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Proposal for new best estimates of the soil-to-plant transfer factor of U, Th, Ra, Pb and Po

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ABSTRACT

There is increasing interest in radiological assessment of discharges of naturally occurring radionuclides into the terrestrial environment. Such assessments require parameter values for the pathways considered in predictive models. An important pathway for human exposure is via ingestion of food crops and animal products. One of the key parameters in environmental assessment is therefore the soil-to-plant transfer factor to food and fodder crops. The objective of this study was to compile data, based on an extensive literature survey, concerning soil-to-plant transfer factors for uranium, thorium, radium, lead, and polonium. Transfer factor estimates were presented for major crop groups (Cereals, Leafy vegetables, Non-leafy vegetables, Root crops, Tubers, Fruits, Herbs, Pastures/grasses, Fodder), and also for some compartments within crop groups. Transfer factors were also calculated per soil group, as defined by their texture and organic matter content (Sand, Loam, Clay and Organic), and evaluation of transfer factors' dependency on specific soil characteristics was performed following regression analysis. The derived estimates were compared with estimates currently in use.

1. Introduction

The transfer of artificial radionuclides along terrestrial food chains has been studied extensively during the last 40 years. The natural radionuclides U and Th have received less research attention than many artificial radionuclides, despite being naturally ubiquitous in the environment. There has been increasing interest in radiological assessments of the discharges of naturally occurring radionuclides in the terrestrial environment, both in terms of current releases from industrial sites as from the presence of historical contaminations.

Apart from the obvious presence of naturally occurring radionuclides (NORs) in uranium deposits, a wide range of uranium- and thorium-bearing minerals (and their daughters) are being mined and processed commercially. In most minerals, natural levels of radionuclides are very low. In others, e.g. zircon and rare earths the concentration of ^{238}U and ^{232}Th may be considerably elevated, with activities up to 40 and 70 kBq kg^{-1} for thorium and uranium, respectively. Enhanced levels of NORs may be associated with abandoned waste dumps, installations and surroundings from certain industries, which have involved extraction or processing of raw materials containing NORs. This can result in considerable exposure to the public. The most prominent examples in Europe, apart from the residues of uranium mining and milling, are the waste generated by the phosphate processing industry, the scales from the oil and gas extraction industry, the ashes from coal-based power production, and the slag produced by the metal mining and smelting industry (Vandenhove et al., 2000; IAEA, 2003).

The processes by which radionuclides can be incorporated into vegetation can either be (1) through activity interception by external plant surfaces (either directly from the atmosphere or from resuspended material), or (2) through uptake of radionuclides via the root system. For this compilation, we intended to assemble data restricted to soil-to-plant transfer. The soil-to-plant transfer factor (TF) is defined as the ratio of the concentrations of radionuclides in plant (Bq kg^{-1} dry mass) to that in soil (Bq kg^{-1} dry mass).

The primary objectives of this review were (1) to compile published information on the soil-to-plant transfer factor of U, Th, ^{226}Ra, ^{210}Po, ^{210}Pb; (2) to carry out a critical review of the data in

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terms of their quality and usefulness; (3) to propose new estimates for transfer factors (TF) for use in terrestrial food chain models; (4) to compare the values derived with previous estimates; and finally (5) to evaluate the dependency of the TF on specific soil and plant characteristics.

This study is carried out in the framework of the activities of a Working Group addressing the current revision of the *Handbook of Parameters Values for the Prediction of Radionuclide Transfer in Temperate Environments – TRS 364* (IAEA, 1994).

2. Data collection and treatment

2.1. Data collection and data acceptance

Literature collection consisted of peer-reviewed publications as well as reports. A total of about 200 references were consulted, and of these 104 were retained. Each reference was critically reviewed and data were retained/excluded based on the following criteria:

- Only individual data from matching crop–soil combinations were retained, with summary data from reviews being excluded;
- Experimental results had to be clear and concise. Clear information on sample collection and preparation was required and if there was any doubt whether concentration in crops (or TF) was expressed relative to fresh or dry mass, data were not considered;
- Information on TF was only included if there was clear indication of which plant compartment was sampled and analyzed;
- The minimal soil information required for associated TF data to be entered was the concentration of radionuclides in the soil and the type of contamination. If soil concentrations were expressed on wet weight basis (and no information available on soil water content to calculated concentrations per dry mass) or if contaminant level was expressed as available fraction, TF data were not included;
- Data from areas with high natural radioactivity were included, except when it concerned specific substrates (non-soils) (e.g. uranium tailings, red mud, phosphogypsum);
- Data from pot experiments were included, independent of pot size.

In addition to TF data, information was collected on, e.g. climate and experimental conditions, contamination history and contaminant concentration, soil type, soil characteristics (pH, sand and clay content, organic matter content, cation exchange capacity, exchangeable Ca and Mg and soil solution concentrations of Ca^{2+} and $Mg^{2+}$and amorphous iron content) and plant characteristics (Ca, Mg, K content, yield) in order to evaluate the possible dependence of the TF on these properties. In cases where the TF or plant concentrations were expressed relative to fresh weight, the fresh weight/dry weight conversion coefficient was applied (IAEA, in preparation). Soil adhering to roots or leaves has the potential to carry NORM to the food chain. Most articles did not include information if the food products were washed or peeled, which may be an additional source of variability.

2.2. Data treatment and statistical analysis

The TF values were grouped according to two criteria (1) crop groups and (2), if sufficient data were available, plant group/soil texture. Plants were grouped in several crop groups as agreed by the EMRAS TRS-364 working group. Crop plant groups included the following: Cereals were considered in one category – All cereals – and as two separate groups, Cereals (e.g. wheat, barley, rye) and Maize because maize grain is more than the other cereal grains used as animal feed. TF data for rice were not included in the Cereal data. The other groups consist of: Leafy vegetables (e.g. lettuce, spinach, Chinese cabbage, Brussels sprouts), Non-leafy vegetables (e.g. tomato, cucumber, egg plant), Legumes (e.g. peas, beans), Root crops (e.g. carrot, radish, turnip), Tubers (e.g. potatoes), Fruit (e.g. apple, pear, berries), Herbs (e.g. mustard, parsley), Other crops (e.g. sunflower seeds, tea leaves), Grasses (single species), Natural pastures, Leguminous fodder (e.g. alfalfa, clover). Additionally, TF to non-edible plant parts (e.g. straw, shoots of root crops, shoots of legumes) were recorded. TF was also calculated for more global crop groups: "Fodder" comprising leguminous pasture species (like clover), straw from Cereals and Maize and shoots of Non-leafy vegetables, Root crops, Tubers; "Pastures/grasses" comprising TF data to Natural pastures and grasses.

Where sufficiency of data allowed, TFs were also calculated based on the plant group/soil texture criterion. Soils were grouped according to the percentages of sand, clay contents and organic matter. A soil was included in the Organic group if the organic matter content was $\geq$20%. For mineral soils, three groups were created according to the following criteria: Sand group: sand fraction $\geq$ 65%; clay fraction $<$ 18%; Clay group: clay fraction $\geq$ 35%; Loam group: mineral soils not fitting above criteria.

It could be argued that in the analysis of the soil-to-plant TF for the long-lived natural radionuclides U, Ra and Th the dependency of the TF on the soil concentration should be considered. Sheppard and Sheppard (1985) and Sheppard and Evenden (1988a) reported a log-normal dependency of TF-U on soil concentration. On the other hand, Blanco et al. (2002) did not find a relation between TF-U and soil concentration. For this compilation, covering a broad range of soil concentrations (7–250,000 Bq kg^{-1} for U, 4–60,000 Bq kg^{-1} for Ra and 4–89,000 Bq kg^{-1} for Th), different soil groups and crop groups and experimental conditions, no relation between TF or log TF and the soil concentration was found ($R^2 < 0.01$). However, it should be born in mind that non-linearity can contribute to the uncertainty in the TF.

For all crop groups considered, the following dataset descriptors were calculated: geometric mean (GM); geometric standard deviation (GSD); arithmetical mean (AM), standard deviation (SD), minimum (min) and maximum (max) values. GM and GSD are preferred to AM and SD since TF values are generally log-normally distributed. GM and GSD were only calculated when the number of observations was $\geq$3 for each crop group. The number of observations is also given. The above descriptors were also calculated per soil group (Clay, Loam, Sand, Organic) if at least 10 entries were available for that crop group. Discussion of data always refers to GM (GSD), unless specified differently. GM (GSD) and AM (SD) were clearly different. Overall, the value derived for AM is 3 to 5-fold higher than the value derived for GM.

Statistical analysis of data was performed with the statistical software packages *Statistica for Windows* (Statsoft, 2004). Outlier analysis was performed using box–whisker plots. A value was defined an outlier if it was over 1.5-times the interquartile range (for the log-transformed data). Normality of the dataset was evaluated with the Shapiro Wilk's test and the Kolmogorov–Smirnov test for normality. Only log-transformed datasets were normally distributed. Ratio data, as the TF, tend to be log-normal based on the central Limit Theorem. Normal distribution could not be verified if the number of data within a crop group was too small (e.g. 3). Log TF data were also normally distributed within a broad soil category [e.g. log TF data obtained for all crop groups for a specific soil category (e.g. Sand)] or crop category (e.g. log TF data obtained irrespective of soil type for a specific crop group e.g. All Cereals). As such the conditions were fullfilled to calculate GM and GSD and perform comparisons between groups with ANOVA. Mean values were ranked by Tukey's multiple range tests when more than two

Table 1
Uranium soil-to-plant transfer factor (kg kg^{-1} DW) for crop groups, crop compartments and crop/soil combinations. Number of entries (*N*), geometric mean (GM), geometric standard deviation (GSD); arithmetical mean (AM), standard deviation (SD), minimum (Min) and maximum (Max) values and number of references from which entries were extracted (# Ref).

Plant group	Plant Compartment	Soil	*N*	GM	GSD	AM	SD	Min	Max	# Ref
All			781	2.27E-02	9.10E+00	2.10E-01	9.12E-01	3.00E-05	1.37E+01	57
Cereals	Grain	All	59	6.18E-03	7.67E+00	4.98E-02	1.44E-01	1.60E-04	8.24E-01	16
		Sand	6	8.90E-03	1.11E+01	2.84E-02	2.46E-02	1.94E-04	6.20E-02	3
		Loam	20	7.72E-03	5.10E+00	1.79E-02	1.87E-02	1.60E-04	6.20E-02	7
		Clay	11	3.80E-03	3.98E+00	9.40E-03	1.49E-02	7.61E-04	5.00E-02	4
	Straw	All	55	2.72E-02	7.53E+00	1.43E-01	4.82E-01	3.00E-05	3.50E+00	13
		Sand	6	3.41E-02	5.96E+00	7.51E-02	6.52E-02	2.10E-03	1.68E-01	3
		Loam	25	5.39E-02	6.30E+00	2.47E-01	7.02E-01	7.43E-04	3.50E+00	7
		Clay	8	1.02E-02	3.55E+00	2.30E-02	3.44E-02	2.80E-03	9.80E-02	2
Maize	Grain	All	9	1.47E-02	1.19E+01	1.21E-01	2.34E-01	5.04E-04	7.11E-01	5
	Straw	All	11	7.81E-03	1.41E+01	1.12E-01	2.87E-01	1.64E-04	9.64E-01	6
Leafy vegetables		All	108	1.97E-02	7.26E+00	2.21E-01	1.14E+00	7.84E-05	8.82E+00	15
		a Sand	7	1.72E-01	1.46E+01	1.48E+00	3.25E+00	1.54E-03	8.82E+00	2
		a Loam	14	4.26E-02	3.92E+00	8.71E-02	8.80E-02	7.65E-03	2.66E-01	3
		b Clay	9	3.55E-03	4.19E+00	1.01E-02	1.61E-02	7.63E-04	4.31E-02	3
		Peat	6	1.82E-01	9.69E+00	1.46E+00	3.21E+00	7.90E-03	8.02E+00	2
Non-leafy vegetables	Fruits	All	38	1.45E-02	4.24E+00	3.57E-02	5.27E-02	5.23E-04	2.03E-01	10
		Sand	7	1.91E-02	5.49E+00	4.88E-02	5.95E-02	1.30E-03	1.64E-01	2
		Loam	4	2.34E-02	2.22E+00	2.84E-02	1.68E-02	7.63E-03	4.74E-02	2
		Clay	7	1.80E-02	4.20E+00	4.77E-02	7.44E-02	5.00E-03	2.03E-01	2
	Shoots	All	6	5.30E-02	9.88E+00	2.57E-01	3.49E-01	4.25E-03	7.05E-01	4
Legumes	Pods	All	19	2.23E-03	1.19E+01	2.23E-02	4.55E-02	5.40E-05	1.53E-01	10
		Loam	4	3.01E-03	1.81E+01	1.51E-02	2.19E-02	5.40E-05	4.74E-02	3
		Clay	7	5.49E-04	4.73E+00	1.38E-03	1.89E-03	5.68E-05	5.00E-03	3
	Shoots	All	21	6.39E-02	1.44E+01	8.35E-01	2.04E+00	7.38E-04	8.69E+00	11
		Sand	6	2.76E-01	1.98E+01	2.39E+00	3.51E+00	5.26E-03	8.69E+00	4
		Loam	6	1.21E-02	6.23E+00	3.48E-02	5.14E-02	7.38E-04	1.37E-01	5
Root crops	Roots	All	46	8.43E-03	6.23E+00	3.61E-02	6.50E-02	4.91E-04	2.63E-01	16
		Sand	9	7.78E-03	5.86E+00	3.78E-02	7.64E-02	9.90E-04	2.30E-01	6
		Loam	10	2.54E-02	3.22E+00	4.28E-02	4.29E-02	2.57E-03	1.24E-01	4
		Clay	5	6.77E-03	6.15E+00	2.30E-02	3.89E-02	7.86E-04	9.20E-02	4
	Shoots	All	37	2.83E-02	5.35E+00	9.54E-02	1.64E-01	2.00E-03	7.02E-01	12
		Sand	9	2.48E-02	5.60E+00	6.69E-02	8.32E-02	2.04E-03	2.37E-01	5
		Loam	11	4.97E-02	2.99E+00	8.56E-02	9.83E-02	1.30E-02	3.21E-01	3
		Clay	5	1.11E-02	4.28E+00	2.16E-02	2.27E-02	2.00E-03	5.80E-02	3
Tubers	Tubers	All	28	5.01E-03	6.37E+00	1.74E-02	2.38E-02	1.75E-04	7.96E-02	11
		a Sand	4	1.88E-02	3.83E+00	3.33E-02	3.42E-02	4.26E-03	7.80E-02	3
		a Loam	3	2.78E-02	3.16E+00	4.03E-02	3.63E-02	8.15E-03	7.96E-02	3
		b Clay	6	9.22E-04	2.95E+00	1.48E-03	1.68E-03	1.90E-04	4.78E-03	3
	Shoots	All	1	1.93E-01	1.00E+00	1.93E-01	0.00E+00	1.93E-01	1.93E-01	1
Fruit	Fruits	All	11	1.20E-02	5.88E+00	5.72E-02	1.15E-01	1.29E-03	3.73E-01	5
	Leaves	All	66	3.48E-01	3.64E+00	6.72E-01	1.10E+00	3.59E-04	7.46E+00	3
Herbs		All	9	3.59E-02	4.86E+00	1.09E-01	1.56E-01	8.55E-03	4.14E-01	4
Other	Leaves (sunflower)	All	39	7.11E-02	3.86E+00	3.12E-01	1.24E+00	8.92E-03	7.82E+00	3
		a Sand	5	4.11E-01	5.25E+00	1.72E+00	3.41E+00	1.62E-01	7.82E+00	2
		b Loam	22	7.05E-02	2.90E+00	1.20E-01	1.43E-01	1.02E-02	6.41E-01	2
		b Clay	11	2.73E-02	2.06E+00	3.48E-02	2.76E-02	8.92E-03	9.96E-02	1
	Grain (sunflower)	All	2	1.54E-02	2.42E+00	1.85E-02	1.46E-02	8.24E-03	2.88E-02	1
Grass		All	147	1.74E-02	9.37E+00	1.22E-01	4.92E-01	2.02E-04	5.54E+00	18
		Sand	19	1.55E-02	1.70E+01	2.50E-01	4.96E-01	5.54E-04	1.75E+00	5
		Loam	34	9.79E-03	8.43E+00	5.51E-02	1.01E-01	3.07E-04	4.56E-01	5
Natural pastures		All	53	4.75E-02	5.33E+00	4.18E-01	1.96E+00	1.33E-03	1.37E+01	9
		Sand	3	2.70E-03	1.84E+00	3.01E-03	1.45E-03	1.33E-03	3.92E-03	1
		Loam	7	7.21E-02	3.34E+01	2.65E+00	5.16E+00	1.79E-03	1.37E+01	3
Leguminous fodder		All	15	1.45E-02	4.17E+00	1.15E-01	4.00E-01	2.00E-03	1.56E+00	4
		Sand	12	9.97E-03	1.96E+00	1.18E-02	5.93E-03	2.00E-03	2.10E-02	1
All cereals		All	69	6.02E-03	7.97E+00	5.37E-02	1.67E-01	1.60E-04	9.64E-01	19
		Sand	7	5.21E-03	1.37E+01	2.43E-02	2.48E-02	1.94E-04	6.20E-02	5
		Loam	22	7.69E-03	4.78E+00	1.71E-02	1.81E-02	1.60E-04	6.20E-02	9
		Clay	15	3.53E-03	4.84E+00	1.01E-02	1.54E-02	1.64E-04	5.00E-02	3
Pastures/grasses		All	200	2.26E-02	8.50E+00	1.99E-01	1.09E+00	2.02E-04	1.37E+01	29
		Sand	22	1.22E-02	1.49E+01	2.17E-01	4.67E-01	5.54E-04	1.75E+00	4
		Loam	41	1.38E-02	1.16E+01	4.86E-01	2.21E+00	3.07E-04	1.37E+01	8

(*continued on next page*)

Table 1 (*continued*)

Plant group	Plant Compartment	Soil	*N*	GM	GSD	AM	SD	Min	Max	# Ref
Fodder		All	251	6.37E-02	7.96E+00	3.63E-01	1.01E+00	3.00E-05	8.69E+00	26
		ab Sand	42	3.09E-02	9.86E+00	5.75E-01	1.87E+00	5.04E-04	8.69E+00	9
		a Loam	69	4.74E-02	4.97E+00	1.65E-01	4.66E-01	7.38E-04	3.50E+00	12
		b Clay	29	1.58E-02	2.85E+00	2.56E-02	2.66E-02	2.00E-03	9.96E-02	8
		a Organic	5	2.19E-01	4.70E+00	3.56E-01	2.04E-01	1.40E-02	5.07E-01	2

If significant differences in TF (GM) between soil types within one plant group occur, TFs are given as different letters.

groups were compared with ANOVA and TFs were considered to be significantly different between crop group or soil types when $p \leq 0.05$. Single parameter regression analysis was performed with Statsoft (2004). Marked correlations are significant at $p < 0.05$ level, unless otherwise mentioned.

Statistical analysis results, except for Descriptive Statistics, were only presented for the log-transformed data since the non-transformed dataset was not normally distributed and no significant differences or significant correlations were found.

3. Description of ranges of TF values: derivation of TF best estimates

3.1. Uranium

Table 1 gives the TF-U estimates for selected crop groups. A total of 781 observations were retained from 57 references. A fully generic TF-U value of 2.27×10^{-2} (GSD 9.1) kg kg^{-1} was derived. Fodder, Pastures/grasses, and Herbs showed the highest TF-U (2.3–6.5 $\times 10^{-2}$ kg kg^{-1}), and Legumes, Cereals and Tubers had the lowest TF-U (2.2–6.2 $\times 10^{-3}$ kg kg^{-1}). TF-U values differed between crop groups by a factor of 10 as was the case in the TF-U best estimates tabulated by IAEA (1994). TF to grain was higher for Maize than for other Cereals. Derived TF-U values were not always significantly different between crop groups (Fig. 1A), with typical ranges within a crop group being 1–5 orders of magnitude. Experimental and climate conditions and contamination history did not significantly affect TF-U.

Comparing present derived values with currently used parameter values, estimates by IAEA (1994) ($N = 61$) were (in kg kg^{-1}): 1.3×10^{-3} for Cereals, 8.3×10^{-3} for Green vegetables, 1.4×10^{-2} for Root crops, 1.1×10^{-2} for potatoes and 2.3×10^{-2} for Grasses. Except for Cereals where a factor 5 difference in estimates is observed, differences in estimates are within a factor 2. Most data used to derive the IAEA (1994) estimates were also included in present compilation.

The TF-U values used in the FARMLAND model (Brown and Simmonds, 1995) are comparable for Cereals, Root crops and Tubers (peeled potatoes). Estimates by Brown and Simmonds (1995) were 2-fold higher for leafy vegetables, 6-fold higher for Pastures, and 4-fold lower for Legumes. Ewers et al. (2003), reviewing transfer data of naturally occurring radionuclides in terms of their applicability to the UK, derived about two times lower values for Cereals, Tubers (peeled potatoes) and Legumes, about 3-fold higher values for Roots and Pastures, and 6-fold higher values for Green vegetables. Sheppard et al. (2005a, 2006) suggested the following TF-U (in kg kg^{-1}; GSD and N between brackets): 3×10^{-3} (8.7, 55) for Cereals, 4.5×10^{-3} (5.0, 81) for Vegetables, 6×10^{-3} (6.2, 64) for Root crops, 2.1×10^{-3} (4.1, 36) for Fruits, berries and nuts, and 1.0×10^{-2} (5.8, 104) for Forages. These derived values are 2 to 6-fold lower than our values. They observed a near 2-fold difference in TF-U for food crops (4.1×10^{-3} kg kg^{-1}, GSD 6.2) and Native browse and forage (9.4×10^{-3} kg kg^{-1}, GSD 8). Based on the present compilation there was no significant difference in TF to food and fodder crops since for example, Leafy vegetables, Non-leafy vegetables, and Fruits, showed an equally high TF-U as forage. Sheppard et al. (2006) obtained an overall geometric mean (7.1×10^{-3} kg kg^{-1}, GSD 6, $N = 502$) that was 3 times lower than our value and they proposed a generic TF-U estimate of 8×10^{-3} kg kg^{-1}.

In order to allow for practitioners of assessment models to appraise the dependency of the TF on global soil characteristics, Table 2 gives TF-U values for soils grouped according to the texture/OM criterion. Generally it is reported that the TF-U values decrease from sandy-loamy-clay soils (Mortvedt, 1994; Sheppard and Evenden, 1988b). In the present study we did find the highest TF-U for Sand and Loam soils, and the lowest for Clay soils (Table 2). The presence of organic matter is reported to decrease the TF-U (Sheppard et al., 1983; Mortvedt, 1994; Ramaswami et al., 2001). However, in present compilation, the highest TF-U was derived for Organic soils. Organic matter may also enhance U availability due to the formation of soluble U-organic compound complexes (e.g. due to the presence of fulvic acid). It should also be noted that a low number of records were entered for organic soils compared to other soils. Significant differences were observed in TF based on texture/OM criterion only for a few crop groups (Table 1). For Fodder, Organic soils showed the highest TF-U, followed by Sand. For Leafy vegetables, Tubers and Other crops, the lowest TF-U was observed for Sand soils.

No significant correlations (overall or per crop group) were found between single soil parameters (pH, CEC, OM or clay content, Amorphous Fe) and TF-U. In earlier compilations, the effect of soil type or soil characteristics was not evaluated.

3.2. Thorium

Thorium is a rather immobile element. The generic GM for TF-Th derived is 3.5×10^{-3} (GSD 15) kg kg^{-1} (6 orders of magnitude range) (Table 3) and is, on the average 10-fold lower than the generic GM for the TF of U, Ra and Pb and comparable to the generic GM derived for Po.

The highest TF-Th values were found for Pastures/grasses (5.7×10^{-2} kg kg^{-1}), followed by Fodder and Fruits ($\sim 5.0 \times 10^{-3}$ kg kg^{-1}), while for Tubers the lowest TF-Th (2.0×10^{-4} kg kg^{-1}) was observed. Variation within a crop group is substantial, with ranges covering 2–4 orders of magnitude. Very few significant differences were observed in derived TF-Th values (Fig. 1B). Recorded TF-Th for Maize were about two orders of magnitude lower than for the other cereals (Table 3). TF-Th to Cereal or Maize straw is a factor two higher than to the related grains. Experimental conditions, climate and contamination history, did not significantly affect the observed TF-Th.

IAEA (1994) presented TF-Th from the Frissel and Van Bergeijk (1989) compilation ($N = 69$, all included in present compilation). Values proposed by IAEA (1994) were 3.4×10^{-5} kg kg^{-1} for Cereals (maize), 1.8×10^{-3} kg kg^{-1} for Green vegetables, 1.2×10^{-4} kg kg^{-1} for Legumes, 5×10^{-3} kg kg^{-1} for Root crops, 5.6×10^{-5} kg kg^{-1} for Tubers, 1.1×10^{-2} kg kg^{-1} for Grasses, and 7.5×10^{-3} kg kg^{-1} for Fodder (maize). Values differ from 4-fold lower values (Maize fodder) to 4-fold higher values (Legumes, Tubers, Grasses). Brown and Simmonds (1995) proposed the following default TF-Th values in the FARMLAND assessment model 6×10^{-4} kg kg^{-1} for Cereals, 4×10^{-3} kg kg^{-1} for Brassicaceae (considered Leafy Vegetables), 5×10^{-3} kg kg^{-1} for Root crops, 2.5×10^{-3} kg kg^{-1} for peeled potato

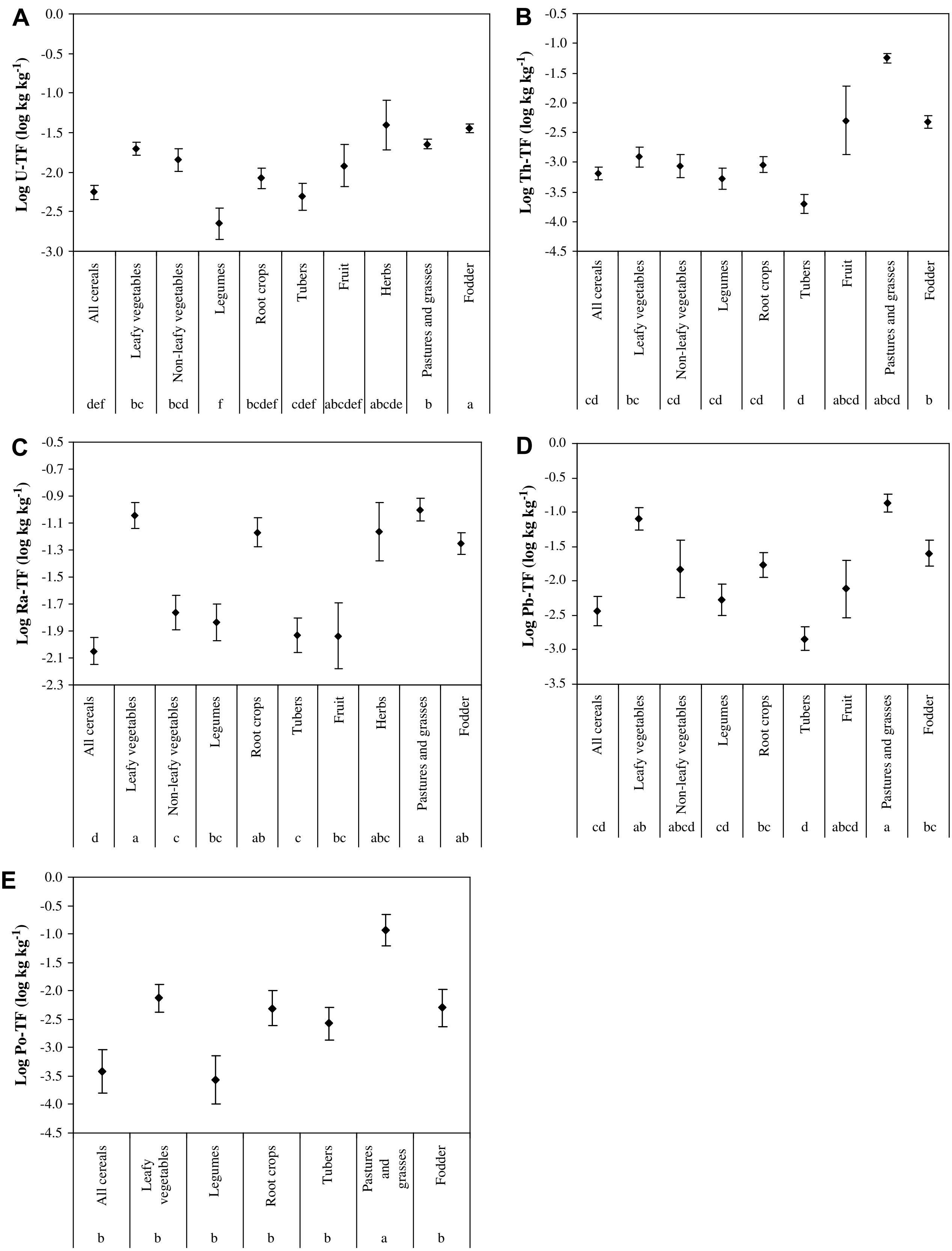

Fig. 1. Logarithm of the U (A), Th (B), Ra (C), Pb(D) and Po (E) soil-to-plant TF [log TF, log (kg kg^{-1})] for the different broad crop groups. Error bars denote residual SE after analysis of variance accounting for the effect of plant type. TF for crops groups assigned the same letter are not significantly different ($p < 0.05$).

Table 2
Transfer factors (kg kg^{-1} DW) for U, Th, Ra and Pb in function of soils grouped according to the texture/OM criterion. Number of entries (*N*), geometric mean (GM), geometric standard deviation (GSD); arithmetical mean (AM), standard deviation (SD), minimum (Min) and maximum (Max) values and number of references from which entries were extracted (# Ref).

	Soil	N	GM	GSD	AM	SD	Min	Max
U	b Sand	105	1.90E-02	1.08E+01	3.84E-01	1.47E+00	1.94E-04	8.82E+00
	ab Loam	173	2.46E-02	7.05E+00	2.03E-01	1.13E+00	5.40E-05	1.37E+01
	c Clay	79	5.65E-03	5.59E+00	1.84E-02	3.16E-02	5.68E-05	2.03E-01
	a Organic	14	9.68E-02	9.23E+00	7.56E-01	2.10E+00	2.30E-03	8.02E+00
Th	a Sand	15	3.18E-03	7.55E+00	1.19E-02	2.37E-02	2.02E-05	9.50E-02
	a Loam	118	1.45E-03	6.62E+00	4.87E-03	7.79E-03	8.21E-06	5.30E-02
	b Clay	83	4.26E-04	1.09E+01	9.17E-03	5.32E-02	1.24E-06	4.78E-01
	ab Organic	11	7.01E-04	4.47E+00	1.42E-03	1.30E-03	8.00E-05	4.00E-03
Ra	a Sand	50	4.39E-02	7.88E+00	1.89E-01	3.13E-01	6.00E-04	1.57E+00
	a Loam	127	4.29E-02	7.54E+00	1.46E-01	2.24E-01	1.09E-05	1.49E+00
	b Clay	140	1.71E-02	6.65E+00	1.03E-01	3.43E-01	1.18E-04	3.31E+00
	ab Organic	21	1.63E-02	1.69E+01	1.29E-01	2.07E-01	8.00E-05	6.20E-01
Pb	a Sand	28	1.84E-02	4.44E+00	3.82E-02	3.72E-02	5.20E-04	1.20E-01
	b Loam	40	1.79E-03	8.50E+00	6.35E-02	2.17E-01	1.48E-04	8.56E-01
	a Clay	24	8.11E-03	5.24E+00	2.51E-02	3.61E-02	4.55E-04	1.17E-01
	ab Organic	2	1.17E-03	1.70E+00	1.25E-03	6.36E-04	8.00E-04	1.70E-03

For soil groups being preceeded by the same letter, the TF values are not significantly different ($p < 0.05$).

and 2×10^{-3} kg kg^{-1} for Pastures. The values are comparable only for Cereals; for the other three crop groups our derivates are 4 to 12-fold lower, and for Pastures/grasses about 30 times higher. Geometric means derived by Ewers et al. (2003) were within a factor of two comparable to the TF-Th estimates proposed by Brown and Simmonds (1995).

In evaluating the overall effect of soil texture on the Th availability for plant uptake, Organic soils showed the lowest TF-Th, and TF-Th for Sand, Loam and Clay soils did not differ significantly. Table 3 shows that a significant effect of soil texture/organic matter content on TF-Th was observed for only a few crop groups (All cereals, Fodder). Following linear regression analysis, clay content explained 28% of the variation observed in log TF-Th (log TF-Th $= -0.02 \times$ Clay% $- 2.5$, $R^2 = 0.28$, $N = 147$). For Legumes and Non-leafy vegetables, clay content explained more than 40% of the variation observed. These results are in agreement with the results of Sheppard et al. (1989), who studied the effects of soil type on TF for soils artificially contaminated with naturally occurring radionuclides. That study demonstrated that TF values for sands were higher than for finer textured soils.

Syed (1999) showed that the Th ion is largely hydrolysed at pH above 3.2 and that the hydroxyl complexes are involved in the sorption process. The adsorption of Th on clays, oxides, and organic matter (OM), increases with increasing pH and is completed at pH 6.5. We found, however, a significant increase in log TF-Th with soil pH (log TF-Th $= 0.51 \times$ pH $- 6.5$, $R^2 = 0.31$, $N = 167$) which points to an increased availability with pH. For some crop groups a more significant dependency of TF-Th on pH was observed (Tubers: $R^2 = 0.62$; Green vegetables: $R^2 = 0.42$). Hunsen and Huntington (1969) suggested that mobility of Th in soil may be less affected by soil pH than by soil organic matter. Tetravalent thorium may be strongly complexed with soil organic matter, thus increasing the mobility of Th in soil. In the present compilation we found a significant increase in log TF-Th with soil OM content (log TF-Th $= 0.12 \times$ OM% $- 3.3$, $R^2 = 0.22$, $N = 212$), yet only 22% of the observed variation was explained by soil OM compared to 31% by pH. For Legumes, OM% explained 67% of the variation observed.

3.3. Radium

Radium is the last member of the alkaline earth metals, a group of metals whose lighter members (Ca and Mg) play a very important role in plant growth and nutrition. A total of 563 observations were obtained from 47 useful references. The derived generic TF-Ra is 2×10^{-2} (GSD 9) kg kg^{-1} but the range in observed values is 7 orders of magnitude (Table 4). Pastures/grasses, Leafy vegetables, Root crops, Fodder and Herbs showed the highest TF-Ra (6×10^{-2}–10^{-1} kg kg^{-1}), Cereals, Non-leafy vegetables, Legumes, Tubers and Fruits showed the lowest (9×10^{-3}–2×10^{-2} kg kg^{-1}) (Table 4 and Fig. 1C). Variation within a crop group was 1–5 orders of magnitude and significant differences in TF-value between crop groups were rarely observed. Recorded TF-Ra for Maize is 10-fold lower than for the other Cereals. TF-Ra to Cereal or Maize straw is a factor two lower than to the corresponding grains. As for TF-U and TF-Th, no significant effect of experimental conditions, contamination history, or climate, could be found on TF-Ra.

As in the present compilation, IAEA (1994) reported a 100-fold difference in TF-Ra between crop groups. Values proposed by IAEA (1994) (total of 98 entries, also included in present database) were 1.2×10^{-3} kg kg^{-1} for Cereals (maize), 4.9×10^{-2} kg kg^{-1} for Green vegetables, 7×10^{-3} kg kg^{-1} for Legumes, 1.6×10^{-2} kg kg^{-1} for Root crops, 1.1×10^{-3} kg kg^{-1} for Tubers, 8×10^{-2} kg kg^{-1} for Grasses and 6.1×10^{-3} kg kg^{-1} for tomato. Derivations in present compilation are a factor of 2 higher than the IAEA (1994) estimates, except for tubers where the derived TF-Ra is 15 times higher. Present TF-Ra estimates are within a factor of 2 in agreement with TF-Ra values derived by Brown and Simmonds (1995) and Ewers et al. (2003), except for Tubers (our value, respectively, factors of 3 and 5 higher).

TF-Ra values proposed by Sheppard et al. (2006) were (in kg kg^{-1}) as follows: 3×10^{-2} for Cereals, 2×10^{-2} for Vegetables, 1.8×10^{-2} for Root crops, 4×10^{-2} for Fruits, berries, nuts and 10^{-2} for Forages. These values are 3–4 times higher than our derived GM for Cereals and Fruits, comparable for Forages and Vegetables, and lower (factor of 4) for Root crops. Sheppard et al. (2005b, 2006) suggested a global TF-Ra value for human food products of 1.7×10^{-2} (GSD 6.2, $N = 315$) kg kg^{-1} and of 6×10^{-2} (GSD 9.3, $N = 432$) kg kg^{-1} for native brows and forage. They recommended a generic TF-Ra of 3.4×10^{-2} (GSD 9, $N = 740$) kg kg^{-1}. This value compares rather well with our observation [4×10^{-2} (GSD 9) kg kg^{-1}].

The Ra-transfer factor depends on soil characteristics, plant type, the plant part concerned, climate conditions, and the physico-chemical form of radium. Radium has a high affinity for the regular exchange sites of the soil. According to Simon and Ibrahim (1987)

Table 3
Thorium soil-to-plant transfer factor (kg kg^{-1} DW) for crop groups, crop compartments and crop/soil combinations. Number of entries (*N*), geometric mean (GM), geometric standard deviation (GSD); arithmetical mean (AM), standard deviation (SD), minimum (Min) and maximum (Max) values and number of references from which entries were extracted (# Ref).

Plant group	Plant compartment	Soil	*N*	GM	GSD	AM	SD	Min	Max	# Ref
All		All	337	3.49E-03	1.51E+01	5.88E-02	2.40E-01	1.24E-06	2.67E+00	28
Cereals	Grain	All	36	2.05E-03	3.39E+00	3.80E-03	4.53E-03	1.60E-04	2.24E-02	10
		Sand	4	4.36E-03	1.35E+00	4.50E-03	1.29E-03	3.00E-03	6.00E-03	1
		Loam	18	2.68E-03	3.38E+00	4.77E-03	5.45E-03	2.10E-04	2.24E-02	7
		Clay	9	1.19E-03	1.56E+00	1.31E-03	6.45E-04	7.00E-04	2.60E-03	3
	Straw	All	28	6.14E-03	2.43E+00	9.04E-03	9.00E-03	1.60E-03	3.70E-02	5
		Sand	4	1.40E-02	1.26E+00	1.43E-02	3.30E-03	1.10E-02	1.80E-02	1
		Loam	11	6.57E-03	1.94E+00	7.77E-03	4.03E-03	2.40E-03	1.30E-02	2
		Clay	8	3.62E-03	1.57E+00	3.95E-03	1.69E-03	2.00E-03	6.00E-03	3
		Organic	3	2.02E-03	1.49E+00	2.13E-03	9.24E-04	1.60E-03	3.20E-03	1
Maize	Grain	All	18	6.35E-05	9.23E+00	8.45E-04	2.58E-03	1.24E-06	1.10E-02	5
		Loam	10	1.96E-04	9.34E+00	1.50E-03	3.38E-03	1.39E-05	1.10E-02	3
		Clay	7	1.49E-05	3.70E+00	2.46E-05	2.08E-05	1.24E-06	5.38E-05	2
	Straw	All	2			1.77E-03	1.74E-03	5.40E-04	3.00E-03	2
Leafy vegetables		All	24	1.22E-03	6.03E+00	1.18E-02	4.29E-02	9.38E-05	2.11E-01	7
		Loam	13	8.62E-04	3.32E+00	1.51E-03	1.60E-03	9.38E-05	5.75E-03	3
		Clay	7	4.88E-04	2.81E+00	9.09E-04	1.42E-03	1.93E-04	4.10E-03	3
Non-leafy vegetables	Fruits	All	17	7.83E-04	6.76E+00	3.43E-03	5.36E-03	6.21E-05	1.62E-02	4
		Loam	10	1.96E-04	9.34E+00	1.50E-03	3.38E-03	1.39E-05	1.10E-02	1
		Clay	7	1.49E-05	3.70E+00	2.46E-05	2.08E-05	1.24E-06	5.38E-05	3
	Shoots	All	6	2.24E-03	5.07E+00	6.09E-03	9.24E-03	3.34E-04	2.44E-02	4
Legumes	Pods	All	22	5.26E-04	9.36E+00	2.27E-02	1.02E-01	2.53E-05	4.78E-01	8
		Loam	14	1.81E-03	3.94E+00	4.38E-03	7.08E-03	1.67E-04	2.43E-02	4
		Clay	10	4.11E-04	2.30E+01	4.91E-02	1.51E-01	2.53E-05	4.78E-01	4
		Organic	4	4.50E-04	7.61E+00	1.44E-03	1.85E-03	8.00E-05	4.00E-03	1
	Shoots	All	7	4.31E-03	3.99E+00	8.46E-03	9.08E-03	5.32E-04	2.43E-02	5
Root crops	Roots	All	33	8.04E-04	1.25E+01	9.33E-03	2.00E-02	8.21E-06	9.50E-02	8
		Loam	14	1.12E-03	1.58E+01	9.11E-03	1.51E-02	8.21E-06	5.30E-02	4
		Clay	14	2.57E-04	5.38E+00	2.00E-03	6.07E-03	4.51E-05	2.30E-02	4
	Shoots	All	8	8.67E-03	4.42E+00	2.14E-02	2.84E-02	2.14E-03	7.80E-02	6
Tubers	Tubers	All	24	1.98E-04	9.92E+00	1.62E-03	3.74E-03	1.26E-05	1.76E-02	8
		Loam	10	2.48E-04	6.40E+00	8.26E-04	1.18E-03	1.31E-05	3.62E-03	5
		Clay	12	9.59E-05	1.09E+01	1.71E-03	5.03E-03	1.26E-05	1.76E-02	3
	Shoots	All	2			1.86E-02	1.94E-02	4.80E-03	3.23E-02	2
Fruit	Fruit	All	2			6.25E-03	5.30E-03	2.50E-03	1.00E-02	3
Other plants	Tea leaves		1			3.37E-03				1
Grasses		All	64	4.16E-02	3.07E+00	7.41E-02	1.03E-01	7.40E-04	6.52E-01	6
Natural pastures		All	36	9.84E-02	5.45E+00	3.65E-01	6.40E-01	2.86E-03	2.67E+00	6
Leguminous fodder		All	5	2.56E-03	1.61E+00	2.79E-03	1.20E-03	1.53E-03	3.99E-03	2
All cereals		All	54	6.44E-04	1.00E+01	2.81E-03	4.20E-03	1.24E-06	2.24E-02	15
		a Sand	5	1.49E-03	1.12E+01	3.60E-03	2.29E-03	2.02E-05	6.00E-03	4
		a Loam	28	1.05E-03	7.81E+00	3.60E-03	5.01E-03	1.39E-05	2.24E-02	11
		b Clay	16	1.75E-04	1.12E+01	7.48E-04	8.10E-04	1.24E-06	2.60E-03	2
		ab Organic	2			1.60E-04	0.00E+00	1.60E-04	1.60E-04	1
Pastures/grasses		All	100	5.67E-02	4.10E+00	1.79E-01	4.14E-01	7.40E-04	2.67E+00	10
		Loam	5	7.47E-03	2.22E+00	9.45E-03	6.74E-03	2.86E-03	1.96E-02	2
Fodder		All	57	4.80E-03	3.19E+00	9.18E-03	1.28E-02	3.34E-04	7.80E-02	9
		a Sand	6	6.01E-03	4.04E+00	9.97E-03	7.12E-03	5.40E-04	1.80E-02	3
		a Loam	26	5.10E-03	3.27E+00	8.80E-03	8.64E-03	3.34E-04	3.23E-02	3
		b Clay	18	4.04E-03	2.79E+00	8.34E-03	1.76E-02	5.00E-04	7.80E-02	2
		ab Organic	5	2.21E-03	1.56E+00	2.40E-03	1.13E-03	1.60E-03	4.00E-03	1

If significant differences in TF (GM) between soil types within one plant group occur, TFs are given different as letters.

organic matter adsorbs about ten times as much radium as clay, which is more adsorptive than other soil minerals. Evaluating the overall effect of soil texture on the Ra availability for plant uptake, Clay and Organic soils showed the lowest TF-Ra and Sand and Loam soil the highest, yet the difference is only 4-fold (Table 2). Table 4 shows that a significant effect of soil texture/organic matter content on TF-Ra was observed for only a few crop groups (Non-leafy vegetables, Root crops). Moreover, following linear regression analysis, clay content and TF-Ra were not correlated (neither overall, nor for specific crop groups). Though we could not derive a significant correlation between OM and TF-Ra considering all crop groups, a significant negative dependency of TF-Ra on OM content was found for Legumes ($R^2 = 0.42$), Leguminous fodder ($R^2 = 0.62$), and Natural pastures ($R^2 = 0.27$).

Gerzabek et al. (1998) conducted lysimeter studies to determine the uptake of ^{226}Ra into agricultural crops and reported significant negative correlations between TF and pH. The pH-effect was explained by the lower radium availability with increasing pH

Table 4
Radium soil-to-plant transfer factor (kg kg^{-1} DW) for crop groups, crop compartments and crop/soil combinations. Number of entries (*N*), geometric mean (GM), geometric standard deviation (GSD); arithmetical mean (AM), standard deviation (SD), minimum (Min) and maximum (Max) values and number of references from which entries were extracted (# Ref).

Plant group	Plant compartment	Soil	*N*	GM	GSD	AM	SD	min	max	# Ref
All		All	563	4.06E-02	8.58E+00	7.05E-01	6.14E+00	1.09E-05	1.25E+02	47
Cereals	Grain	All	24	1.71E-02	1.20E+01	1.07E-01	1.86E-01	8.00E-05	6.66E-01	8
		Loam	7	2.89E-02	9.70E+00	1.59E-01	2.60E-01	7.97E-04	6.66E-01	3
		Clay	10	3.18E-02	9.88E+00	1.34E-01	1.82E-01	2.40E-04	5.00E-01	3
	Straw	All	20	3.63E-02	4.78E+00	9.37E-02	1.29E-01	1.60E-03	4.34E-01	4
		Loam	10	5.18E-02	4.44E+00	1.27E-01	1.64E-01	7.20E-03	4.34E-01	2
Maize	Grain	All	28	2.44E-03	5.43E+00	1.07E-02	2.31E-02	1.18E-04	1.11E-01	9
		Loam	4	1.65E-03	1.78E+00	1.86E-03	1.01E-03	9.03E-04	3.02E-03	3
		Clay	16	1.36E-03	4.81E+00	9.15E-03	2.77E-02	1.18E-04	1.11E-01	5
	Straw	All	6	1.84E-02	5.24E+00	3.68E-02	3.32E-02	9.57E-04	8.46E-02	3
Leafy vegetables		All	77	9.07E-02	6.67E+00	2.58E+00	1.49E+01	1.76E-03	1.25E+02	16
		Loam	10	1.20E-01	2.47E+00	1.61E-01	1.23E-01	1.63E-02	4.44E-01	4
		Clay	20	4.01E-02	4.49E+00	9.21E-02	1.13E-01	1.76E-03	4.23E-01	4
		Organic	9	4.85E-02	2.08E+00	6.18E-02	4.60E-02	2.04E-02	1.41E-01	2
Non-leafy vegetables	Fruit	All	44	1.72E-02	8.38E+00	2.62E-01	1.01E+00	2.41E-04	6.25E+00	12
		b Sand	3	2.22E-03	2.14E+00	2.70E-03	2.04E-03	1.10E-03	5.00E-03	4
		a Loam	4	4.82E-02	5.63E+00	1.19E-01	1.54E-01	6.92E-03	3.40E-01	2
		a Clay	17	2.22E-02	2.82E+00	4.12E-02	6.00E-02	3.92E-03	2.10E-01	1
	Shoots	All	13	6.12E-02	6.44E+00	3.07E-01	5.68E-01	6.67E-03	1.82E+00	4
Legumes	Pods	All	40	1.39E-02	8.20E+00	2.39E-01	1.02E+00	3.20E-04	6.17E+00	14
		Loam	12	9.81E-03	4.53E+00	2.17E-02	2.57E-02	4.80E-04	8.65E-02	5
		Clay	15	9.33E-03	4.22E+00	2.18E-02	3.01E-02	7.95E-04	1.10E-01	5
	Shoots	All	18	2.75E-02	1.13E+01	1.43E-01	3.47E-01	1.09E-05	1.50E+00	8
		Loam	6	1.05E-02	3.24E+01	4.80E-02	4.61E-02	1.09E-05	1.10E-01	3
Root crops	Roots	All	60	6.97E-02	9.22E+00	1.93E+00	7.81E+00	2.04E-03	5.56E+01	16
		c Sand	3	4.78E-03	2.31E+00	5.95E-03	4.52E-03	2.04E-03	1.09E-02	2
		a Loam	8	9.11E-02	1.92E+00	1.07E-01	5.91E-02	2.89E-02	1.97E-01	3
		b Clay	23	3.18E-02	2.86E+00	5.08E-02	5.20E-02	3.18E-03	2.21E-01	4
	Shoots	All	22	7.05E-02	4.61E+00	1.75E-01	2.20E-01	2.52E-03	7.11E-01	9
		Loam	6	1.45E-01	5.63E+00	3.11E-01	2.79E-01	9.60E-03	7.11E-01	2
Tubers	Tubers	All	45	1.07E-02	6.83E+00	1.38E-01	5.85E-01	2.40E-04	3.87E+00	15
		Loam	8	1.20E-02	1.06E+01	9.21E-02	2.14E-01	2.40E-04	6.20E-01	4
		Clay	24	5.40E-03	2.51E+00	9.49E-03	1.62E-02	1.26E-03	8.00E-02	7
	Shoots	All	6	1.56E-01	2.18E+00	1.92E-01	1.09E-01	4.32E-02	3.25E-01	3
Herbs	Herbs	All	20	6.87E-02	4.46E+00	2.63E-01	7.25E-01	5.30E-03	3.31E+00	5
Fruits	Fruits	All	12	1.15E-02	3.71E+00	2.69E-02	4.61E-02	1.39E-03	1.68E-01	4
Other	Sunflower-3/peanut-1	All	4	4.18E-01	3.03E+00	5.83E-01	4.17E-01	8.50E-02	1.10E+00	2
	Tea leaves	All	1			3.33E-02				1
Grasses		All	62	1.26E-01	3.97E+00	2.62E-01	3.20E-01	3.58E-03	1.57E+00	19
		Sand	24	1.42E-01	4.18E+00	3.13E-01	3.98E-01	5.35E-03	1.57E+00	7
		Loam	14	2.56E-01	2.00E+00	3.17E-01	2.13E-01	9.63E-02	7.19E-01	2
		Clay	3	4.20E-02	1.51E+00	4.43E-02	1.70E-02	2.70E-02	6.10E-02	1
Natural pastures		All	42	7.10E-02	7.62E+00	1.92E-01	2.75E-01	5.12E-05	1.60E+00	16
		Sand	3	7.99E-03	3.79E+00	1.24E-02	1.07E-02	1.80E-03	2.32E-02	1
		Loam	6	8.78E-03	1.94E+01	3.92E-02	3.99E-02	5.12E-05	1.07E-01	4
Leguminous fodder		All	16	1.67E-01	3.09E+00	3.02E-01	3.70E-01	3.40E-02	1.49E+00	4
		Sand	5	1.70E-01	2.54E+00	2.41E-01	2.20E-01	8.00E-02	5.65E-01	3
		Loam	8	1.22E-01	3.86E+00	3.09E-01	5.07E-01	3.40E-02	1.49E+00	2
All cereals		All	68	8.95E-03	9.71E+00	6.41E-02	1.31E-01	8.00E-05	6.66E-01	12
		Loam	17	1.31E-02	8.52E+00	8.14E-02	1.52E-01	2.40E-04	5.00E-01	6
		Clay	26	3.36E-03	8.49E+00	4.87E-02	1.46E-01	1.18E-04	6.66E-01	9
Pastures/grasses		All	104	9.99E-02	5.41E+00	2.34E-01	3.03E-01	5.12E-05	1.60E+00	10
		Sand	27	1.03E-01	5.33E+00	0.00E+00	3.86E-01	1.80E-03	1.57E+00	9
		Loam	20	9.30E-02	9.69E+00	2.34E-01	2.21E-01	5.12E-05	7.19E-01	6
		Clay	3	4.20E-02	1.51E+00	4.43E-02	1.70E-02	2.70E-02	6.10E-02	1
Fodder		All	105	5.58E-02	5.96E+00	1.78E-01	3.13E-01	1.09E-05	1.82E+00	13
		Sand	11	6.08E-02	7.63E+00	1.64E-01	1.75E-01	9.57E-04	5.65E-01	5
		Loam	46	5.60E-02	6.96E+00	1.70E-01	2.70E-01	1.09E-05	1.49E+00	11
		Clay	7	1.92E-01	5.24E+00	5.15E-01	7.00E-01	1.43E-02	1.82E+00	4
		Organic	6	2.06E-02	1.20E+01	1.51E-01	2.24E-01	1.60E-03	4.40E-01	2

If significant differences in TF (GM) between soil types within one plant group occur, TFs are given as different letters.

(Hewamanna et al., 1988). Overall, we did not observe a significant pH-effect on Ra uptake. For Leguminous fodder ($R^2 = 0.48$) and Grasses ($R^2 = 0.32$) a significant negative dependency of TF-Ra on pH was observed.

It has been documented that alkaline earth metals may compete for adsorption binding sites on the surface of roots. In the presence of high soil concentrations of alkaline earth cations the uptake of radium may be suppressed owing to adsorption competition. Several authors found that total soil bivalent cation concentration (Simon and Ibrahim, 1990; Gerzabek et al., 1998, Vandenhove et al., 2005, Vandenhove and Van Hees, 2007), and exchangeable Ca and Mg (Gerzabek et al., 1998) suppressed radium uptake. In the present compilation, TF-Ra was not correlated with exchangeable soil Ca, except for Grasses ($R^2 = 0.28$). Several authors reported a positive correlation between shoot Ca content and shoot Ra content (Kopp et al., 1989; Linsalata et al., 1989; Million et al., 1994). There was no significant correlation between the observed TF and plant cation contents (Ca, Mg and/or K).

Sheppard et al. (2008) reported the unexpected observation that ^{228}Ra seemed to be 5-fold more bioavailable than ^{226}Ra for natural vegetation at Canadian background sites. Linsalata (1986) did not find a significant difference in ^{226}Ra and ^{228}Ra TF averaged for a series of crops grown at the Poços de Caldas plateau (Brazil). For present database, considering those studies where both ^{226}Ra and ^{228}Ra were measured (Paul and Pillai, 1986; Linsalata, 1986; Cooper et al., 1995), an overall 2.5-fold higher TF was found for ^{228}Ra (GM: 0.035; GSD: 5.5) than for ^{226}Ra (GM: 0.013; GSD: 5.9). For a large number of crops (maize, brown beans, manioc, carrot, lettuce, grasses, herbs) no significant difference in TF for both isotopes was recorded. For some other crops, TF for ^{228}Ra was significantly higher (ratio between brackets): rice straw (2.5) zucchini (2.7), potato (3), collard green (3.9), rice grain (6). Mechanisms of these higher TF for ^{228}Ra are not clear. In-growth from mother radionuclides or decay cannot be at the basis since half-lives of mothers and radium isotopes of concern are too long.

3.4. Lead

The main source of ^{210}Pb in the environment is from the decay of ^{222}Rn gas evolved from the soil into the atmosphere. These radionuclides deposit on the ground in association with aerosols via washouts and sedimentation. Other sources include burning of fossil fuels and tetraethyl lead in petrol (Ewers et al., 2003). Several sources have reported that superphosphate fertilizers contain significant concentrations of ^{210}Pb and ^{210}Po, which can provide a source of these radionuclides to plants (Amaral et al., 1992; Santos et al., 1989).

From 24 references, 208 entries were retained. For most crop groups a fair number of observations was recorded except for Non-leafy vegetables, Fruits and Leguminous fodder. Table 5 shows TF-Pb for the different crop groups. The overall GM for the TF-Pb is 2.0×10^{-2} (GSD 14) kg kg^{-1} and the range covers 5 orders of magnitude. TF-Pb was highest for Pastures/grasses (1.4×10^{-1} kg kg^{-1}), followed by Leafy vegetables (8.0×10^{-2} kg kg^{-1}) and Fodder (2.5×10^{-2} kg kg^{-1}) and was lowest for Tubers (1.5×10^{-3} kg kg^{-1}). Within a crop group variation is low (factor 10 or less) to substantial (4 orders of magnitude). Therefore, very few TF-Pb are significantly different between crop groups (Fig. 1D). TF-Pb to Cereal grain was about a factor 2 lower than to the Cereal straw (Table 5). TF-Pb to Maize grain and straw is 10-fold lower than for other Cereals.

Uptake of ^{210}Pb in plants can occur both through the root system, and from atmospheric deposition e.g. in the vicinity of metal smelters (Pettersson et al., 1988; Ham et al., 2001; Pietrzak-Flis and Skowrofiska, 1995). The relative importance of these two pathways depends upon the concentration of the radionuclides in the soil, the soil–plant TF, and the rate of deposition onto the above-ground plant parts. Activity concentrations in crops such as root and tuber crops, cereals and legumes, where the edible portion is protected by inedible plant parts, should not be significantly affected by direct deposition. For leafy vegetables observed concentrations may be higher due to deposition effects. Pietrzak-Flis and Skowrofiska (1995) evaluated the contribution of atmospheric deposition to the TF of ^{210}Pb (and ^{210}Po) to a number of food and fodder crops. Considering data from all plant groups tested the TF was 4-fold higher when deposition was included (Table 6). For Grasses, Straw, and Leafy vegetables, differences are up to 20-fold. For Cereal grains TF values were similar or were up to 3-fold higher. For Root crops and Tubers TFs were the same if deposition was involved or not. For this compilation, TF data resulting from known deposition were excluded. However, inclusion of these TF data did not significantly affect the overall TF-Pb to a significant extent (results not shown).

Soil-atmosphere transfer of radon followed by deposition of ^{210}Pb (and ^{210}Po) onto leaves may also contribute to the ^{210}Pb uptake. It is, however, difficult to assess the contribution of root uptake and foliar transfer to the total ^{210}Pb uptake. Comparing TF values for stable Pb and ^{210}Pb could help elucidate this process. Tamponnet (in press) reported lead transfer factors in the same range for both stable and radioactive lead (with slightly higher values for stable lead). The contribution from foliar uptake following radon emanation is hence expected to be minimal.

Comparison of derivations for TF-Pb from this compilation with other TF-Pb estimates highlights some differences. IAEA (1994) presented following values: for Cereals (4.7×10^{-3} kg kg^{-1}, $N = 3$), Mixed green vegetables (1.0×10^{-2} kg kg^{-1}, $N = 6$), Mixed roots (2.0×10^{-2} kg kg^{-1}, $N = 1$), potato (1.3×10^{-3} kg kg^{-1}, $N = 2$) and Fodder (1.1×10^{-3} kg kg^{-1}, $N = 2$). These values are 10-fold lower (Cereals and Fodder) or similar (other crops), compared to present compilation. IAEA (1994) data were obtained from Frissel and Van Bergeijk (1989) and were also included in present compilation.

The values derived by Brown and Simmonds (1995) (1.1×10^{-2} kg kg^{-1} for Cereals, 10^{-1} kg kg^{-1} for Root crops and 4.8×10^{-2} kg kg^{-1} for potato) exceeded the default values derived under present compilation, except for Pastures and grasses where present estimate is 3-fold higher, and for Leafy vegetables where similar values were obtained in both studies. Geometric means derived by Ewers et al. (2003) were 8×10^{-3} kg kg^{-1} for Cereals, 5×10^{-2} kg kg^{-1} for Brassicaceae (cfr Leafy vegetables), 2×10^{-2} kg kg^{-1} for Root crops and 1.0×10^{-2} kg kg^{-1} for potato (Tubers). These estimates are comparable with the values derived in present study except for Tubers where a 10-fold higher estimate was suggested.

In considering the effect of soil parameters on TF-Pb, Table 2 reveals that TF-Pb are highest for Sand and Clay soils. Variation within a soil category is three orders of magnitude. For Organic soils only two observations are recorded. Any significant differences in TF-Pb observed for a given crop resulting from soil texture, are indicated in Table 5. Correlations between TF-Pb (or log TF-Pb) and other soil characteristics (pH, CEC, OM, clay) were not significant.

3.5. Polonium

As described for ^{210}Pb, polonium (^{210}Po) originates mostly from ^{222}Rn, fossil fuels, and superphosphate fertilizers (Amaral et al., 1992). Uptake of ^{210}Po in plants can occur both indirectly through the root system and via direct deposition from atmosphere as is the case for ^{210}Pb.

Table 7 presents information on soil-to-plant transfer factors of Po for different crop groups. In total, 57 observations were entered.

Table 5
Lead soil-to-plant transfer factor (kg kg^{-1} DW) for crop groups, crop compartments and crop/soil combinations. Number of entries (*N*), geometric mean (GM), geometric standard deviation (GSD); arithmetical mean (AM), standard deviation (SD), minimum (Min) and maximum (Max) values and number of references from which entries were extracted (# Ref).

Plant group	Plant compartment	Soil	*N*	GM	GSD	AM	SD	Min	Max	# Ref
All			210	2.01E-02	1.43E+01	6.33E-01	2.85E+00	1.48E-04	2.46E+01	24
Cereals	Grain	All	9	1.07E-02	3.63E+00	1.84E-02	1.58E-02	1.90E-03	4.80E-02	5
	Straw	All	4	2.25E-02	3.54E+00	3.81E-02	4.09E-02	5.10E-03	9.60E-02	3
Maize	Grain	All	9	1.23E-03	2.30E+00	1.68E-03	1.36E-03	5.20E-04	3.84E-03	4
	Straw	All	3	2.82E-03	6.64E+00	8.48E-03	1.28E-02	6.00E-04	2.33E-02	2
Rice	Grain	All	2			2.22E-02	1.44E-02	1.20E-02	3.24E-02	3
Leafy vegetables		All	31	8.03E-02	1.26E+01	2.11E+00	6.12E+00	3.21E-03	2.46E+01	9
		b Sand	4	7.26E-02	1.54E+00	0.077814	0.032574	0.049283	0.113537	1
		a Loam	3	8.16E-01	1.04E+00	0.816780	0.035278	0.788728	0.856386	1
		b Clay	7	2.76E-02	4.13E+00	5.14E-02	4.75E-02	4.10E-03	1.17E-01	3
Non-leafy vegetables	Fruits	All	5	1.50E-02	2.59E+01	7.77E-01	1.72E+00	1.47E-03	3.86E+00	3
	Shoots	All	2			8.77E-03	4.15E-03	5.83E-03	1.17E-02	2
Legumes	Pods	All	17	5.33E-03	1.17E+01	3.38E-01	1.20E+00	4.55E-04	4.94E+00	6
		Sand	3	2.72E-03	3.16E+00	4.16E-03	3.43E-03	6.53E-04	8.91E-03	2
		Loam	5	1.42E-03	4.41E+00	0.004158	0.003433	0.000653	0.008910	2
		Clay	4	8.00E-04	1.00E+00	0.003279	0.004715	0.000455	0.010273	2
	Shoots	All	1			8.00E-04				1
Root crops	Roots	All	27	1.46E-02	1.61E+01	4.14E-01	9.77E-01	2.40E-04	3.30E+00	9
		a Sand	5	6.44E-02	1.59E+00	7.03E-02	3.36E-02	4.18E-02	1.20E-01	3
		b Loam	5	2.26E-03	4.66E+00	5.01E-03	6.83E-03	2.40E-04	1.70E-02	2
	Shoots	All	12	6.29E-02	1.54E+01	2.47E+00	5.73E+00	2.95E-03	1.64E+01	4
Tubers	Tubers	All	30	1.45E-03	7.36E+00	9.12E-02	4.80E-01	1.48E-04	2.63E+00	10
		a Sand	5	6.35E-03	3.48E+00	1.20E-02	1.56E-02	1.63E-03	3.93E-02	3
		b Loam	17	5.20E-04	2.37E+00	7.32E-04	6.20E-04	1.48E-04	2.28E-03	4
Fruits	Fruits	All	5	7.72E-03	2.63E+00	1.00E-02	5.96E-03	1.49E-03	1.66E-02	3
	Leaves	All	1			2.51E-01				1
Grasses		All	17	3.13E-01	1.77E+00	3.64E-01	2.18E-01	1.11E-01	1.00E+00	2
Natural pastures		All	34	9.19E-02	4.75E+00	2.27E-01	2.90E-01	2.23E-03	1.00E+00	7
Leguminous fodder		All	1			1.61E-02				1
All cereals		All	20	4.29E-03	4.69E+00	1.13E-02	1.41E-02	5.20E-04	4.80E-02	4
		Sand	5	6.11E-03	5.32E+00	1.29E-02	1.29E-02	5.20E-04	3.22E-02	3
		Loam	8	1.74E-03	3.92E+00	5.33E-03	1.10E-02	5.93E-04	3.24E-02	3
		Clay	6	9.02E-03	4.01E+00	1.77E-02	1.84E-02	2.20E-03	4.80E-02	4
Pastures/grasses		All	51	1.38E-01	4.18E+00	2.73E-01	2.74E-01	2.23E-03	1.00E+00	6
Fodder		All	24	2.53E-02	1.17E+01	1.25E+00	4.15E+00	6.00E-04	1.64E+01	11
		Sand	4	4.46E-02	2.25E+00	5.58E-02	3.99E-02	1.61E-02	1.09E-01	1
		Clay	4	8.22E-03	5.69E+00	2.71E-02	4.59E-02	1.60E-03	9.60E-02	2

If significant differences in TF (GM) between soil types within one plant group occur, TFs are given as different letters.

Only six references were found recording TF-Po. The generic value for TF-Po was 5.6×10^{-3} (GSD 13) kg kg^{-1} and values entered covered 5 orders of magnitude. For several crop groups data were very scarce (Cereals, Legumes, Leguminous fodder) or non-existent (Non-leafy vegetables, Fruit).

Cereals and Legumes have generally low transfer factors (10^{-4} kg kg^{-1}) compared to the other crops. The reason can be physical - the edible parts being protected from Po deposition - or physiological, as observed for many radio-contaminants, transfer from vegetative mass to seeds is limited. Other crops have TFs in order of 10^{-3} kg kg^{-1}. Highest TFs (1.2×10^{-2} kg kg^{-1}) were found for Pastures and grasses and the observed difference is significant (Fig. 1e).

Pietrzak-Flis and Skowrofiska (1995) conducted a study investigating the effect of atmospheric deposition of ^{210}Po on their transfer to food or fodder crops. As for ^{210}Pb, the data obtained

Table 6
Effect of deposition on lead and polonium soil-to-plant TF (kg kg^{-1} DW) (after Pietrzak-Flis and Skowrofiska, 1995).

	N	GM	GSD	AM	SD	Min	Max
Pb							
No deposition	19	1.81E-02	3.17E-01	4.87E-02	3.23E-02	9.76E-03	1.14E-01
Deposition	20	7.11E-02	5.28E-01	2.01E-01	1.83E-01	1.15E-02	5.45E-01
Po							
No deposition	14	2.51E-02	2.01E+00	3.15E-02	2.37E-02	8.00E-03	9.65E-02
Deposition	16	7.92E-02	3.17E+00	1.36E-01	1.36E-01	9.14E-03	4.87E-01

Number of entries (N), geometric mean (GM), geometric standard deviation (GSD); arithmetical mean (AM), standard deviation (SD), minimum (Min) and maximum (Max) values.

Table 7
Polonium soil-to-plant transfer factor (kg kg^{-1} DW) for crop groups, crop compartments and crop/soil combinations. Number of entries (*N*); geometric mean (GM); geometric standard deviation (GSD); arithmetical mean (AM), standard deviation (SD), minimum (Min) and maximum (Max) values and number of references from which entries were extracted (# Ref).

Plant group	Plant compartment	*N*	GM	GSD	AM	SD	Min	Max	# Ref
All excluding deposition		57	5.57E-03	1.31E+01	5.63E-02	1.61E-01	1.60E-05	1.02E+00	6
All including deposition		73	1.01E-02	1.31E+01	7.37E-02	1.59E-01	1.60E-05	1.02E+00	6
Cereals	Grain	2			2.42E-04	2.55E-05	2.24E-04	2.60E-04	1
Maize	Grain	2			2.42E-04	3.17E-04	1.80E-05	4.66E-04	1
Rice	Grain	1			1.68E-02				1
Leafy vegetables		12	7.43E-03	6.89E+00	1.90E-02	1.72E-02			3
Non-leafy vegetables	Shoots	2			1.93E-04	2.50E-04	1.60E-05	3.70E-04	1
Legumes	Pods	4	2.73E-04	3.87E+00	4.75E-04	4.58E-04	6.00E-05	1.02E-03	4
	Shoots	1			Fod-leg				1
Root crops	Roots	10	5.80E-03	4.29E+00	1.20E-02	1.65E-02	2.40E-04	4.92E-02	4
	Shoots	2			7.74E-02	2.71E-02	5.80E-02	9.70E-02	1
Tubers	Tubers	9	2.69E-03	5.75E+00	7.98E-03	1.15E-02	1.43E-04	3.40E-02	3
Natural pastures		10	1.15E-01	4.19E+00	2.59E-01	3.23E-01	2.20E-02	1.02E+00	2
Leguminous fodder		2			1.08E-02	2.00E+00	2.55E-05	2.24E-04	1
All cereals		5	3.83E-04	1.17E+01	3.56E-03	7.43E-03	1.80E-05	1.68E-02	3
Pastures/grasses		10	1.15E-01	4.19E+00	2.59E-01	3.23E-01	1.80E-02	1.02E+00	2
Fodder		8	5.01E-03	2.23E+01	2.48E-02	3.48E-02	1.60E-05	9.65E-02	4

indicate that atmospheric deposition is the main source of ^{210}Po in the above-ground parts of plants. Overall, a 3-fold higher TF is observed when atmospheric deposition is allowed (Table 6). For Grasses, Straw, and Leafy vegetables, differences were 10 to 15-fold. For Cereals, Root crops, and Tubers, TFs were comparable. This is confirmed by observations by Ham et al. (2001). Furthermore, these authors suggested that translocation from shoots to roots was negligible.

Comparing our observations with other proposed estimates, IAEA (1994) proposed TF-Po for wheat grain (2.3×10^{-3} kg kg^{-1}), potato (7×10^{-3} kg kg^{-1}), vegetables (1.2×10^{-3} kg kg^{-1}) and grasses (9×10^{-2} kg kg^{-1}) all from the study by Hölzer and Wichterey (1991, in IAEA, 1994). It is mentioned that these values were not corrected for aerial contamination and that actual uptake values were likely to be 2–10 fold lower. For present compilation, values for Cereals are about a factor 10 lower, and are comparable or higher for the other crop groups. The values derived for most crops exceeded the default values considered by Brown and Simmonds (1995) by about 2-fold, except for Pastures and grasses where present estimate is more than 100-fold higher, and for Cereals where for both studies similar values were obtained. Geometric means derived by Ewers et al. (2003) were considerably higher than the values derived in present study. These authors calculated GM values for TF-Po of 3×10^{-2} kg kg^{-1} for Cereals, 3×10^{-2} kg kg^{-1} for Brassicaceae (cfr Leafy vegetables), 6×10^{-2} kg kg^{-1} for Root crops, and 1.5×10^{-2} kg kg^{-1} for potato (Tubers).

4. Conclusions

Soil-to-plant transfer factors (TF) for the natural radionuclides U, Th, Ra, Pb and Po were reviewed and grouped according to crop group and then according to soil group and organic matter content and where availability of data allowed, related to soil characteristics.

The TF values were generally about 10-fold lower for Th and Po than for U, Ra and Pb. However, there is a clear lack of TF-Po data and sources reporting on adequate TF-Po data are very few. For most crop groups data are scarce or even non-existing.

Overall, highest TF derivations were obtained for Fodder, Pastures and grasses, and Leafy vegetables while lowest TF estimates were obtained for Legumes and Cereals. There is a large variability among TF data even at the crop group level (GSD around 10). Therefore, TF estimates may be valuable for screening assessment, but more site specific values may be required for predicting effective impact. The fact that only very few estimates were significantly different between crop groups could call for a generic TF value for each radionuclide. This could be recommended for generic long-time assessment involving large uncertainties. For more site specific assessment, the crop-based TF estimates may be more appropriate.

Since estimates between crop groups were generally not significantly different for a given radionuclide, other means of categorizing or predicting soil-to-plant transfer could be more appropriate. In that perspective the influence of soil characteristics on the soil-to-plant transfer was evaluated. A striking observation was that the majority of soil-to-plant TF data were reported without information on soil properties. Only about 50% of the entries contained information on soil type. Information on pH, CEC or OM was generally even less frequently recorded. Generally, TF was highest on coarse textured soils, and lowest on fine textured and organic soils, but TF values derived per texture class were seldom significantly different. Soil characteristics and environmental conditions will affect the transfer processes and it would be an advantage if the mechanistics of transfer could be understood and modeled. At this stage, with little information available, no mechanistic prediction of the soil-to-plant TF based on soil properties could be made.

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