.00E+0	2.10E-1	0.0	0.011	n/a	0.001
Pu	0.00E+0	1.90E-1	0.0	0.010	n/a	0.001
Am	0.00E+0	1.30E-1	0.0	0.0071	n/a	0.001
Cm	0.00E+0	0.00E+0	0.0	0.0	n/a	0.001

Notes for Tab. 4:

* The representation of the behaviour of C-14 within the soil-plant system in SwiBAC is supported by more detailed modelling described in Nagra (2013). Interception and translocation is unimportant for C-14 and is not represented in SwiBAC.

† Contamination remaining on external plant surfaces after weathering was previously represented as being fully assigned to the grain. It is now recommended that translocation to the grain is explicitly represented using the new translocation fractions.

2.4 Food Processing Factor

The food processing factor[8] represents the fraction of external radionuclide contamination associated with harvested plant tissues (i.e. from interception and soil contamination) that remains after food processing. It is unitless. Section 11 of IAEA (2010) presents data for the fraction of radionuclides in raw plant tissues that is retained following food processing. IAEA (2009) note that the efficiency of radionuclide removal through processing of plant products varies widely and can remove up to 99% of the initial activity in raw material, or as little as none.

The interception model used in SwiBAC assigns all external intercepted contamination to the edible part of the crops. Whilst this is appropriate for some green vegetables (e.g. cabbage), it is inappropriate for other green vegetables (e.g. beans), grain, root vegetables and fruit (see also the discussion in Section 3.2). The food processing factor applies to both externally intercepted contamination and external soil contamination. Different values are appropriate to external intercepted contamination and external soil contamination, however, this is not currently possible. The food processing factors therefore remain unchanged (see Tab. 5) and it is recommended that the interception model be reviewed.

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[8] The mathematical representation of the SwiBAC model refers to this parameter by f_{crop}.

Tab. 5: Fraction Remaining after Food Processing, [-].

Element	**Grain**	**Green Vegetables**	**Root Vegetables**	**Fruit**
C	1	1	1	1
K	0.15	0.5	0.5	1
Tc, I, Cs	0.5	0.5	0.5	0.5
Np, Pu, Am	0.1	0.5	0.5	0.5
Other elements	0.15	0.5	0.5	0.5

Note for Tab. 5:

The conceptual model supporting SwiBAC assumes that pasture is subject to no processing prior to consumption by animals, so pasture is not included in the table.

2.5 Transfer Factor from Feed to Meat

The transfer factor from feed to meat[9] represents the equilibrium concentration in meat given a rate of radionuclide ingestion in animal feed and has units of (Bq/kg fw) per (Bq/day).

New values are primarily based on transfer factors to beef in IAEA (2010) where data are available, and in Walke et al. (2013) where not. The previously used and new values are given in Tab. 6 and compared in Fig. 2.

Tab. 6: Transfer Factor from Feed to Meat, [(Bq/kg fw) per (Bq/day)].

Element	**Previous**	**New**	**Notes**
Be	8.0E-4	1E-2	1
C	3.0E-2	8E-2	2
Cl	8.0E-2	2E-2	3
K	2.6E-2	2E-2	4
Ca	8.1E-4	1E-2	3
Co	1.3E-2	4E-4	3
Ni	2.0E-3	1E-2	2
Se	1.8E+0	1E-1	2
Sr	8.1E-4	1E-3	3
Zr	2.0E-2	2E-4	5
Nb	3.0E-7	2E-4	5
Mo	6.8E-3	1E-3	3
Tc	1.0E-3	8E-4	2
Pd	2.0E-3	1E-3	2

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[9] The mathematical representation of the SwiBAC model refers to this parameter by K_{meat}.

Tab. 6: (continued)

Element	Previous	New	Notes
Ag	1.0E-3	8E-3	2
Sn	4.0E-4	2E-3	2
I	1.2E-2	7E-3	3
Cs	2.6E-2	2E-2	3
Sm	6.0E-2	1E-4	2
Eu	6.0E-2	1E-4	2
Ho	6.0E-2	1E-4	2
Pb	4.0E-4	7E-4	3
Po	4.0E-3	3E-3	2
Ra	9.0E-4	2E-3	3
Ac	6.0E-2	5E-5	2
Th	2.0E-4	2E-4	3
Pa	8.0E-2	1E-3	2
U	4.0E-4	4E-4	3
Np	2.0E-4	1E-4	2
Pu	2.0E-6	1E-6	3
Am	2.0E-4	5E-5	6
Cm	2.0E-4	5E-5	2

Notes for Tab. 6:

1. In the absence of data, analogue with Ca assumed; note that this probably over-estimates the transfer because Be is poorly absorbed from the gastrointestinal tract in animals (ATSDR 2002), unlike Ca.
2. Table 20 of Walke et al. (2013).
3. Table 30 of IAEA (2010).
4. Table 13 of Thorne (2007).
5. Very low values are reported in Table 30 of IAEA (2010), however, these are only based on a single sample in each case. A value of 2E-4 is preferred here based on Sections 4.7 and 4.8 of Thorne (2003) and consistent with Thorne (2008) and Walke et al. (2013).
6. From Table 20 of Walke et al. (2013), which is preferred over the single value for Am in Table 30 of IAEA (2010) because (i) Am and Cm are very similar biochemically, and (ii) there is evidence that the bioavailability of Am is intermediate between that of Pu and that of Np (see discussion in Walke et al. 2012).

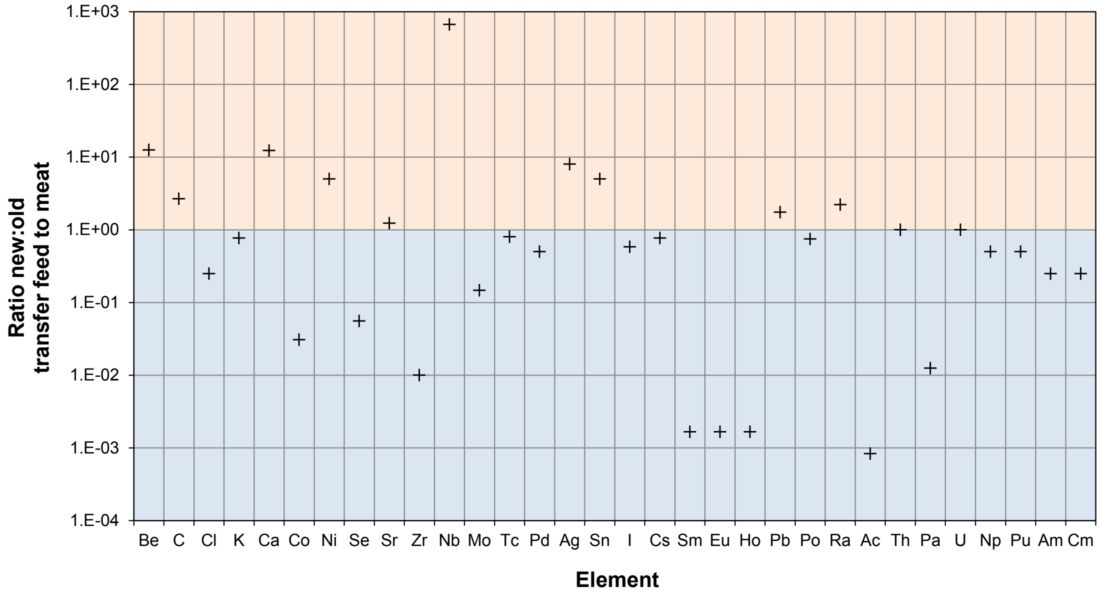

Fig. 2: Ratio of New:Old Feed to Meat Transfer Factors.

Whilst many of the new values are within about an order of magnitude of the previously used values, there are some changes that are notably greater: Zr, Nb, Sm, Eu, Ho, Ac and Pa are of particular note. The previous and new sources of the data are given in Tab. 7. Specific references are not provided for each value in Nagra (2003), which instead notes that the database of transfer factors for Nagra has a rather long history, with reference to several reports from the 1980's.

Tab. 7: Sources of Data for Certain Elements for Feed to Meat Transfer Factors.

Element	**Previous Source***	**New Source**	**Discussion**
Zr and Nb	Nagra (1985) for Zr, Nagra (2003) for Nb	Thorne (2003)	The previous value was inconsistent with the low bioavailability of Zr. One expects similar values (to within an order of magnitude) for Zr and Nb because they are similar xenobiotic, unavailable elements.
Sm, Eu and Ho	Nagra (2003)	Use La as analogue (e.g. consistent with Walke et al. 2013). La data from Table 30 of IAEA (2010)	The reduction in values for the lanthanides better reflects their low bioavailability.
Ac	Nagra (1985)	Use Am and Cm as analogues, consistent with Walke et al. (2013) and based on Thorne (2008)	Bioavailability of Ac is similar to higher actinides, and new value better reflects that.
Pa	Nagra (1985)	Table 20 of Walke et al. (2013), which traces back to Table 72 of Thorne (2003)	

Note for Tab. 7:

* Based on source reference, if defined in Table 11-2 of Nagra (2003). Where no source is explicitly listed in Nagra (2003), the values are described in Nagra (2003) as being based on expert judgement and comparison with values in the literature.

2.6 Transfer Factor from Feed to Milk

The transfer factor from feed to milk[10] represents the equilibrium concentration in milk given a rate of radionuclide ingestion in animal feed and has units of (Bq/kg fw) per (Bq/day).

The data in IAEA (2010) are presented as (Bq/L) per (Bq/day). However, in practice 1 L of milk has a mass of approximately 1 kg fresh weight (Walke et al. 2012) meaning that values reported in IAEA (2010), and in other sources, are used directly here. The previous and new recommended values are given in Tab. 8 and compared in Fig. 3.

Tab. 8: Transfer Factor from Feed to Milk, [(Bq/kg fw) per (Bq/day)].

Element	Previous	New	Notes
Be	2.0E-5	1E-4	1
C	1.0E-2	9E-3	2
Cl	5.0E-2	2E-2	2
K	7.1E-3	7E-3	3
Ca	1.4E-3	1E-2	4
Co	1.0E-3	1E-4	4
Ni	1.0E-3	1E-3	4
Se	3.0E-2	4E-3	4
Sr	1.4E-3	1E-3	4
Zr	3.0E-5	4E-6	4
Nb	2.5E-3	4E-7	4
Mo	1.4E-3	1E-3	4
Tc	2.5E-2	8E-4	2
Pd	1.0E-3	1E-3	2
Ag	3.0E-2	3E-4	2
Sn	1.2E-3	1E-3	2
I	9.9E-3	5E-3	4
Cs	7.1E-3	5E-3	4
Sm	5.0E-6	2E-5	2
Eu	5.0E-6	2E-5	2
Ho	5.0E-6	2E-5	2
Pb	2.6E-4	2E-4	4
Po	3.0E-4	2E-4	4

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[10] The mathematical representation of the SwiBAC model refers to this parameter by K_{milk}.

Tab. 8: (continued)

Element	Previous	New	Notes
Ra	6.2E-4	4E-4	4
Ac	5.0E-6	2E-6	2
Th	5.0E-6	1E-4	5
Pa	5.0E-6	1E-6	2
U	3.7E-4	2E-3	4
Np	5.0E-6	5E-6	2
Pu	1.0E-7	1E-6	2
Am	4.1E-7	4E-7	4
Cm	5.0E-6	4E-7	6

Notes for Tab. 8:

1. A value of 8.3E-7 day/L is reported in Table 26 of IAEA (2010). However, it is only based on a single sample. Be is less bioavailable than other alkaline earths, but not greatly so. A value of 1E-4 day/kg_{fw} is therefore recommended, being a little lower than the value for Ra.
2. Table 20 of Walke et al. (2013).
3. Table 13 of Thorne (2007).
4. Table 26 of IAEA (2010).
5. No data in IAEA (2010). Walke et al. (2013) use 1E-3 day/kg_{fw} based on Thorne (2008), however that value draws on a precursor to IAEA (2010) and the values did not appear in the final publication. A value of 1E-4 day/kg_{fw} is recommended, based on a biokinetic analysis in Section 4.15 of Thorne (2003).
6. Am and Cm are very similar biochemically, so the value for Am from IAEA (2010) is adopted.

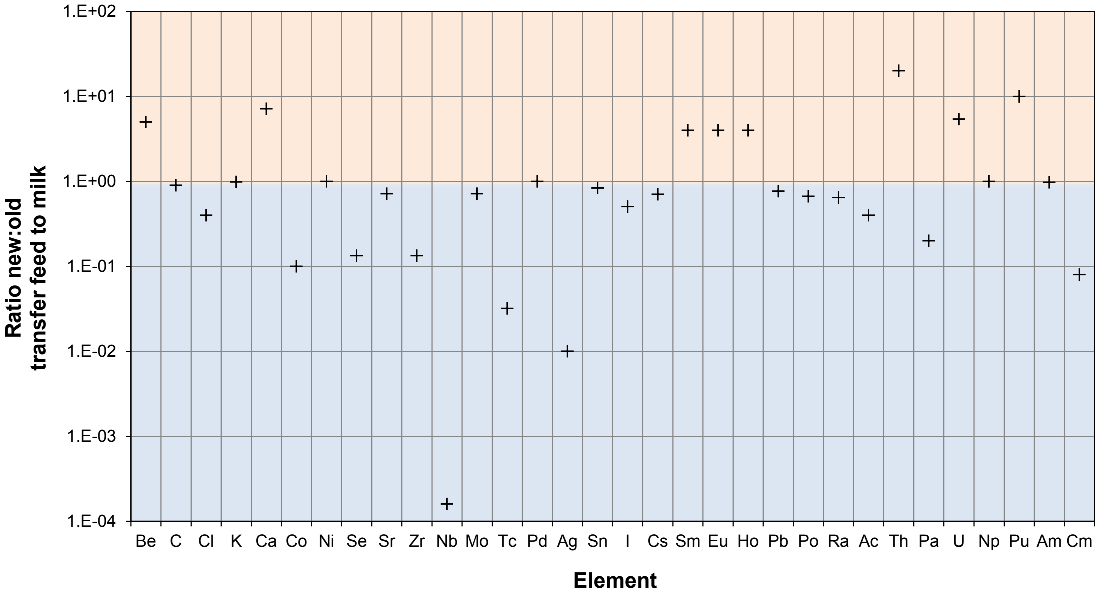

Fig. 3: Ratio of New:Old Feed to Milk Transfer Factor.

There are a number of elements for which the new recommendations differ from the previous values by more than an order of magnitude. For those elements with the largest changes in values, the sources of the old and new values are summarised in Tab. 9 below.

Tab. 9: Sources of Data for Certain Elements for Feed to Milk Transfer Factors.

Element	**Previous Source***	**New source**	**Discussion**
Be	Nagra (2003)	Based on consideration of bioavailability.	See footnote to Tab. 8.
Ca	Nagra (2003)	Table 26 of IAEA (2010)	Relatively high value would be expected. New value based on 15 observations in IAEA (2010).
Nb	Nagra (2003)	Table 26 of IAEA (2010)	New value is consistent with that for Zr, with which a similarity would be expected.
Th	Nagra (1985)	Section 4.15 of Thorne (2003)	See footnote to Tab. 8.
Pu	Nagra (1985)	Walke et al. (2013), which traces back to Section 4.19 of Thorne (2003)	Based on biokinetic modelling in Thorne (2003). Consistent with other higher actinides, but lower than the value of 1E-5 d/L in IAEA (2010), which merits consideration in any sensitivity analyses.

Note for Tab. 9:

* Based on source reference, if defined in Table 11-2 of Nagra (2003). Where no source is explicitly listed in Nagra (2003), the values are described in Nagra (2003) as being based on expert judgement and comparison with values in the literature.

2.7 Transfer Factor from Feed to Eggs

The transfer factor from feed to eggs[11] represents the equilibrium concentration in eggs given a rate of radionuclide ingestion in chicken feed. Data for this parameter is presented in units of (Bq/egg fw) per (Bq/day). However, elsewhere, and notably in IAEA (2010), the parameter is expressed on a mass basis, avoiding uncertainty about the mass of an individual egg.

It is recommended that transfer factors to eggs primarily be defined on a mass basis rather than on a per egg basis[12]. This ensures that the data is expressed in a format that is consistent with the way that the source data is typically expressed.

In Nagra (2003)[13], it was assumed that the average weight of an egg without shell is 48 g, and the weight of an egg with shell is 50-60 g, based on information from SVE (1993). In Brennwald and van Dorp (2008) a generic egg weight of 55 g/egg was assumed, based on SVB (2000). More recently, a mass of 60 g/egg has been used in verification of SwiBAC in conjunction with the food energy content of eggs to calculate an intake rate by humans.

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[11] The mathematical representation of the SwiBAC model refers to this parameter by K_{eggs}.

[12] This recommendation has been implemented in SwiBAC 1.2 (Walke & Keesmann 2013).

[13] Nagra (2003), p. 81, parameter 116.

The data presented in Table 10 as previous data are those from Nagra (2003), converted to (Bq/kg fw) per (Bq/day) using the 60 g/egg assumption mentioned above. The new data are reported directly on a (Bq/kg fw) per (Bq/day) basis.

The old and new values are given in Tab. 10, and are compared in Fig. 4.

Tab. 10: Transfer Factor from Feed to Eggs, [(Bq/kg fw) per (Bq/day)].

Element	**Previous**		**New**	**Notes**
	(Bq/egg) per (Bq/day)	(Bq/kg fw) per (Bq/day)	(Bq/kg fw) per (Bq/day)	
Be	1.00E-3	1.7E-2	5E-1	1
C	1.00E-1	1.7E+0	8E+0	2
Cl	1.00E+0	1.7E+1	2E+0	2
K	2.50E-2	4.2E-1	1E+0	3
Ca	1.60E-2	2.7E-1	4E-1	4
Co	5.00E-3	8.3E-2	3E-2	4
Ni	5.20E-2	8.7E-1	1E+0	2
Se	3.17E-1	5.3E+0	2E+1	4
Sr	1.60E-2	2.7E-1	4E-1	4
Zr	1.00E-4	1.7E-3	2E-4	4
Nb	6.00E-5	1.0E-3	1E-3	4
Mo	2.60E-2	4.3E-1	6E-1	4
Tc	9.80E-2	1.6E+0	1E-1	2
Pd	5.20E-2	8.7E-1	1E-2	2
Ag	5.00E-2	8.3E-1	8E-2	2
Sn	4.60E-2	7.7E-1	1E-1	5
I	4.17E-1	7.0E+0	2E+0	4
Cs	2.50E-2	4.2E-1	4E-1	4
Sm	5.00E-2	8.3E-1	3E-3	2
Eu	5.00E-2	8.3E-1	3E-3	2
Ho	5.00E-2	8.3E-1	3E-3	2
Pb	4.60E-2	7.7E-1	1E+0	2
Po	5.00E-5	8.3E-4	4E-1	6
Ra	7.22E-3	1.2E-1	4E-2	2
Ac	5.00E-2	8.3E-1	5E-3	2
Th	5.00E-2	8.3E-1	3E-3	7
Pa	5.00E-2	8.3E-1	1E-1	2
U	6.67E-2	1.1E+0	1E+0	4
Np	1.11E-3	1.9E-2	1E-2	2
Pu	3.90E-4	6.5E-3	1E-3	4
Am	4.40E-4	7.3E-3	3E-3	4
Cm	4.40E-4	7.3E-3	3E-3	8

Notes for Tab. 10:

1. Taken to be a value of 50 (10 to 100) times that of the meat transfer, in the absence of specific data. If the transfer factor scaled inversely with the mass of the animal (i.e. the retention function was the same across species), then the transfer factor would be a factor of 500 kg : 3 kg = 167 larger. However, in practice, retention is generally less in smaller animals. Allometric arguments based on metabolisable energy requirements suggest a ratio of masses to the power 0.75 (Lawrence and Fowler 2002)[14], thus giving a scale factor of 46 rather than 167. Given the uncertainties in this argument, a range of 10 to 100 seems plausible with a reference value of 50.
2. Table 20 of Walke et al. (2013).
3. The potassium content of tissues is homeostatically controlled at about 2 g/kg (ICRP 1975). Typical potassium concentrations in the diet of hens are 10 to 20 g/kg dry matter (Table 8.1 of Underwood and Suttle 2001). The dry mass intake by hens is around 0.1 kg dry matter/day, so the potassium intake is about 2 g/day. This implies that the required transfer factor is 2 g/kg / (15 $g/kg_{dm} \cdot 0.1\ kg_{dm}/day$) = 1.3 day/kg. A rounded value of 1.0 is recommended. This is consistent with, although slightly larger than, that for its analogue Cs.
4. Table 35 of IAEA (2010).
5. The biokinetics of Sn is similar across different animal species (Coughtrey et al. 1983) so allometric scaling should apply, consistent with note 1 above.
6. Table 35 of IAEA (2010) gives a value of 3.1 day/kg based on a single source. Po is quite well taken up from the gastrointestinal tract and uniformly distributed in soft tissues (Walke et al. 2012). However, a value of 3.1 day/kg reported in Table 35 of IAEA (2010) is based on only one measurement and is probably too large. The value would not be expected to be larger than that for Cs, which is also well absorbed and uniformly distributed in soft tissues. Therefore a value of 0.4 day/kg is recommended by analogy with Cs.
7. Walke et al. (2013) and Thorne (2008) use a value of 3E-2 day/kg based on consideration of an input to the development of IAEA (2010) which was not included in the final report or its supporting IAEA (2009). Therefore a value of 3E-3 day/kg is recommended here, based on the discussion in Section 2.17.3 of Thorne (2008), which is consistent with the values for Pu, Am and Cm, as would be expected.
8. Am and Cm are very similar biochemically, so the value for Am from Table 35 of IAEA (2010) is adopted.

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[14] Lawrence and Fowler (2002), p. 221, Section 11.7.

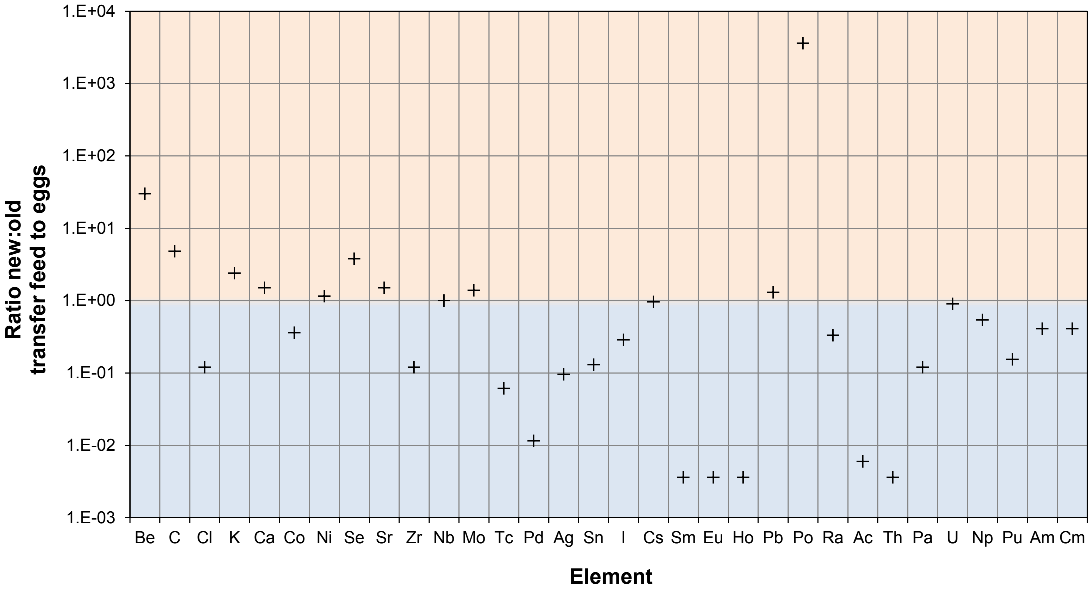

Fig. 4: Ratio New:Old of Transfer Factor from Feed to Eggs.

There are a number of elements for which the new recommendations differ from the previous values by more than an order of magnitude. For those elements with the largest changes in values, the sources of the old and new values are summarised in Tab. 11 below.

Tab. 11: Sources of Data for Certain Elements for Feed to Egg Transfer Factors.

Element	**Previous Source***	**New Source**	**Discussion**
Tc	Nagra (1985)	Reported in Table 20 of Walke et al. (2013), with reference to Thorne and Limer (2009).	Section 3.4 of Thorne and Limer (2009) includes a comprehensive evaluation of the available literature.
Pd	Nagra (1985)	Reported in Table 20 of Walke et al. (2013), with value an order of magnitude higher than beef.	The previous value is unreasonably high. The fractional gastrointestinal absorption of Pd is about 0.001 (Walke et al. 2012) and only a small fraction of that absorbed is retained in soft tissues.
Sm, Eu, Ho	Nagra (2003)	Reported in Table 20 of Walke et al. (2013) as using Ce for an analogue. Ce data from IAEA (2010).	The new values are consistent with values for higher actinides, which is as expected.
Po	Nagra (2003)	Based on consideration of the biokinetics of Po.	See footnote to Tab. 10.
Ac	Nagra (1985)	Reported in Table 20 of Walke et al. (2013), with use of Am and Cm as analogues, based on Thorne (2008).	The new value is consistent with values for higher actinides.
Th	Nagra (1985)	Based on biokinetic analysis in Section 4.15 of Thorne (2003), see footnote to Tab. 10.	The new value is consistent with values for higher actinides.

Note for Tab. 11:

* Based on source reference, if defined in Table 11-2 of Nagra (2003). Where no source is explicitly listed in Nagra (2003), the values are described in Nagra (2003) as being based on expert judgement and comparison with values in the literature.

2.8 Surface Water to Fish Transfer Factor

The surface water to fish transfer factor[15] represents the equilibrium concentration in edible fish tissues for a given radionuclide concentration in filtered freshwater. Data for this parameter is presented in units of (Bq/kg fw) per (Bq/m^3). The recommended parameter values are given in Tab. 12, with the ratio of the new to old values shown in Fig. 5. Unless otherwise stated, the data recommended are the geometric mean data for fish muscle presented in Table 57 of IAEA (2010).

Neither IAEA (2010) nor the supporting IAEA (2009) discuss whether the transfer factors relate to filtered or unfiltered water. Good experimental protocols use filtered water, however this is not always the case and the degree of filtration will vary between studies. The IAEA (2010) values are preferentially adopted in Tab. 12, based on the assumption that the review excluded studies that did not adopt good experimental protocols and that the data can therefore be taken to represent transfer factors relating to filtered water.

Tab. 12: Surface Water to Fish Transfer Factor, [(Bq/kg fw) per (Bq/m^3)].

Element	**Previous**	**New**	**Notes**
Be	2.0E-3	1E-2	1
C	5.0E+0	4E+2	2
Cl	5.0E-2	5E-2	2
K	1.0E+0	3E+0	2
Ca	3.0E-2	1E-2	2
Co	3.0E-1	8E-2	2
Ni	1.0E-1	2E-2	2
Se	2.0E-1	6E+0	2
Sr	3.0E-2	3E-3	2
Zr	2.0E-1	2E-2	2
Nb	1.0E-2	2E-2	3
Mo	2.0E-1	2E-3	2
Tc	1.5E-2	3E-2	4
Pd	1.0E-1	1E-1	4
Ag	5.0E-3	1E-1	2
Sn	3.0E+0	3E+0	4
I	5.0E-2	3E-2	2
Cs	1.0E+0	3E+0	2

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[15] The mathematical representation of the SwiBAC model refers to this parameter by K_{ff}.

Tab. 12: (continued)

Element	Previous	New	Notes
Sm	1.0E-1	1E-1	5
Eu	1.0E-1	1E-1	2
Ho	1.0E-1	1E-1	5
Pb	1.0E-1	3E-2	2
Po	5.0E-1	4E-2	2
Ra	1.5E-2	4E-3	2
Ac	1.0E-1	2E-1	6
Th	3.0E-2	6E-3	2
Pa	1.0E-2	2E-1	6
U	2.7E-3	1E-3	2
Np	1.5E-1	1E-2	4
Pu	5.0E-3	3E-2	7
Am	2.5E-2	2E-1	2
Cm	2.5E-2	2E-1	6

Notes for Tab. 12:

1. Based on analogy with Ca.
2. Table 57 of IAEA (2010).
3. Based on analogy with Zr.
4. Table 13 of Thorne (2007).
5. Based on analogy with Eu.
6. Based on analogy with Am.
7. Table 57 of IAEA (2010) gives a geometric mean of 21 m^3/kg, however, the value is completely inconsistent with that for other higher actinides and may well reflect an error in transcribing units. Thorne (2008) recommends a reference value of 0.03 m^3/kg (with a range from 0.001 to 1 m^3/kg) for Np, Pu, Am and Cm. A value of 0.03 is therefore recommended for Pu, based on Thorne (2008).

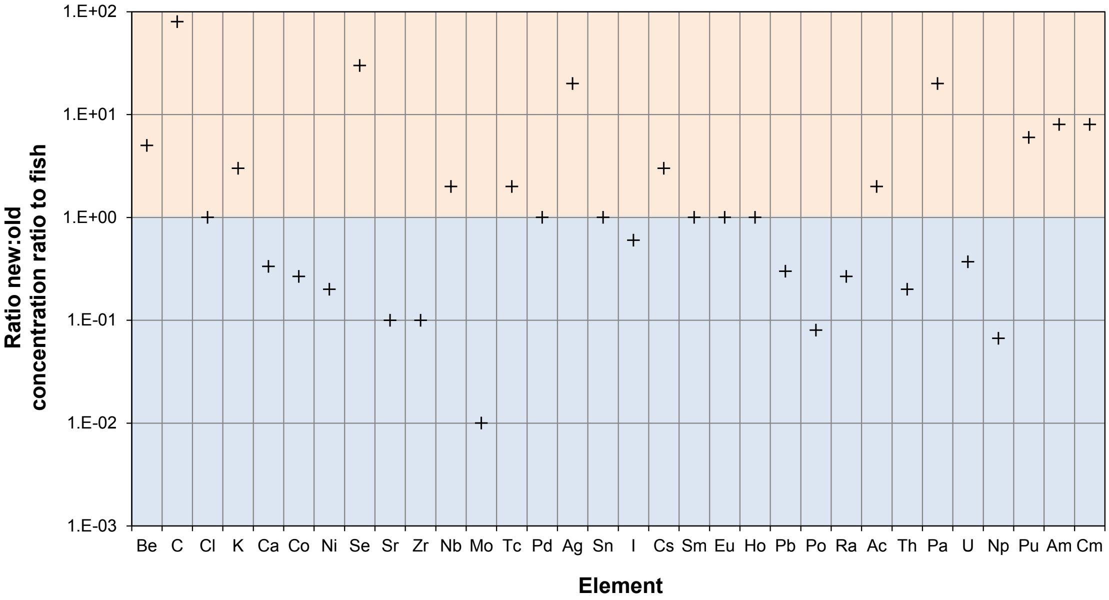

Fig. 5: Ratio of New:Old Surface Water to Fish Transfer Factors.

There are a number of elements for which the new recommendations differ from the previous values by more than an order of magnitude. It is noted that an increase in the transfer factor to fresh water fish might be expected if the previous values were based on data relating to unfiltered water. However, it is not possible to be definitive about these differences without tracing data back to the original source references, which is beyond the scope of the present study. For those elements with the largest changes in values, the sources of the old and new values are summarised in Tab. 13 below.

Tab. 13: Sources of Data for Certain Elements for Transfer Factor to Freshwater Fish.

Element	**Previous Source***	**New Source**	**Discussion**
C	Nagra (2003)	Table 57 of IAEA (2010)	Thorne (2008) suggests that consideration of the dissolution of CO_2 in water and the carbon content of aquatic organisms imply an upper bound value of 100 m^3/kg and recommends a value of 50 m^3/kg. However, the IAEA (2010) value is based on three studies, all of which give values greater than this. The IAEA (2010) value is therefore conservatively adopted, although further review is recommended if this is a key parameter.
Se	Nagra (1985)	Table 57 of IAEA (2010)	The new value is based on a reasonable number of samples (14) and is considered well-founded.
Mo	Unknown†	Table 57 of IAEA (2010)	The new value is based on a large number of samples (64) and is considered well-founded.

Notes for Tab. 13:

* Based on source reference, if defined in Table 11-2 of Nagra (2003). Where no source is explicitly listed in Nagra (2003), the values are described in Nagra (2003) as being based on expert judgement and comparison with values in the literature.

† A value of 2E-7 (Bq/kg fw) per (Bq/m^3) is given in Table 11-2 of Nagra (2003). A value of 2E-1 (Bq/kg fw) per (Bq/m^3) was used in the TAME calculations supporting Nagra (2010).

3 Results

Implications of the new recommendations for the BDCFs are explored in Section 3.1. The effect of explicitly representing translocation for grain is explored in Section 3.2.

3.1 Implications for Biosphere Dose Conversion Factors

Nagra (2010) presents the most recent set of biosphere dose conversion factors (BDCFs) for a 'Reference' ('Temperate') climate and a 'Warmer/Drier' climate; with the exception of the BDCF for C-14, which is updated in Nagra (2013).

Calculations with SwiBAC 1.1 have been undertaken with the new set of element-specific parameter values described in Section 2. The new BDCFs are compared against the previous set in Tab. 14 for both the 'Reference' and 'Warmer/Drier' variants and are compared graphically in Fig. 6.

In most cases the change in the BDCF resulting from updated parameter recommendations is relatively limited. For the 'Reference' climate:

- the BDCF increases for 20 radionuclides and decreases for 34 radionuclides;
- the new BDCFs are within a factor of two of the original values for 46 out of 54 radionuclides and within a factor of ten for 51 radionuclides.

The most significant changes are discussed in more detail below.

- The BDCF for Ca-41 increases by almost an order of magnitude, due to increases in the transfer factors from feed to milk and meat as well as increases in the transfer factors from soil to plant produce.
- The BDCF for Se-79 decreases by between a factor of 13 and 17 due to a reduction in the transfer factors from feed to meat and milk coupled with a reduction in the transfer factor from soil to pasture.
- The BDCF for Pa-231 decreases by between a factor of 23 and 26 due to decreases in the transfer factors from feed to animal produce for Pa-231 and its daughter Ac-227, as well as decreases in the transfer factors from soil to plant produce.
- The BDCF for U-235 decreases by between a factor of 11 and 13 due to decreases in the transfer factors from feed to animal produce for its daughters Pa-231 and Ac-227, which previously dominated the BDCF for U-235, along with decreases in their transfer factors from soil to plant produce.

The changes in the BDCF for C-14 since Nagra (2010) are shown in Tab. 15.

Tab. 14: Comparison of Biosphere Dose Conversion Factors, [Sv/Bq].

Radio-nuclide	**Reference Climate**			**Warmer/Drier Climate**		
	Previous	New	New:Previous	Previous	New	New:Previous
Be10	4.0E-16	5.9E-16	1.5	2.2E-15	4.4E-15	2.0
C14*	3.0E-15	3.7E-15	1.2	1.0E-14	1.2E-14	1.2
Cl36	7.0E-15	4.0E-15	0.56	8.5E-14	5.7E-14	0.67
K40	7.7E-15	7.9E-15	1.0	6.5E-14	6.8E-14	1.0
Ca41	3.3E-16	2.7E-15	8.2	4.6E-15	4.3E-14	9.5
Ni59	1.2E-16	1.3E-16	1.1	7.0E-16	7.6E-16	1.1
Co60	2.2E-17	2.0E-17	0.92	4.3E-17	3.9E-17	0.92
Ni63	4.3E-18	4.6E-18	1.1	7.7E-18	8.2E-18	1.1
Se79	6.6E-14	5.1E-15	0.077	7.6E-13	4.5E-14	0.059
Sr90	2.9E-15	2.2E-15	0.75	6.1E-15	4.2E-15	0.70
Mo93	2.8E-15	1.7E-15	0.60	3.5E-14	1.5E-14	0.41
Nb93m	1.0E-18	5.4E-19	0.54	1.7E-18	7.5E-19	0.45
Zr93	7.8E-15	1.1E-15	0.14	2.0E-14	2.3E-15	0.12
Nb94	1.6E-13	1.6E-13	0.99	1.2E-12	1.2E-12	0.99
Tc99	5.2E-14	2.8E-14	0.55	8.6E-13	4.8E-13	0.56
Pd107	7.7E-17	8.8E-17	1.1	4.8E-16	5.6E-16	1.2
Ag108m	7.9E-15	1.9E-15	0.24	7.0E-14	2.2E-14	0.31
Sn121m	1.3E-17	6.8E-18	0.53	2.4E-17	1.1E-17	0.46
Sn126	4.1E-13	3.9E-13	0.95	2.8E-12	2.6E-12	0.95
I129	2.0E-13	1.1E-13	0.58	1.9E-12	9.8E-13	0.51
Cs135	2.8E-14	2.5E-14	0.89	1.2E-13	1.0E-13	0.89
Cs137	1.3E-16	1.1E-16	0.87	2.4E-16	2.1E-16	0.86
Sm151	4.7E-19	1.5E-19	0.32	8.4E-19	2.2E-19	0.26
Ho166m	1.4E-14	1.3E-14	0.98	2.4E-14	2.3E-14	0.98
Eu154	2.9E-18	2.5E-18	0.87	5.6E-18	4.8E-18	0.86
Ra228	6.3E-15	6.4E-15	1.0	9.4E-15	9.6E-15	1.0
Th228	3.8E-18	3.6E-18	0.93	5.3E-18	4.8E-18	0.90
Th232	2.4E-11	2.4E-11	1.0	5.6E-11	5.6E-11	1.0
U232	9.9E-15	1.5E-14	1.5	1.7E-14	2.8E-14	1.6
U236	2.1E-14	3.9E-14	1.8	1.3E-13	3.3E-13	2.5
Pu240	1.8E-14	1.8E-14	0.96	2.7E-14	2.6E-14	0.96
Cm244	7.9E-17	7.5E-17	0.95	1.1E-16	1.1E-16	0.94
Th229	9.4E-14	1.1E-13	1.2	1.6E-13	1.9E-13	1.2
U233	4.5E-14	7.0E-14	1.6	3.4E-13	6.2E-13	1.8
Np237	3.4E-14	3.6E-14	1.1	2.0E-13	2.2E-13	1.1
Am241	1.0E-15	1.1E-15	1.1	1.3E-15	1.4E-15	1.1

Tab. 14: (continued)

Radio-nuclide	**Reference Climate**			**Warmer/Drier Climate**		
	Previous	New	New:Previous	Previous	New	New:Previous
Pu241	3.5E-17	3.6E-17	1.1	4.5E-17	4.9E-17	1.1
Cm245	4.9E-14	4.4E-14	0.90	8.0E-14	7.1E-14	0.88
Pb210	3.1E-15	3.0E-15	0.96	4.7E-15	4.5E-15	0.95
Po210	7.1E-18	7.1E-18	1.0	1.0E-17	1.0E-17	1.0
Ra226	2.8E-13	2.4E-13	0.87	1.7E-12	1.3E-12	0.81
Th230	3.3E-12	2.8E-12	0.87	2.6E-11	2.1E-11	0.81
U234	7.5E-14	8.6E-14	1.1	1.7E-12	1.6E-12	0.94
Pu238	2.5E-16	2.7E-16	1.1	8.8E-16	8.8E-16	1.0
U238	2.3E-14	4.1E-14	1.8	1.9E-13	3.9E-13	2.0
Am242m	4.2E-16	4.5E-16	1.1	7.1E-16	7.4E-16	1.1
Pu242	8.1E-14	7.2E-14	0.89	1.7E-13	1.5E-13	0.87
Cm246	1.4E-14	1.2E-14	0.85	2.3E-14	1.8E-14	0.82
Ac227	1.0E-15	3.3E-16	0.33	1.7E-15	4.2E-16	0.24
Pa231	1.4E-11	6.0E-13	0.043	3.0E-11	1.2E-12	0.038
U235	7.9E-13	7.2E-14	0.091	8.2E-12	6.5E-13	0.080
Pu239	4.6E-14	4.2E-14	0.91	7.9E-14	7.1E-14	0.90
Am243	4.3E-14	4.1E-14	0.95	7.5E-14	7.1E-14	0.95
Cm243	1.1E-16	1.1E-16	0.93	1.8E-16	1.6E-16	0.91

Notes for Tab. 14:

The 'previous' values are those presented in Nagra (2010), with the exception of C-14 (*), for which the 'previous' value reflects the update described in Nagra (2013). The ratio of the new to previous values is based on the calculated BDCFs prior to rounding to two significant figures.

Tab. 15: Changes in the Biosphere Dose Conversion Factor for C-14, [Sv/Bq].

Basis	**Reference**	**Warmer/Drier**
NAB 10-15 (Nagra 2010)	7.4E-16	9.6E-15
NAB 12-26 (Nagra 2013)	3.0E-15	1.0E-14
New BDCF	3.7E-15	1.2E-14

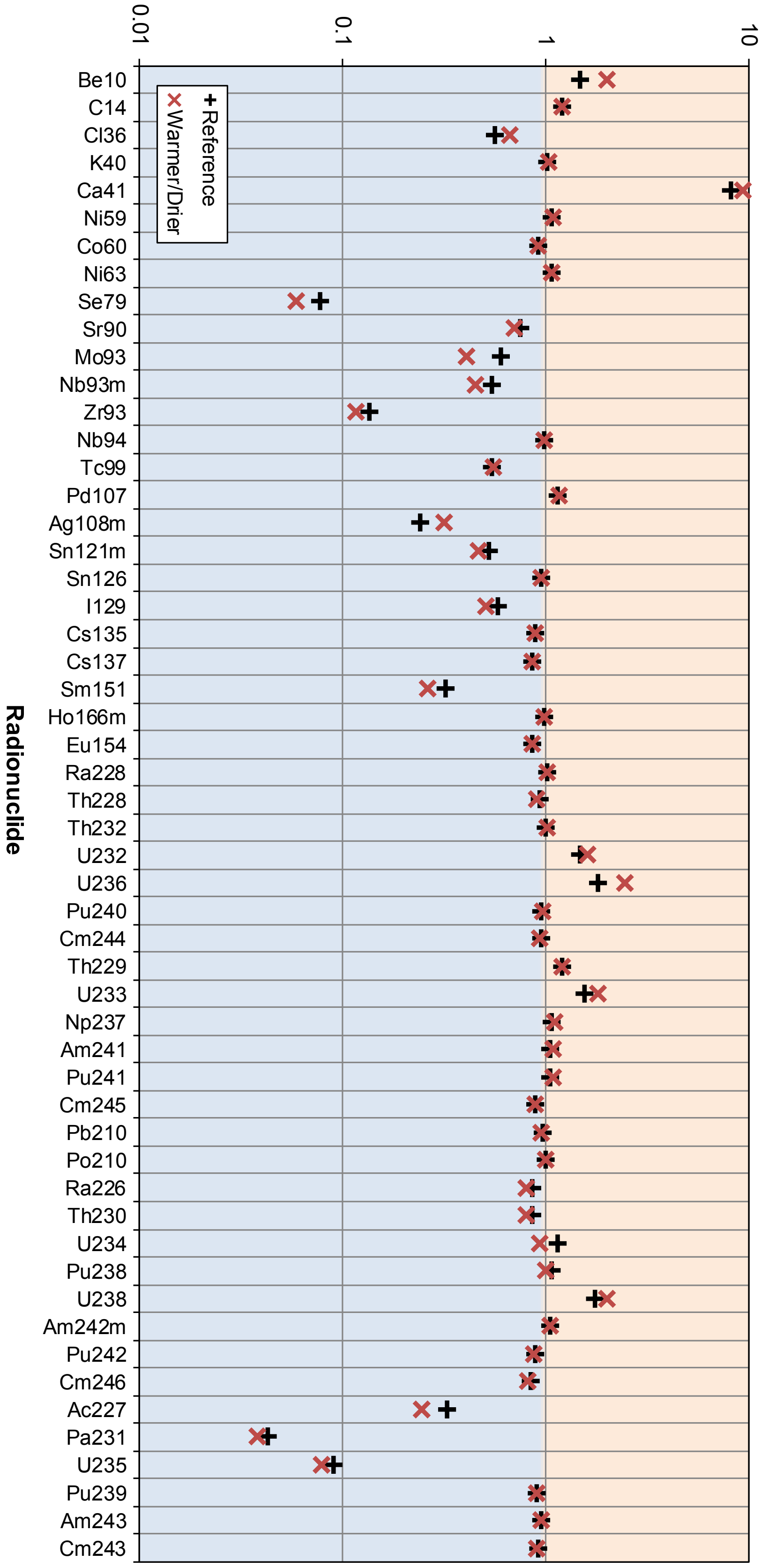

Fig. 6: Ratio of New Biosphere Dose Conversion Factors to the Previous Values for the 'Reference' and 'Warmer/Drier' Climate Cases.

3.2 Effect of Including Translocation for Grain on BDCFs

The mathematical model for SwiBAC includes the absorption and translocation of external contamination resulting from the interception of contaminated irrigation water to edible plant tissues. This translocated fraction is not subject to weathering.

The new data set explicitly represents translocation for grain, which was not previously included in the model. The effect of including translocation for grain on BDCF values has been explored by undertaking calculations with the updated data set, with and without translocation for grain (see Tab. 16). The table shows that including translocation for grain results in a relatively small increase (up to about 9.8%) in BDCF values.

Tab. 16: Comparison of BDCF values with and without Translocation from External Plant Contamination to Grain.

Radionuclide	**BDCF [Sv/Bq]**		**Ratio of BDCFs with translocation for grain to those without translocation for grain**
	With translocation for grain	**Without translocation for grain**	
Be10	5.9E-16	5.6E-16	1.07
C14	3.7E-15	3.7E-15	1.00
Cl36	4.0E-15	3.9E-15	1.01
K40	7.9E-15	7.7E-15	1.03
Ca41	2.7E-15	2.7E-15	1.00
Ni59	1.3E-16	1.3E-16	1.01
Co60	2.0E-17	2.0E-17	1.01
Ni63	4.6E-18	4.4E-18	1.04
Se79	5.1E-15	5.0E-15	1.02
Sr90	2.2E-15	2.1E-15	1.05
Mo93	1.7E-15	1.6E-15	1.07
Nb93m	5.4E-19	4.9E-19	1.10
Zr93	1.1E-15	9.9E-16	1.08
Nb94	1.6E-13	1.6E-13	1.00
Tc99	2.8E-14	2.8E-14	1.00
Pd107	8.8E-17	8.7E-17	1.01
Ag108m	1.9E-15	1.8E-15	1.04
Sn121m	6.8E-18	6.4E-18	1.06
Sn126	3.9E-13	3.9E-13	1.00
I129	1.1E-13	1.1E-13	1.03
Cs135	2.5E-14	2.5E-14	1.00
Cs137	1.1E-16	1.1E-16	1.02
Sm151	1.5E-19	1.5E-19	1.01
Ho166m	1.3E-14	1.3E-14	1.00
Eu154	2.5E-18	2.5E-18	1.00

Tab. 16: (continued)

Radionuclide	**BDCF [Sv/Bq]**		**Ratio of BDCFs with translocation for grain to those without translocation for grain**
	With translocation for grain	**Without translocation for grain**	
Ra228	6.4E-15	5.9E-15	1.08
Th228	3.6E-18	3.5E-18	1.01
Th232	2.4E-11	2.3E-11	1.07
U232	1.5E-14	1.4E-14	1.05
U236	3.9E-14	3.7E-14	1.04
Pu240	1.8E-14	1.7E-14	1.01
Cm244	7.5E-17	7.4E-17	1.01
Th229	1.1E-13	1.1E-13	1.00
U233	7.0E-14	6.9E-14	1.03
Np237	3.6E-14	3.6E-14	1.01
Am241	1.1E-15	1.1E-15	1.01
Pu241	3.6E-17	3.6E-17	1.01
Cm245	4.4E-14	4.4E-14	1.01
Pb210	3.0E-15	2.8E-15	1.08
Po210	7.1E-18	6.5E-18	1.09
Ra226	2.4E-13	2.3E-13	1.04
Th230	2.8E-12	2.7E-12	1.04
U234	8.6E-14	8.3E-14	1.04
Pu238	2.7E-16	2.7E-16	1.01
U238	4.1E-14	4.0E-14	1.04
Am242m	4.5E-16	4.4E-16	1.01
Pu242	7.2E-14	7.2E-14	1.01
Cm246	1.2E-14	1.2E-14	1.01
Ac227	3.3E-16	3.2E-16	1.01
Pa231	6.0E-13	6.0E-13	1.00
U235	7.2E-14	7.0E-14	1.02
Pu239	4.2E-14	4.2E-14	1.01
Am243	4.1E-14	4.1E-14	1.01
Cm243	1.1E-16	1.1E-16	1.01

The relatively small impact of translocation for grain is unexpected, given that interception is an important contributor to plant concentrations and grain is generally the dominant plant type. It arises due to the model for interception (given below) effectively assigning all of the intercepted activity to the edible part of the plants.

In SwiBAC, the radionuclide concentration on plant produce that remains in external contamination following interception of irrigation water, $C_{\substack{irrigation \\ interception}}$, is given by:

$$C_{\substack{irrigation \\ interception}} = \left(\frac{1 - e^{-\mu_{crop} Y_{crop}}}{Y_{crop} \left(W_{crop} + H_{crop} + T_{crop} \right)} \right) S_{irrigation} \qquad \text{[Bq/kg]} \qquad (3)$$

where:

μ_{crop}	is the interception factor for the crop	[m^2/kg];
Y_{crop}	is the yield of the crop	[kg fw/m];
W_{crop}	is the weathering loss term from the external surfaces of the crop	[/a];
H_{crop}	is the harvesting factor for the crop	[/a];
T_{crop}	is the translocation rate between intercepted contamination and internal edible portions of the crop; and	[/a]
$S_{irrigation}$	is the radionuclide source term to the crops in irrigation water	[Bq/m^2].

The associated input parameter values that are not dependent on element are given in Tab. 17.

Tab. 17: Input Parameters Associated with the Interception Model that are not Dependent on Element.

Parameter	**Crop**				**Notes**
	Grain	**Green Vegetables**	**Root Vegetables**	**Fruit**	
Yield of the crop, Y_{crop} [kg fw/m^2]	0.61	3.0	4.0	2.5	These values are representative of fresh weight crop yields, not standing biomass at the time of irrigation.
Interception factor for the crop, μ_{crop} [m^2/kg]	0.66	0.14	0.10	0.16	Yield is fresh weight, so units must be m^2/kg fw.
Harvesting factor for the crop, H_{crop} [/a]	1	2	1	1	Representative of the number of crops per year.

The loss from external plant surfaces due to absorption and translocation shown in Equation 3 is compensated for in the calculation of the effective dose due to consumptions of crops, D_{crops}:

$$D_{crops} = \sum_{crops} H_{ing} I_{crop} \left(C_{\substack{root \\ uptake}} + \left(f_{crop} + \frac{T_{crop}}{H_{crop}} \right) C_{\substack{irrigation \\ interception}} + f_{crop} C_{\substack{surface \\ contamination}} \right) \qquad \text{[Sv/a]} \qquad (4)$$

where:

H_{ing}	is the effective dose per unit intake via ingestion	[Sv/Bq];
I_{crop}	is the ingestion rate of crops on a fresh weight basis	[kg/a];
$C_{\substack{root\\uptake}}$	is the concentration in crops arising from root uptake	[Bq/kg fw];
f_{crop}	is the food processing factor (i.e. the fraction of external contamination that remains after food processing) for the edible crop; and	[-]
$C_{\substack{surface\\contamination}}$	is the concentration on crops arising from soil contamination	[Bq/kg fw].

The following observations can be made about the representation of interception in the SwiBAC model:

- The Chamberlain model (Chamberlain 1970) is used for interception, where the fraction intercepted is given by 1-exp($-\mu$ w) and where w is the above-ground standing biomass at the time of deposition (typically expressed on a dry weight basis).
- Above-ground standing biomass is equated to the crop yield in the justification for interception factors given against parameter number 124 in Nagra (2003).
- The model is parameterised to give an interception fraction of 0.33 for all crops based on expert judgement and referenced to Simmonds and Crick (1982).

As a result of these assumptions, all intercepted activity is assigned to the harvested crop. This means that the only difference made by including a translocation fraction for grain is to protect that additional small fraction from weathering losses, which explains the relatively small effect demonstrated in Tab. 16.

The model is appropriate to some green vegetables (e.g. cabbage), but is inappropriate for other green vegetables (e.g. beans), grain, root vegetables and fruit. For beans, grain and fruit, the harvested component (comprising the yield) accounts for some fraction of the total above-ground crop, so the model overestimates contamination of the edible part of the plants. For root vegetables, the model also overestimates plant concentrations because none of the contamination remaining on the outside of plants due to interception should be assigned to the edible roots.

It is also noted that it is inappropriate to equate the above-ground standing biomass at the time of irrigation to the yield of edible crops. However, the interception coefficient is back-calculated from a defined interception fraction. Although this results in unusual interception coefficients when compared to the literature, it means that the inappropriate use of crop yield has no impact on the SwiBAC results.

For these reasons, and the observation about food processing factors in Section 2.4, it is recommended that the model for interception be reviewed.

4 Conclusions

New parameter values are recommended for element-dependent biosphere parameters, excluding sorption coefficients. The new parameter values update the database used in support of Nagra's biosphere modelling, in particular, to take account of relatively recent compilation, review and recommendations co-ordinated by the IAEA. The updated parameter values are also more consistent with those used in biosphere models of other organisations responsible for radioactive waste disposal.

Transfer factors for Nagra's biosphere modelling were previously given to two or even three significant figures. The new recommendations are typically given to one significant figure, recognising the degree of uncertainty associated with the parameter values.

SwiBAC calculations undertaken with the changes described in this report implemented and with the new parameter recommendations show that, in most cases, BDCFs remain within a factor two of the previous values used by Nagra. The most significant changes are:

- an increase in the BDCF for Ca-41 by almost a factor of ten;
- a decrease in the BDCF for Se-79 by up to a factor of seventeen; and
- a decrease in the BDCFs for U-235 and Pa-231 by up to factors of thirteen and twenty six, respectively.

In addition to changes in parameter values, three further recommendations are made:

- The model for calculating radionuclide concentrations in plant produce resulting from interception of irrigation water should be reviewed, in particular to ensure that it appropriately represents the contribution of intercepted activity remaining on the external surfaces of the plants to radionuclide concentrations in food produce.
- Translocation of radionuclides from intercepted irrigation water to edible parts of the plant was previously defined by a rate. Updated values are defined, based on the fraction of intercepted activity that is absorbed and translocated to edible tissues. It is recommended that translocation be defined as a fraction, to be consistent with the input data without the need for conversion, which requires other model parameters.
- Transfer from animal feed to eggs was previously represented with a transfer factor expressed on a 'per egg' basis. The supporting data, including the recommendations of the IAEA, are almost exclusively represented on a mass basis. It is recommended that transfer factors from feed to eggs be expressed on a mass basis to be consistent with the available information without the need for conversion.

The latter two recommendations have been addressed in SwiBAC 1.2 (Walke & Keesmann 2013).

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