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A revised IAEA data compilation for estimating the soil to plant transfer of radionuclides in tropical environments

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Highlights

- Plant-soil concentration ratio data for tropical environments were compiled in the IAEA MODARIA II programme.
- More than 800 summary values were derived from over 10,000 observations.
- Plant-soil concentration ratios are generally higher in tropical environments than temperate environments.
- A new IAEA Technical Document on soil to plant transfer in non-temperate environments is being prepared.

Abstract

A revision of the International Atomic Energy Agency (IAEA) Technical Report Series No. 472 (TRS 472) transfer parameter data for root uptake of radionuclides by crops in tropical environments was conducted under the IAEA Modelling and Data for Radiological Impact Assessments (MODARIA II) programme (2016–2019). Data on concentration ratios between plant and soil ($CR_{plant\text{-}soil}$) were collated and summarised following a specific data selection process based on the Köppen-Geiger classification of tropical (class A) climates. An overview of the data collation and analysis methods is presented together with a comparison of $CR_{plant\text{-}soil}$ values between the revised tropical dataset and TRS 472 datasets. The revised dataset of $CR_{plant\text{-}soil}$ values for tropical environments is part of the IAEA MODARIA II programme Technical Document on soil to plant transfer of radionuclides in non-temperate environments.

1. Introduction

Assessing the impact of radionuclides released into the environment is a general requirement of international safety standards (IAEA, 2014). Such releases can occur through routine human activities and/or accidents. Furthermore, radionuclides existing in the environment as a result of past practices may require management for mitigating radiological consequences. Predictive models, underpinned by realistic parameterisation, are essential tools to better allow us to assess and manage these exposure situations.

Releases impacting upon agricultural environments can lead to enhanced radionuclide activity concentrations in crops via direct deposition on aerial parts and root uptake from soil. The rate and extent of soil to plant transfer of radionuclides is influenced by various biogeochemical and physicochemical factors (see below). However, in many radiological assessment models the quantification of such transfer is simplified to a single key parameter termed the plant-soil concentration ratio ($CR_{plant-soil}$) which is the equilibrium ratio of the radionuclide activity concentration in the plant (edible portion) to that in the soil (IAEA, 2001; Yu et al., 2020).

In addition to the need for impact assessment, the study of the movement of radionuclides provides insights into the mechanisms and kinetics of environmental processes thereby improving our understanding of ecosystem behaviour. Such studies have shown that numerous factors influence the soil to plant transfer of radionuclides and the related $CR_{plant-soil}$ value. Plant uptake physiology may be linked to environmental variables such as temperature (affecting biochemical reaction rates), rainfall intensity and periodicity, as well as photoperiod and light intensity (Adams and Langton, 2005; Criddle et al., 1997; Feng et al., 2012). Soil type and chemistry are also important factors. In particular, the availability of nutrient analogues of the radionuclide of interest, the overall nutrient conditions, the degree of complexation by organic and inorganic ligands in the soil, clay minerals, pH and soil water availability, amongst others (Tagami et al., 2012). The net effect of these factors may differ by site.

The International Atomic Energy Agency (IAEA) has for many years supported efforts to compile data on the transfer of radionuclides through the food chain to humans. A key reference source of such data is the Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, published as Technical Reports Series No. 472 (TRS 472) (IAEA, 2010). The TRS 472 handbook includes $CR_{plant-soil}$ values derived from published studies (note that in TRS 472 the equivalent parameter to $CR_{plant-soil}$ is called transfer factor and is denoted as F_v). Most of the $CR_{plant-soil}$ values in TRS 472 relate to temperate environments, with only a comparatively small dataset available for tropical environments. Within TRS 472 there are no clear criteria applied to classify data as 'tropical'.

The need to conduct radiological assessments in tropical environments may increase in the future due to both climate change (which may lead to more parts of the world having hotter and more humid conditions) and an expansion of nuclear power in these regions (IAEA, 2020). Reliable data for tropical environments will be needed to support such assessments.

Within the IAEA Modelling and Data for Radiological Impact Assessments (MODARIA II) programme (2016–2019), the issue of climate as one of the essential differences between regions of the world was considered under the broad umbrella of Working Group 4 "Transfer processes and data for radiological impact assessment". A subgroup of Working Group 4 focussed on soil to plant transfer in non-temperate climate regions, particularly tropical and arid regions. The subgroup collated and analysed $CR_{plant-soil}$ data based on the Köppen-Geiger (K-G) climate classification of tropical (class A) and arid (class B) climates (Beck et al, 2018). The K-G classification of 'tropical' specifically refers to warm and humid climates rather than to any other climate type that may exist in the Tropics. This paper describes the work of the subgroup in relation to tropical environments. The derived summary values of $CR_{plant-soil}$ will be published in an associated IAEA Technical Document (TECDOC). The work of the subgroup to develop a complementary dataset for arid environments is described in a separate paper in this special issue (Semioschkina and Voigt, this issue).

2. Methods

2.1. Data collation

Most of the data for tropical environments originally compiled for TRS 472 were used as the starting point for the revision. These data were checked against source references as a quality assurance process and also evaluated to determine if they were acquired from sites that satisfied the K-G classification for the tropical climate sub-types of rainforest (Af), monsoon (Am) or savannah (Aw) as defined in Beck et al. (2018). A literature search for additional data was also undertaken. The literature search focused on original source publications reporting data and did not include review articles. Data for sites meeting the K-G climate criteria were collated together with associated environmentally relevant information (e.g. location, plant species, soil properties, agricultural practice, etc) that facilitated the attribution of the data into more refined subsets.

The data collation included both radionuclides and stable isotopes. Combining data for radioactive and stable isotopes of the same element could lead to some bias, as recently produced radionuclides entering the environment may be more bioaccessible than stable isotopes encased within the crystalline soil matrix. However, the chemical similarity between different isotopes of the same element means that they generally behave in a similar manner within comparable environments. The use of stable isotopes as analogues to estimate the transfer of radionuclides is a common approach due to their comparative ease of measurement and also because of diminishing inventories of some radionuclides (e.g. ^{137}Cs and ^{90}Sr) in the environment in parts of the world.

The data collation focused on sites where equilibrium had likely been established between the movements of radionuclides and stable isotopes into and out of the relevant compartments of the environment based on site description information available in the source references. These were either planned or existing exposure situations (e.g. long-term discharges of radionuclides or contaminants, fallout radionuclides from past nuclear weapons testing, radionuclides and stable isotopes in natural and semi-natural systems, etc). Data for dynamic or changing conditions (such as an accidental release or emergency exposure situation) were not included and generally not available.

As part of the data collation, source references were evaluated for descriptions of equipment, procedures and controls relating to data quality. This included: (i) descriptions of sampling strategy; (ii) descriptions of measurement techniques and equipment; and (iii) descriptions of analytical measurement quality control processes (e.g. participation in proficiency tests or inter-comparison exercises and/or use of reference materials for internal validation of measurements). The presence/absence of such information was noted with each data entry.

2.2. Categorising plants and soils

The categorisation of plants and soils followed that of TRS 472, but with some minor adjustments to account for specific features in the data.

Plant groups and their associated compartments are shown in Table 1. A new group of ‘medicinal plants’ (subdivided as shrubs, woody trees and non-woody trees) was introduced to account for the medicinal use of certain compartments (e.g. bark and leaves) that are not otherwise consumed. While some herbs are also used for medicine, they were not included as a subgroup of medicinal plants since they are generally also used for food or as a condiment. Instead, the primary group of ‘herbs’ is applicable to both culinary and medicinal uses of herbs. Within the ‘fruits’ group, a new subgroup termed non-woody trees was added and included crops such as banana, papaya and palm fruits.

Grasses were treated as a single plant group with no distinction between cultivated species, pasture and leguminous fodder, as was done in TRS 472.

Soil groups are shown in Table 2. Similar to TRS 472, the primary means of categorising soils was based on percentages of clay, sand and organic matter. However, in the absence of quantitative soil characterisation data, qualitative information on soil texture was used as a secondary means of categorisation. A new soil group of 'coral sand' was added to distinctly categorise Marshall Islands soils based on their unique matrix of high calcium carbonate concentrations and virtual absence of clay minerals which affects radionuclide leachability and bioavailability (Simon et al., 2002; Robison et al., 2006). The TRS 472 tropical dataset specified that Marshall Islands soils were outside the applied classification scheme and grouped them as 'other'. Similar soils to those of the Marshall Islands would be present on most coral atolls that fall within the K-G classification of tropical (class A) climates across the Pacific Ocean region, within the Caribbean and in the Indian Ocean and nearby seas.

2.3. Data treatment

Some treatment of the data was required prior to deriving the final summary $CR_{plant\text{-}soil}$ values and is described in the TECDOC. In brief, this included applying a standard set of assumptions to estimate the number of observations in a study if not reported in the source reference, converting plant concentration data from fresh to dry mass and calculating means and standard deviations from individual measurement values for each study as necessary.

2.4. Calculating $CR_{plant\text{-}soil}$ values

The final summary $CR_{plant\text{-}soil}$ values were calculated for each element by plant group (and subgroup where applicable), plant compartment and soil group. They were also derived for all soil groups combined and for all soil groups excluding coral sand. The reason for the latter exclusion was to permit more direct comparisons with the $CR_{plant\text{-}soil}$ values in the TRS 472 datasets for subtropical and temperate environments where there are no coral sand soil data present.

The final summary $CR_{plant\text{-}soil}$ values for all plant groups other than fruits were calculated relative to plant dry mass concentrations. The values for fruits were calculated relative to plant fresh mass concentrations, as was the case in TRS 472.

The weighted arithmetic mean (AM) and combined standard deviation ($SD_{combined}$) accounting for within and between study variation were calculated from the $CR_{plant\text{-}soil}$ values for each study as:

$$AM = \frac{\sum_i n_i CR_i}{N}$$

$$SD_{combined} = \sqrt{\frac{\sum_i \left((n_i - 1)SD_i^2 + n_i CR_i^2\right) - \frac{(\sum_i n_i CR_i)^2}{N}}{N-1}}$$

where n_i is the number of observations in study i, CR_i is the mean $CR_{plant\text{-}soil}$ for study i, N is the total number of observations in all studies and SD_i is the standard deviation for study i.

Approximate estimates of the geometric mean (GM) and geometric standard deviation (GSD) were calculated from the AM and SD as:

$$GM = exp\left(-0.5 ln\left(\frac{SD^2 + AM^2}{AM^4}\right)\right)$$

$$GSD = exp\left(\sqrt{ln\left(\frac{SD^2 + AM^2}{AM^2}\right)}\right)$$

Note that the *GM* and *GSD* were only calculated in cases where $N \geq 3$.

2.5. Comparing datasets

The $CR_{plant\text{-}soil}$ values in the revised tropical dataset and the TRS 472 datasets for tropical, subtropical and temperate environments were evaluated for similarities and differences. The evaluation was based on values with equivalent element – plant group – plant compartment – soil group combinations. As all the raw data (i.e. individual measurement values) underpinning the datasets were unavailable, a direct statistical comparison of the best measures of central tendency (be they single values, *GM* or *AM* values) was not possible. Instead, the approach taken was to compare the mean values in each dataset based on the ratio between them (i.e. revised/TRS 472). The ratios were also assessed using a sign test (https://www.real-statistics.com/non-parametric-tests/sign-test/) to compare the datasets overall.

In calculating the ratio, the relevant *GM* value from each dataset was used if available, otherwise the *AM* value was used. Also, $CR_{plant\text{-}soil}$ values for soils lacking characterisation information (i.e. 'unspecified') were compared with $CR_{plant\text{-}soil}$ values derived across all soil groups. Coral sand data were excluded from comparisons with the TRS 472 subtropical and temperate datasets.

3. Results

3.1. Data coverage

The data underpinning the revised tropical dataset were collated from nearly 100 source references (publication list provided in the TECDOC). They covered 36 elements (Al, Am, As, Ba, Ca, Cd, Co, Cr, Cs, Cu, Fe, Hg, K, La, Mg, Mn, Mo, Na, Ni, P, Pb, Po, Pu, Ra, Rb, S, Sb, Sc, Se, Sm, Sr, Th, U, V, Y and Zn) including data for radionuclides and stable isotopes. The geographical coverage included 21 countries (Australia, Bangladesh, Benin, Brazil, Cameroon, Cuba, Ecuador, French Polynesia, Ghana, Honduras, India, Indonesia, Malaysia, Marshall Islands, Nigeria, Peru, Philippines, Sri Lanka, Tanzania, Thailand and Vietnam) spread across four continents (Africa, Asia, Australia and South America). More than 100 plant species were covered, including many that are common crops in tropical environments (e.g. *Amaranthus*, *Brassica*, *Manihot*, *Musa*, *Oryza*, *Solanum*) and some that are also harvested in subtropical and temperate environments (e.g. bean, cabbage, citrus, maize, potato, sorghum).

3.2. Description of the revised tropical dataset and data availability

The revised tropical dataset is too large to include in this paper and is available in the TECDOC. The dataset contains $CR_{plant\text{-}soil}$ values for more than 800 element – plant group – plant compartment – soil group combinations based on more than 10,000 total observations. Compared to the TRS 472 dataset for tropical environments, there are about a factor of five higher number of reported combinations and about a factor of ten higher number of observations. Much of the new data arose from the inclusion of stable isotopes and studies published after the publication of TRS 472.

Table 3 summarises the overall data availability in the revised tropical dataset. For each element and plant group, it shows the approximate number of $CR_{plant\text{-}soil}$ values across all plant compartments and soil groups. Fruits are the best represented plant group, with $CR_{plant\text{-}soil}$ values available for 31 elements based on more than 3000 total observations. Other plant groups with good overall data availability include leafy vegetables (18 elements, >1000 observations), non-leafy vegetables (21 elements, >800 observations), rice (19 elements, >1000 observations) and tubers (28 elements, >600 observations). The plant groups with lower data availability include cereals (7 elements, <100 observations), grasses (12 elements, <200 observations) and maize (15 elements, <200 observations). Elements of potential interest to radiological impact assessment with good overall data availability include Cs, Sr, U, Th and Ra, while those with low data availability include Am, Po and Pu.

Table 4 shows the availability of $CR_{plant\text{-}soil}$ values for specific soil groups within the revised tropical dataset. The number of such values was low due to the lack of soil characterisation data (including descriptions of soil texture) in most source references. Hence, most of the $CR_{plant\text{-}soil}$ values in the revised tropical dataset relate to unspecified soils. Where soil information was available, the specified soil group was mainly loam or sand.

For the newly introduced coral sand soil group, $CR_{plant\text{-}soil}$ values were limited to K and fallout radionuclides (Am, Cs, Pu and Sr) from past nuclear weapons testing (Table 4). When compared to all soils excluding coral sand, the Cs $CR_{plant\text{-}soil}$ for coral sand soils was generally one order of magnitude higher in cereals, fruits, herbs, leafy vegetables, non-leafy vegetables, leguminous vegetables and tubers (Figure 1). This is likely due to the very low clay mineral content in coral sand soils, making Cs more readily available for uptake. In contrast to Cs, the Sr $CR_{plant\text{-}soil}$ values in fruits (the only plant group for which Sr data for coral sand soils were available) were about two orders of magnitude lower than those for all soils excluding coral sand. The marked difference in root uptake for Sr is likely due to strong competition from the nutrient Ca, which is chemically similar to Sr (both group II elements) and is a major component of the coral sand soil matrix. The available $CR_{plant\text{-}soil}$ values for K were generally similar between coral sand soils and all other soils, possibly due to the regulation of K uptake as an essential macronutrient in plants. No comparative $CR_{plant\text{-}soil}$ values between coral sand and other soils were available for Am and Pu.

3.3. Revised $CR_{plant\text{-}soil}$ values for selected elements

Sub-datasets for selected elements with isotopes that are radiologically relevant are presented in Tables 5–8. Cs (Table 5) and Sr (Table 6) are given as examples of artificial radionuclides that can be released into the environment from nuclear facilities. U (Table 7) and Ra (Table 8) are given as examples of natural radionuclides whose environmental concentrations can be enhanced through activities such as uranium mining and phosphate fertiliser production. The $CR_{plant\text{-}soil}$ values presented in Tables 5–8 relate to all soil groups combined and all soil groups excluding coral sand where applicable (Cs and Sr). Soil group specific data are provided in the TECDOC.

3.4. Comparison with TRS 472 $CR_{plant\text{-}soil}$ values

Table 9 summarises the outcome of determining the ratio between the $CR_{plant\text{-}soil}$ values in the revised tropical dataset and those in TRS 472 for equivalent element – plant group – plant compartment – soil group combinations. The evaluation considered the TRS 472 datasets for temperate, subtropical and tropical environments, as well as those for rice (combined TRS 472 datasets for radionuclides and stable isotopes in rice), which were not assigned to any particular environment type in TRS 472. The total number of comparisons across all TRS 472 datasets was 319.

The comparison of the revised tropical dataset to the TRS 472 temperate dataset yielded ratios that were mostly (>80%) greater than 1. About 40% of the ratios were greater than 10 and about 14% were greater than 100. By comparison, only about 2% of the ratios were less than 0.1. Ratios greater than 100 were observed for leafy vegetables (Fe, Pb, Sb and Th), non-leafy vegetables (Na and Th), root crops (Ba, Ra, Th and U) and tubers (Ba, Cr, Pb, Sr and Th) for various soil types. The sign test, which assessed whether there were significantly more ratios >1 than <1, provided a highly significant result ($p<<0.001$) that the $CR_{plant\text{-}soil}$ values in the revised tropical dataset were generally greater than those in the TRS 472 temperate dataset. As an illustrative example, Figure 2 shows ratios of the revised tropical $CR_{plant\text{-}soil}$ values in the Cs, Sr, U and Ra sub-datasets (Tables 5–8) to the equivalent entry in the TRS 472 temperate tables.

The comparison to the TRS 472 subtropical dataset gave a similar result to that for the temperate dataset. The general trend was for ratios greater than 1, with the sign test confirming that this trend was highly significant ($p<<0.001$).

For the comparison to the TRS 472 tropical dataset, about 73% of the ratios were between 0.1 and 10, indicating that the $CR_{plant\text{-}soil}$ values in the revised tropical dataset were mostly within a factor of 10 lower or higher than those in the TRS 472 tropical dataset. This is not unexpected, as the climate categories of the two datasets are more closely aligned. The sign test indicated no significant difference ($p>0.05$) between the two datasets overall based on ratios. However, the ratios still generally tended towards higher values. Examples of ratios greater than 10 included Cs and natural radionuclides (Ra, Th and U) across a range of plant and soil types. There were only seven ratios less than 0.1, with most of these being for fruits.

For the comparison to the TRS 472 rice data, most (>90%) of the ratios were greater than 1 and many (>50%) were greater than 10. Examples of ratios greater than 10 included Cs, Ra and Th for a range of soil types. The sign test returned a highly significant result ($p<<0.001$) that the rice $CR_{plant\text{-}soil}$ values in the revised tropical dataset were generally higher than those in the TRS 472, which were derived from data across a range of climate types.

4. Discussion

4.1. Processes leading to higher $CR_{plant\text{-}soil}$ values in tropical environments

The $CR_{plant\text{-}soil}$ values in the revised tropical dataset, compiled based on the K-G classification of tropical (class A) climates, tend towards higher values overall than those in TRS 472 across all environment types (Table 9). Although that was not a consistent outcome for each individual $CR_{plant\text{-}soil}$ value in the revised tropical dataset (at least one comparable value was lower by a factor of >100), it was highly statistically significant ($p<<0.001$) across the range of comparable values for comparisons to the TRS 472 temperate and subtropical datasets.

The tropical (class A) climates considered in the revised dataset are both warm and humid. The rainfall in these climates can be either seasonal or continuous, but is quite reliable and copious in either case. As a result, the type of vegetation growing in these environments tends to be lush and abundant, even if sometimes seasonal. Soil microbiota, the main drivers of nutrient cycles in soils, also tend towards higher populations in more humid environments (Sieverding, 1990; Twining et al., 2004; Visser, 1969). Overall, vigorous plant growth is typical under these climatic conditions. However, such growth also depends on the type and nutritional status of the associated soil.

Common and abundant soils in tropical environments include Acrisols, Alisols, Andosols, Ferralsols, Gleysols, Lixisols and Nitisols (IUSS Working Group WRB, 2015). Despite the common opinion that these soils are generally lateritic, acidic and infertile, it is only the case for about 7% of tropical soils (Sanchez, 2000). Most tropical soils are deep and well developed. However, the upper layers are often depleted in more complex clay minerals such as illite, with 1:1 type clays such as kaolinite being more common (Finkl, 2008; Punke, 2017). The prevailing clay mineralogy can substantively reduce cation exchange capacity (CEC) and hence make dissolved elements (including radionuclides) in the active rooting zone more available for uptake in these environments. This characteristic may be one reason for the generally higher $CR_{plant\text{-}soil}$ values in tropical environments.

The tendency towards luxuriant growth is constrained by, and contributes to, nutrient limitation in the surface soils in tropical environments. The low levels of nutrients are also exacerbated by the low CEC noted above in that any nutrients may be washed down the soil profile by the abundant input of rainwater to the soil surface. These processes lead to reduced levels of dissolved substances in surface soils and may be another factor for comparatively higher $CR_{plant\text{-}soil}$ values in tropical environments by decreasing surface soil concentrations of elements and radionuclides available for root uptake.

As noted above, soil microbial populations, particularly fungi, are supported by ready availability of soil moisture. Soil fungi associated with plant roots, particularly vesicular arbuscular mycorrhiza (VAM), greatly enhance effective root surface areas (Bonfante and Genre, 2010; Garrett, 1981; Hoeksema et al., 2018). Given their relative abundance in moist tropical soils, this is another possible reason for the observed tendency towards higher $CR_{plant\text{-}soil}$ values in tropical environments. The high microbial loads also lead to rapid decomposition of infalling organic matter, particularly leaf litter, and the re-adsorption of associated nutrients and their chemical analogues. Hence, any materials lost by leaf fall are readily made available to the roots of the plants. Further, the rapid decomposition of organics leads to a reduction in the ability of such ligands to complex with any dissolved elements. This may also contribute to the observed trend for higher $CR_{plant\text{-}soil}$ values in tropical environments.

The issues discussed above are pertinent to natural ecosystems. The same basic principles apply to agricultural land within tropical (class A) climates. However, human activities inevitably have some influence on altering natural patterns. Agricultural systems applied across tropical environments range from gathering wild plants and basic subsistence methods, such as 'slash and burn', to broad scale industrial agriculture using machines and chemicals (National Research Council, 1993). All such systems employ methods to enhance plant nutrition, to amend soil organic loads and to adapt soil moisture levels. As such, there are a multitude of potential factors that could influence radionuclide transfer and related $CR_{plant\text{-}soil}$ values within such systems. Some of the more critical factors include alteration of dissolved nutrient levels, artificial physical alteration of soil profiles, irrigation, soil organic matter amendment, soil pH, soil Eh, crop type and others. A more detailed discussion of these factors as they relate to tropical systems is available in Tagami et al. (2012).

4.2. Application of the revised tropical $CR_{plant\text{-}soil}$ values

The revised $CR_{plant\text{-}soil}$ values for tropical environments have been derived from data for numerous sites worldwide that meet the K-G definition of tropical (class A) climate. Hence, they are broadly representative of the soil to plant transfer of radionuclides under such climate conditions and can be considered generic values for tropical environments globally.

The revised $CR_{plant\text{-}soil}$ values can be used in radiological assessment models to predict radionuclide activity concentrations in crops due to root uptake from soils. However, given their generic nature, their accuracy is limited to providing a general guide of the expected doses. Therefore, the values are most suitable for use in screening assessments to evaluate the radiological significance of exposures via the food chain. It is generally expected that several conservative assumptions would accompany the use of the values in screening assessments to ensure that doses are not underestimated.

Similar to the advice given in TRS 472, the revised $CR_{plant\text{-}soil}$ values are not generally recommended for use in situations where an accurate estimate of the dose is required. This may include situations where the initial screening assessment was not passed or where there is a specific need to document the actual radiation risk from crops (possibly so it can be put into context with other known risks). In such cases, site-specific data will likely provide the most realistic estimate of the dose. The revised $CR_{plant-soil}$ values are also not recommended for use in emergency exposure situations where equilibrium conditions for the movements of radionuclides into and out of the relevant environmental compartments are not met. Assessors should consider the purpose of their assessment and ensure that the use of the revised $CR_{plant-soil}$ values available in the TECDOC is fit for that purpose.

4.3. Addressing data gaps

Although the revised tropical dataset is an improvement over that of TRS 472, data gaps remain (as can be seen in Table 3) and may need filling depending on the specific scenario under assessment. Gap filling methods are described in TRS 472 and include the use of analogue isotopes, analogue elements and analogue species (i.e. plant groups). However, gap filling represents a source of uncertainty in the assessment and careful selection of analogues is required to minimise this uncertainty to the extent practicable.

5. Conclusions

The revised dataset of $CR_{plant-soil}$ values for tropical environments developed under the IAEA MODARIA II programme provides many additional entries than were available in TRS 472 for tropical environments. It also benefits from being based on clearly defined criteria for data selection by following the K-G classification of tropical (class A) climates.

Where comparisons could be made, the $CR_{plant-soil}$ values in the revised tropical dataset were generally higher than those in TRS 472 for the equivalent element – plant group – plant compartment – soil group combination. This trend was significant ($p<0.05$) for comparisons made to the TRS 472 datasets for temperate and subtropical environments and rice, but not for tropical environments.

Various biogeochemical factors pertinent to tropical environments may lead to higher $CR_{plant-soil}$ values. These factors include soil moisture levels, a preponderance of low activity clays, low nutrient availability and high microbial populations in soil, amongst others. Regional agricultural practice factors are also likely to influence the data. Experimental studies would be beneficial to confirm these observations.

The revised $CR_{plant-soil}$ values can be used to predict radionuclide activity concentrations in crops due to root uptake from soil in tropical environments. However, they are generic values, best suited for conservative screening assessments. Where accurate estimates of radiation dose are required, site-specific data should be used.

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Table 1. Plant groups (subgroups) and plant compartments in the revised tropical dataset.

Plant group	Plant compartment
Cereals	Grains, seeds and pods
	Stems and shoots
Maize	Grains, seeds and pods
	Stems and shoots
Rice	Grains, seeds and pods
	Stems and shoots
Leafy vegetables	Leaves
Non-leafy vegetables	Fruits, heads, berries and buds
Leguminous vegetables	Grains, seeds and pods
Root crops	Roots
Tubers	Tubers
Fruits (herbaceous plants, shrubs, woody trees, non-woody trees)	Fruits, heads, berries and buds
Grasses	Stems and shoots
Herbs	Grains, seeds and pods
	Leaves
	Rhizomes
	Roots
	Stems and shoots
	Whole plant
Medicinal plants (shrubs, woody trees, non-woody trees)	Bark
	Leaves
Other crops	Cacao beans
	Coffee beans
	Peanuts

Table 2. Soil groups in the revised tropical dataset.

Soil group	Definition
Sand	Sand content ≥ 65% and clay content < 18%, or texture described as sandy
Clay	Clay content ≥ 35%, or texture described as clayey
Loam	Clay content between 18% and 35%, or texture described as loamy
Organic	Organic matter content ≥ 20%
Coral sand	Marshall Islands soils
Unspecified	No characterisation information

Table 3. Data availability for $CR_{plant\text{-}soil}$ values in the revised tropical dataset.

Element	Cereals	Maize	Rice	Leafy vegetables	Non-leafy vegetables	Leguminous vegetables	Root crops	Tubers	Fruits	Grasses	Herbs	Medicinal plants	Other crops
Al	0	0	1–10	0	0	0	0	11–50	51–100	0	0	1–10	0
Am	0	0	0	0	0	0	0	0	11–50	0	0	0	0
As	1–10	1–10	11–50	>100	>100	51–100	11–50	11–50	51–100	0	11–50	0	0
Ba	0	0	0	0	0	0	1–10	11–50	>100	0	0	0	11–50
Ca	0	0	0	0	11–50	0	0	11–50	51–100	0	0	1–10	0
Cd	0	1–10	11–50	51–100	11–50	11–50	1–10	11–50	51–100	1–10	51–100	11–50	>100
Co	0	1–10	11–50	11–50	11–50	1–10	1–10	11–50	11–50	1–10	1–10	0	11–50
Cr	0	1–10	>100	>100	11–50	11–50	1–10	11–50	51–100	0	1–10	1–10	0
Cs	11–50	51–100	11–50	>100	51–100	1–10	11–50	1–10	>100	11–50	51–100	51–100	1–10
Cu	0	11–50	51–100	51–100	11–50	11–50	11–50	11–50	>100	1–10	11–50	11–50	11–50
Fe	0	1–10	51–100	51–100	1–10	11–50	1–10	11–50	51–100	0	11–50	11–50	11–50
Hg	0	0	0	0	0	0	0	0	11–50	0	0	11–50	0
K	1–10	1–10	>100	51–100	51–100	11–50	51–100	51–100	>100	11–50	>100	>100	0
La	0	0	0	0	0	0	0	0	0	0	0	1–10	0
Mg	0	0	0	0	11–50	0	0	11–50	>100	0	0	0	0
Mn	0	1–10	51–100	11–50	11–50	1–10	1–10	11–50	>100	0	1–10	1–10	11–50
Mo	0	0	0	0	0	0	1–10	1–10	1–10	0	1–10	0	11–50
Na	0	0	0	0	11–50	0	0	0	11–50	0	0	1–10	0
Ni	0	1–10	>100	11–50	11–50	11–50	11–50	11–50	11–50	1–10	1–10	1–10	11–50
P	0	0	0	0	0	0	0	1–10	11–50	0	0	0	0
Pb	0	11–50	>100	>100	11–50	11–50	1–10	11–50	>100	11–50	51–100	11–50	11–50
Po	0	0	11–50	0	11–50	0	0	1–10	11–50	0	1–10	1–10	0
Pu	0	0	0	0	0	0	0	0	11–50	0	0	0	0
Ra	0	1–10	>100	51–100	51–100	11–50	51–100	11–50	>100	11–50	>100	>100	0
Rb	0	0	0	0	0	0	0	1–10	11–50	0	0	0	0
S	0	0	0	0	0	0	0	11–50	51–100	0	0	0	0
Sb	0	0	0	11–50	0	0	0	1–10	0	0	0	0	0
Sc	0	0	0	0	0	0	0	0	0	0	0	1–10	0
Se	0	0	0	0	0	0	0	1–10	11–50	0	1–10	0	0
Sm	0	0	0	0	0	0	0	0	0	0	0	1–10	0
Sr	1–10	0	11–50	11–50	1–10	11–50	1–10	11–50	>100	1–10	1–10	11–50	1–10
Th	1–10	1–10	51–100	11–50	51–100	1–10	51–100	51–100	>100	11–50	51–100	11–50	1–10
U	1–10	1–10	11–50	1–10	11–50	0	11–50	11–50	>100	1–10	1–10	11–50	1–10
V	0	0	1–10	1–10	1–10	0	1–10	1–10	11–50	0	1–10	0	0
Y	0	0	0	0	0	1–10	0	0	0	0	0	0	0
Zn	1–10	11–50	51–100	51–100	11–50	11–50	11–50	11–50	>100	1–10	1–10	11–50	11–50

Key	0		1–10		11–50		51–100		>100	

Table 4. Availability of $CR_{plant-soil}$ values with specific soil group information in the revised tropical dataset.

Element	Cereals	Maize	Rice	Leafy vegetables	Non-leafy vegetables	Leguminous vegetables	Root crops	Tubers	Fruits	Grasses	Herbs	Medicinal plants	Other crops
Al			Loam										
Am									X				
As											Loam		
Ba													
Ca													
Cd					Sand				Loam, Sand	Sand	Loam	Loam	Loam, Sand, Clay
Co			Loam	Loam	Loam, Sand	Loam			Loam	Loam, Sand			Loam
Cr			Loam, Clay										
Cs	Loam, Sand, X	X	Loam, Sand, Clay	Loam, Sand, Clay, X	Loam, Sand, Clay, X	Loam, Sand, X	Loam, Clay	Clay, X	Loam, Sand, X	Loam, Sand, Clay	Sand, Clay, X		Loam
Cu		Sand	Loam, Clay	Loam, Clay	Sand, Clay	Clay	Sand		Loam	Sand		Loam	Loam
Fe			Loam, Clay										Loam
Hg									Loam			Loam	
K	Loam	Sand	Loam, Sand, Clay, O	Loam, Sand, Clay	Loam, Sand, Clay	Loam	Loam, Sand, O, X	Loam, O	Loam, Sand, X	Loam, Sand, Clay	Loam, Sand, X	Loam, X	
La													
Mg													
Mn			Loam, Clay										Loam
Mo													
Na													
Ni		Sand	Loam, Clay		Sand		Sand		Sand	Sand			Loam
P													
Pb		Sand	Loam, Clay	Loam, Clay	Sand, Clay	Clay			Loam	Sand	Loam	Loam	Loam
Po													
Pu									X				
Ra			Loam, Sand, Clay, O	Loam, Sand, Clay	Loam, Clay		Loam, Sand, O	Loam, O	Sand	Loam, Sand	Loam, Sand	Loam, Sand	
Rb													
S													
Sb													
Sc													
Se											Loam		
Sm													
Sr	Loam, Sand		Loam, Sand	Loam, Sand	Loam	Loam, Sand			Loam, X	Loam			Loam
Th	Loam	Sand	Loam, Sand, Clay, O	Loam, Sand, Clay			Loam, Sand, O	Loam, O	Sand	Sand	Sand	Sand	
U	Loam	Sand		Sand			Loam, Sand	Loam	Sand				
V													
Y							Loam						
Zn	Loam, Sand	Sand	Loam, Clay	Loam, Clay	Loam, Sand, Clay	Loam, Sand, Clay	Sand		Loam, Sand	Loam, Sand		Loam	Loam

Key	Loam		Sand		Clay		Organic	O	Coral sand	X

Table 5. Revised tropical $CR_{plant\text{-}soil}$ values for Cs for all soil groups (an asterisk (*) indicates all soil groups excluding coral sand).

Plant group (subgroup)	Plant compartment	N[a]	AM[b]	SD[c]	GM[d]	GSD[e]	Minimum	Maximum
Cereals	Grains, seeds and pods	21	9.4E+0	9.1E+0	6.7E+0	2.3	1.3E-1	3.1E+1
Cereals	*Grains, seeds and pods*	*6*	*2.3E-1*	*1.2E-1*	*2.1E-1*	*1.6*	*1.3E-1*	*3.3E-1*
Rice	Grains, seeds and pods	33	2.6E-1	3.2E-1	1.7E-1	2.6	3.4E-2	3.7E-1
Leafy vegetables	Leaves	117	2.3E+1	3.9E+1	1.2E+1	3.2	3.4E-1	2.5E+2
Leafy vegetables*	Leaves	66	1.8E+0	1.6E+0	1.3E+0	2.2	3.4E-1	2.9E+0
Non-leafy vegetables	Fruits, heads, berries and buds	66	1.0E+0	1.6E+0	5.5E-1	3.0	2.8E-3	9.7E+0
Non-leafy vegetables*	Fruits, heads, berries and buds	55	5.2E-1	5.5E-1	3.6E-1	2.4	2.8E-3	2.3E+0
Leguminous vegetables	Grains, seeds and pods	8	6.6E-1	1.3E+0	2.9E-1	3.6	8.4E-3	3.9E+0
Leguminous vegetables*	Grains, seeds and pods	7	1.9E-1	1.0E-1	1.7E-1	1.6	8.4E-3	2.6E-1
Root crops	Roots	18	2.9E-1	3.3E-1	1.9E-1	2.5	7.1E-2	8.1E-1
Tubers	Tubers	7	1.6E+0	1.5E+0	1.2E+0	2.2	1.6E-1	3.8E+0
Tubers*	Tubers	4	5.7E-1	3.4E-1	4.9E-1	1.7	1.6E-1	1.0E+0
Fruits (all fruits)	Fruits, heads, berries and buds	718	2.5E+0	2.6E+1	2.5E-1	8.6	4.5E-3	4.1E+1
Fruits (all fruits)*	Fruits, heads, berries and buds	14	6.4E-2	6.7E-2	4.4E-2	2.4	4.5E-3	2.3E-1
Fruits (woody trees)	Fruits, heads, berries and buds	42	3.2E-1	1.1E+0	8.7E-2	5.0	4.5E-3	3.7E+0
Fruits (woody trees)*	Fruits, heads, berries and buds	7	2.4E-2	5.1E-2	1.0E-2	3.7	4.5E-3	1.4E-1
Fruits (non-woody trees)	Fruits, heads, berries and buds	671	2.7E+0	2.6E+1	2.8E-1	8.4	1.0E-1	4.1E+1
Grasses	Stems and shoots	16	1.3E-1	7.7E-2	1.1E-1	1.8	4.0E-2	3.4E-1
Herbs	Leaves	48	5.1E+0	1.1E+1	2.1E+0	3.8	4.0E-2	5.7E+1
Herbs*	Leaves	40	6.3E-1	1.7E-1	6.1E-1	1.3	4.0E-2	3.0E+0
Medicinal plants (woody trees)	Leaves	55	3.4E-1	1.7E-1	3.0E-1	1.6	5.0E-2	1.5E+0
Medicinal plants (non-woody trees)	Leaves	12	6.3E-1	n/a[f]	n/a	n/a	2.3E-1	1.3E+0

[a]N: number of observations in all studies.

[b]AM: arithmetic mean.

[c]SD: standard deviation.

[d]GM: geometric mean.

[e]GSD: geometric standard deviation.

[f]n/a: value not available.

Table 6. Revised tropical $CR_{plant\text{-}soil}$ values for Sr for all soil groups (an asterisk (*) indicates all soil groups excluding coral sand).

Plant group (subgroup)	Plant compartment	N[a]	AM[b]	SD[c]	GM[d]	GSD[e]	Minimum	Maximum
Cereals	Grains, seeds and pods	6	6.0E-1	2.0E-1	5.7E-1	1.4	4.4E-1	7.6E-1
Rice	Grains, seeds and pods	28	3.5E-1	3.4E-1	2.6E-1	2.2	1.2E-1	8.9E-1
Leafy vegetables	Leaves	35	8.1E+0	8.0E+0	5.8E+0	2.3	1.6E-1	1.8E+1
Non-leafy vegetables	Fruits, heads, berries and buds	4	6.2E-1	5.9E-2	6.1E-1	1.1	5.5E-1	6.9E-1
Leguminous vegetables	Grains, seeds and pods	17	3.4E+0	1.4E+0	3.2E+0	1.5	5.8E-1	5.9E+0
Root crops	Roots	6	2.0E+0	2.2E-1	2.0E+0	1.1	1.1E+0	3.0E+0
Tubers	Tubers	23	3.8E+1	6.2E+1	2.0E+1	3.1	7.0E-2	2.2E+2
Fruits (all fruits)	Fruits, heads, berries and buds	191	4.4E-1	1.1E+0	1.6E-1	4.1	6.0E-4	7.4E+0
Fruits (all fruits)*	Fruits, heads, berries and buds	93	9.0E-1	1.5E+0	4.6E-1	3.2	1.9E-3	7.4E+0
Fruits (herbaceous plants)	Fruits, heads, berries and buds	18	2.1E-1	5.5E-1	7.8E-2	4.1	1.9E-3	2.5E+0
Fruits (shrubs)	Fruits, heads, berries and buds	6	5.5E-1	5.0E-1	4.1E-1	2.2	4.8E-2	1.4E+0
Fruits (woody trees)	Fruits, heads, berries and buds	76	1.0E+0	1.6E+0	5.4E-1	3.1	1.4E-2	7.4E+0
Fruits (non-woody trees)	Fruits, heads, berries and buds	91	1.2E-2	8.9E-2	1.6E-3	7.5	6.0E-4	8.3E-1
Herbs	Leaves	8	1.0E+0	7.6E-1	8.3E-1	1.9	9.0E-2	2.8E+0
Medicinal plants (woody trees)	Leaves	15	1.2E+0	7.1E-1	1.1E+0	1.7	1.8E-1	2.7E+0

[a]N: number of observations in all studies.

[b]AM: arithmetic mean.

[c]SD: standard deviation.

[d]GM: geometric mean.

[e]GSD: geometric standard deviation.

Table 7. Revised $CR_{plant\text{-}soil}$ values for U for all soil groups.

Plant group (subgroup)	Plant compartment	N[a]	AM[b]	SD[c]	GM[d]	GSD[e]	Minimum	Maximum
Cereals	Grains, seeds and pods	6	2.0E-3	5.4E-4	1.9E-3	1.3		
Maize	Grains, seeds and pods	4	6.4E-1	1.4E-1	6.2E-1	1.2	4.7E-1	8.0E-1
Rice	Grains, seeds and pods	15	9.2E-2	5.1E-2	8.1E-2	1.7	4.0E-2	2.0E-1
Leafy vegetables	Leaves	9	4.9E-1	4.1E-1	3.8E-1	2.1	2.1E-2	1.3E+0
Non-leafy vegetables	Fruits, heads, berries and buds	33	1.2E-2	2.3E-2	5.9E-3	3.4	6.0E-4	3.1E-2
Root crops	Roots	34	4.8E-1	5.6E-1	3.1E-1	2.5	1.9E-2	2.7E+0
Tubers	Tubers	49	1.8E-1	2.6E-1	1.0E-1	2.9	1.6E-3	1.5E+0
Fruits (all fruits)	Fruits, heads, berries and buds	134	1.3E-2	4.6E-2	3.7E-3	5.0	1.2E-5	3.5E-1
Fruits (herbaceous plants)	Fruits, heads, berries and buds	15	2.1E-3	3.3E-3	1.2E-3	3.0	1.2E-5	1.0E-2
Fruits (shrubs)	Fruits, heads, berries and buds	12	2.1E-3	3.8E-3	1.0E-3	3.3	1.4E-4	1.3E-2
Fruits (woody trees)	Fruits, heads, berries and buds	84	2.2E-3	3.7E-3	1.1E-3	3.2	3.7E-5	2.2E-2
Fruits (non-woody trees)	Fruits, heads, berries and buds	23	6.7E-2	9.6E-2	3.9E-2	2.9	1.4E-4	3.5E-1
Grasses	Stems and shoots	2	3.1E-1	-	-	-	2.6E-1	3.5E-1
Herbs	Leaves	2	2.7E-3	-	-	-	n/a[f]	n/a
Medicinal plants (shrubs)	Leaves	5	5.7E-3	2.3E-3	5.3E-3	1.5	n/a	n/a
Medicinal plants (woody trees)	Leaves	10	9.6E-3	3.5E-3	9.0E-3	1.4	5.5E-3	1.4E-2
Medicinal plants (non-woody trees)	Leaves	10	3.0E-3	8.2E-4	2.8E-3	1.3	1.4E-3	4.5E-3
Other crops	Peanuts	3	5.1E-1	7.0E-1	3.0E-1	2.8	1.0E-2	1.5E+0

[a]N: number of observations in all studies.
[b]AM: arithmetic mean.
[c]SD: standard deviation.
[d]GM: geometric mean.
[e]GSD: geometric standard deviation.
[f]n/a: value not available.

Table 8. Revised tropical $CR_{plant\text{-}soil}$ values for Ra for all soil groups.

Plant group (subgroup)	Plant compartment	N[a]	AM[b]	SD[c]	GM[d]	GSD[e]	Minimum	Maximum
Maize	Grains, seeds and pods	1	8.5E-3	-	-	-	-	-
Rice	Grains, seeds and pods	78	1.3E-1	2.2E-1	7.0E-2	3.1	2.2E-3	9.8E-1
Leafy vegetables	Leaves	69	3.3E-1	3.5E-1	2.2E-1	2.4	1.0E-2	2.0E+0
Non-leafy vegetables	Fruits, heads, berries and buds	85	1.4E-1	2.5E-1	6.6E-2	3.4	1.2E-3	7.6E-1
Leguminous vegetables	Grains, seeds and pods	15	1.3E-1	1.3E-1	9.7E-2	2.2	6.3E-3	4.2E-1
Root crops	Roots	52	7.9E-1	7.8E-1	5.6E-1	2.3	4.0E-2	5.0E+0
Tubers	Tubers	45	6.2E-1	9.0E-1	3.5E-1	2.9	3.9E-3	4.1E+0
Fruits (all fruits)	Fruits, heads, berries and buds	177	2.8E-2	5.6E-2	1.2E-2	3.6	2.4E-4	4.6E-1
Fruits (herbaceous plants)	Fruits, heads, berries and buds	21	1.6E-2	2.4E-2	8.8E-3	3.0	2.5E-4	9.5E-2
Fruits (shrubs)	Fruits, heads, berries and buds	11	2.0E-2	2.9E-2	1.2E-2	2.9	1.1E-3	9.1E-2
Fruits (woody trees)	Fruits, heads, berries and buds	105	2.0E-2	2.6E-2	1.2E-2	2.7	2.4E-4	1.0E-1
Fruits (non-woody trees)	Fruits, heads, berries and buds	40	5.5E-2	1.0E-1	2.7E-2	3.4	3.8E-4	4.6E-1
Grasses	Stems and shoots	35	5.9E+0	7.4E+0	3.7E+0	2.6	4.0E-3	3.0E+1
Herbs	Leaves	90	2.1E-1	2.7E-1	1.3E-1	2.7	6.3E-3	2.0E+0
Medicinal plants (shrubs)	Bark	1	7.0E-2	-	-	-	-	-
Medicinal plants (shrubs)	Leaves	11	1.2E-1	8.8E-2	9.2E-2	2.0	3.7E-2	3.3E-1
Medicinal plants (woody trees)	Bark	28	1.4E-1	7.1E-2	1.2E-1	1.6	7.0E-2	2.7E-1
Medicinal plants (woody trees)	Leaves	83	1.1E-1	1.0E-1	8.1E-2	2.2	1.5E-2	6.5E-1
Medicinal plants (non-woody trees)	Leaves	20	8.6E-2	7.6E-2	6.4E-2	2.1	9.7E-3	3.8E-1

[a]N: number of observations in all studies.

[b]AM: arithmetic mean.

[c]SD: standard deviation.

[d]GM: geometric mean.

[e]GSD: geometric standard deviation.

Table 9. Ratio of $CR_{plant\text{-}soil}$ values between the revised tropical dataset and TRS 472 datasets.

TRS 472		Number of comparisons by ratio class						
Table no.	Description	≤0.01	>0.01–0.1	>0.1–1	>1–10	>10–100	>100	All
17 & 19	Temperate	0	3	25	64	43	22	157
20	Tropical	1	6	41	20	7	9	84
21	Subtropical	0	1	8	25	13	2	49
22 & 23	Rice	0	0	2	10	10	7	29

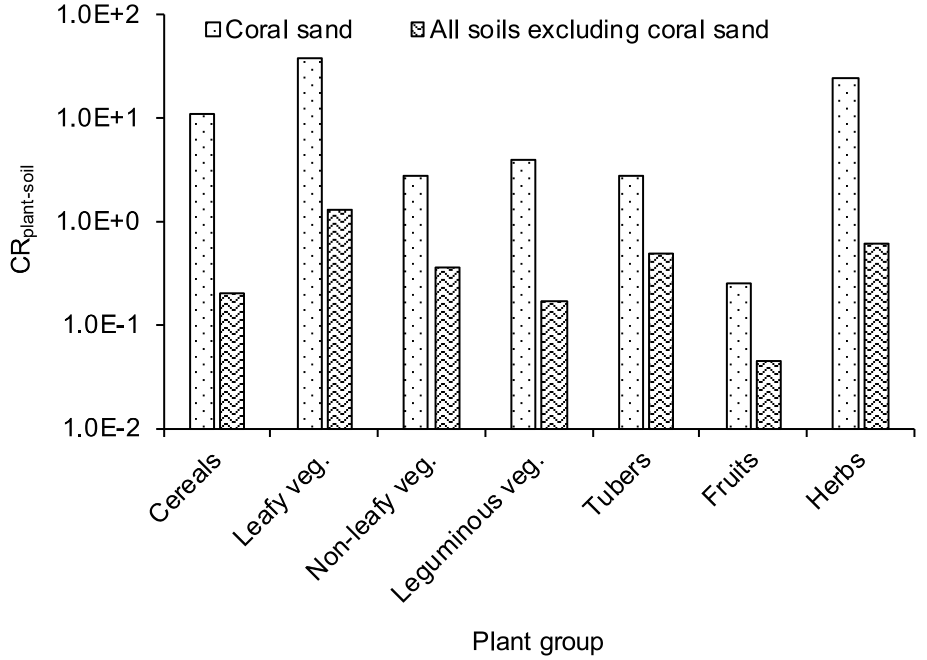

Figure 1. Geometric mean values of the Cs $CR_{plant\text{-}soil}$ for coral sand soils and all soils excluding coral sand.

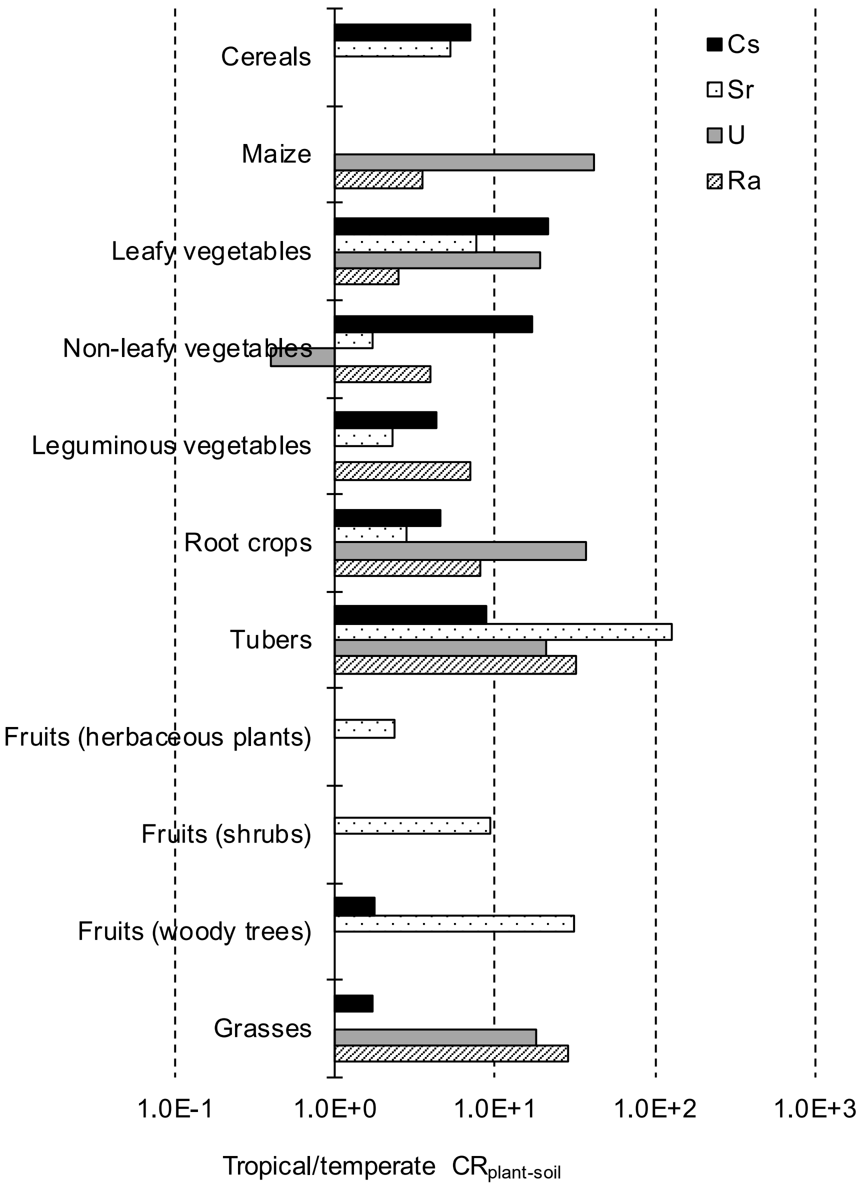

Figure 2. Illustrative example of the ratios between $CR_{plant\text{-}soil}$ values in the revised tropical dataset and the equivalent entry in the TRS 472 temperate dataset for selected elements (ratios were calculated using the relevant *GM* value from each dataset if available, otherwise the *AM* value was used; ratios >1 indicate higher $CR_{plant\text{-}soil}$ values in the revised tropical dataset and ratios <1 indicate higher $CR_{plant\text{-}soil}$ values in the TRS 472 temperate dataset).