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PAPER

Updated soil to fruit concentration ratios for radiocaesium compiled under the IAEA MODARIA II Programme

C Doering[1,*], F Carini[2], M Sato[3], BJ Howard[4,5], AR Harbottle[6], J Brown[6], J Twining[7] and H Velasco[8]

[1] Environmental Research Institute of the Supervising Scientist, Darwin, Australia
[2] Università Cattolica del Sacro Cuore, Piacenza, Italy
[3] Faculty of Food and Agriculture, Fukushima University, Fukushima, Japan
[4] Centre for Ecology and Hydrology, Lancaster, United Kingdom
[5] Division of Agricultural and Environmental Sciences, University of Nottingham, Nottingham, United Kingdom
[6] International Atomic Energy Agency, Vienna, Austria
[7] Austral Radioecology, Sydney, Australia
[8] GEA—Instituto de Matemática Aplicada San Luis (IMASL), Universidad Nacional de San Luis, Consejo Nacional de Investigaciones Científicas y Técnicas., San Luis, Argentina
[*] Author to whom any correspondence should be addressed.

E-mail: che.doering@environment.gov.au

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Abstract

Under the International Atomic Energy Agency (IAEA) Modelling and Data for Radiological Impact Assessments (MODARIA II) Programme, Working Group 4 activities included collating radionuclide transfer data from Japan following the Fukushima Daiichi Nuclear Power Plant accident and separately collating concentration ratio (CR) data for root uptake of radionuclides by crops grown in tropical and arid climates. In this paper, the newly compiled radiocaesium CR data for fruit from Japan, tropical and arid climates have been combined with the data originally compiled for the IAEA Technical Reports Series No. 472 (TRS 472) and additional data identified from the literature to produce an enhanced MODARIA II dataset of fruit radiocaesium CR values. Statistical analysis of the MODARIA II dataset by climate class (based on the Köppen–Geiger climate classification) indicated that the CR values for tropical climates were significantly higher ($p < 0.05$) than those for arid, temperate and cold climates. Statistical analysis of the MODARIA II dataset by soil group (based on soil texture) indicated that the CR values for coral sand soil (tropical climates only) and organic soil (temperate climates only) were significantly higher ($p < 0.05$) than those for the clay, loam and sand soil groups. Statistical analysis of the MODARIA II dataset by plant group (based on plant morphology) indicated that the CR values for non-woody trees (tropical climate bias) were significantly higher ($p < 0.05$) than those for herbaceous plants, shrubs and woody trees. Comparison of the MODARIA II dataset with original TRS 472 values showed only small changes in the fruit radiocaesium CR values for herbaceous plants and shrubs in temperate climates. There was a decrease in the CR values for woody trees in temperate climate across all soil groups. There was also a decrease in the CR values for tropical climates for all comparable soil groups.

1. Introduction

Fruits are an important food and agricultural product that are grown, consumed and traded globally. Many fruits are of high nutritional value to humans [1] and economically valuable to some countries [2]. Therefore, confidence in the safety of the fruit supply to domestic and international markets is of importance to producers, consumers, traders and governments worldwide.

Radioactivity released into the atmosphere from nuclear fuel cycle activities and nuclear or radiological accidents may contaminate a wide range of crops, including fruits. The associated risk can be transboundary and persist over timescales of years to decades or longer [3]. Knowledge of environmental transfer processes and related data are needed for relevant radionuclides to enable assessment of the radiation doses associated with radioactive contamination of crops in planned, existing and emergency situations.

With a physical half-life of approximately 30 years, ^{137}Cs is likely to be one of the most important radionuclides with a long-term presence in the environment following an atmospheric release of radioactivity from a nuclear facility. Therefore, the transfer of ^{137}Cs, and the shorter-lived isotope of ^{134}Cs ($T_{1/2} \approx 2$ years), needs to be quantified to predict both the short- and long-term radiocaesium activity concentrations of affected crops, including perennial plants such as fruit trees. The need for better information on the transfer of radiocaesium to fruit was highlighted after the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident because fruit was a key agricultural product grown in Fukushima Prefecture [4, 5].

Data on the transfer of radiocaesium to fruit have mostly been collected in affected areas after the Chernobyl [6–11] and FDNPP [4, 12–14] accidents. Following these discrete radioactive deposition events over several days, the main initial pathways for radiocaesium contamination of fruits from woody trees were identified as direct interception onto above-ground parts (e.g. foliage and bark) and subsequent translocation to fruit [5, 12–15]. The importance of these initial interception pathways for radiocaesium transfer to fruit depends on the stage of plant development at the time of deposition and the growth characteristics, plant structure and fruit type [4, 16]. Due to the identification of these interception pathways, initially after the Chernobyl accident and with many more data after the FDNPP accident, it was realised that root uptake of radiocaesium from soil for perennial plants may only become a significant transfer pathway several years after the deposition event. Therefore, radiocaesium uptake from soil is likely to be relatively more important over longer time periods after nuclear accidents, particularly for deciduous woody fruit trees [17]. This long-term soil to fruit transfer pathway is generally quantified using equilibrium concentration ratio (CR) values [18, 19].

International data compilations for predicting the transfer of radionuclides through the food chain to humans have been made over the last few decades through various coordinated initiatives of the International Atomic Energy Agency (IAEA). These compilations have been published within Technical Reports Series (TRS) and Technical Documents (TECDOC), including TRS 364 [20], TECDOC 1616 [16] and TRS 472 [19]. Recently, the IAEA released TECDOC 1927 [4] which compiles data on the environmental transfer of radionuclides in Japan following the FDNPP accident. TECDOC 1927 includes data for radiocaesium transfer to fruit, particularly for fruit from woody trees. The TECDOC is an output of Working Group 4 (WG4) 'Transfer Processes and Data for Radiological Impact Assessment' of the IAEA MODARIA II (Modelling and Data for Radiological Impact Assessments) Programme [21]. Also, within the MODARIA II WG4, the CR data from TRS 472 for root uptake by crops growing in tropical climates were updated [22] and the first international dataset of CR values for crops growing in arid climates was compiled [23]. The updated tropical dataset and newly compiled arid dataset are based on the Köppen–Geiger (K–G) climate classification [24]. These datasets are published in TECDOC 1979 [25] on soil to plant transfer of radionuclides in non-temperate environments.

In this paper, the fruit radiocaesium CR values in the newly compiled MODARIA II datasets from Japan, tropical and arid climates have been combined with those originally compiled for TRS 472 and additional data identified from the literature to form an enhanced MODARIA II fruit radiocaesium dataset. This enhanced dataset has been analysed for differences between the different fruit CR values based on K–G climate class, soil and plant type. It has also been compared with the original TRS 472 dataset to highlight where new data have been added and the associated changes in CR values.

2. Methods

The fruit radiocaesium dataset that was originally compiled for TRS 472 was supplemented with new data from: (a) Japan after the FDNPP accident [4]; (b) tropical and arid climates [25]; and (c) other studies identified through literature review and contacts of MODARIA II WG4 participants. The data were compiled in a dataset to put them in a structured format and facilitate analysis.

The CR data were compiled using fruit fresh mass (fm) and soil dry mass (dm) activity concentrations, which is consistent with the approach used in TRS 472. Where necessary, conversions of fruit data from a dm to fm basis were made by multiplying by the fractional dry matter content of the fruit. In order of preference, the sources for quantifying the fractional dry matter content values used were: (a) the source reference reporting the CR value; (b) the US Department of Agriculture National Nutrient Database for Standard Reference [26]; and (c) other published studies reporting information for the same type of fruit.

The data were divided into K–G climate classes following the worldwide map of present-day (1980–2016) classifications developed by Beck *et al* [24]. However, for the data from Fukushima Prefecture, more site-specific climate classification information [27] and the expert advice of MODARIA II WG4 participants

Table 1. Plant groups, with common and Latin names of associated fruits and K–G climate classes for which data were available.

Plant group	Common name	Latin name	Climate(s)[a]
Herbaceous plants	Melon	—	C
	Passionfruit	*Passiflora actinia*	A
	Pineapple	*Ananas comosus*	A
	Strawberry	*Fragaria × ananassa*	C, D
	Watermelon	*Citrullus lanatus*	B, C
Shrubs	Blackcurrant	*Ribes nigrum*	C, D
	Blueberry	*Vaccinium* spp.	C
	Gooseberry	*Ribes uva-crispa*	C
	Redcurrant	*Ribes rubrum*	D
	Red raspberry	*Rubus idaeus*	D
Woody trees	Apple	*Malus domestica*	B, C, D
	Apricot	*Prunus armeniaca*	B
	Breadfruit	*Artocarpus altilis*	A
	Cupuacu	*Theobroma grandiflorum*	A
	Fig	*Ficus* spp.	B, C
	Grape	*Vitis vinifera*	B, C
	Grapefruit	*Citrus paradisi*	A
	Guava	*Psidium guajava*	A
	Jackfruit	*Artocarpus integra*	A
	Japanese chestnut	*Castanea crenata*	C
	Kiwi	*Actinidia deliciosa*	C
	Lemon	*Citrus limon*	A
	Lime	*Citrus aurantiifolia*	A
	Mandarin	*Citrus reticulata*	C
	Mango	*Mangifera indica*	A
	Nectarine	*Prunus persica*	B, C
	Noni	*Morinda citrifolia*	A
	Olive	*Olea europaea*	B, C
	Orange	*Citrus aurantium, Citrus sinensis*	A, C
	Peach	*Prunus persica*	C
	Pear	*Pyrus* spp.	C
	Persimmon	*Diospyros kaki*	C
	Pomegranate	*Punica granatum*	A, B, C
	Rambutan	*Nephelium lappaceum*	A
	Satsuma mandarin	*Citrus unshiu*	C
Non-woody trees	Banana, plantain, platano	*Musa* spp.	A, C
	Buriti	*Mauritia vinifera*	A
	Coconut	*Cocos nucifera*	A
	Pandanus	*Pandanus* spp.	A
	Papaya, paw paw	*Carica papaya*	A

[a] A, tropical; B, arid; C, temperate; D, cold.

from Japan was followed. Overall, the data covered the K–G climate classes of tropical (A), arid (B), temperate (C) and cold (D). There were no data for polar (E) climates.

The data were also divided into plant and soil groups compatible with those described in TRS 472 to amalgamate sufficient data into more specific, useable subsets. Due to the paucity of data, some of the plant groups were somewhat arbitrary. The criterion adopted in TRS 472 (and followed in MODARIA II) was based on plant morphology and physiology, resulting in four plant groups, namely ‘herbaceous plants’, ‘shrubs’, ‘woody trees’ and ‘non-woody trees’. The category of non-woody trees was newly added during MODARIA II [22] to represent predominantly tropical crops such as banana (one of the most globally traded fruits [2]), papaya and palm fruits (e.g. buriti and coconut) which were not categorised in TRS 472. The fruits corresponding to each plant group and the associated K–G climate class(es) for which data were available are shown in table 1. Data were compiled for 40 different types of fruit. The data for most of the fruit types were specific to a single K–G climate class.

The soil groups used in the MODARIA II dataset were ‘clay’, ‘loam’, ‘sand’, ‘organic’ and ‘coral sand’ and were based on soil texture (see TRS 472 for the typical ranges of values of selected soil parameters for each soil group, except coral sand). The coral sand soil group was newly added during MODARIA II [22] to represent highly calcareous soils such as those of the Marshall Islands [28, 29] which were not categorised in TRS 472. Soils without textural information were grouped as ‘unspecified’.

Whilst compiling the MODARIA II fruit radiocaesium CR dataset, further quality control was conducted to check the allocation of the TRS 472 data to the K–G climate classes considered in this analysis. This led to some changes in the climate allocation of some data compared with that in TRS 472. Specifically, data from Sweden (shrubs, $N = 4$) were reallocated from temperate to cold climate and data from Syria (herbaceous plants, $N = 1$) were reallocated from temperate to arid climate. Furthermore, data for rhubarb ($N = 2$) that were included as herbaceous plants in the original TRS 472 data compilation were removed from the MODARIA II dataset, as rhubarb is considered a vegetable rather than a fruit.

Summary CR values were calculated by K–G climate class, soil and plant group. They were also calculated for all soil groups combined ('all'), which is consistent with the approach adopted in TRS 472.

About 10% of the CR data compiled in the MODARIA II dataset were excluded from the calculation of summary values and further analysis. The excluded data included values reported as being less than detection limits and some post-Chernobyl data where the main contamination pathway was considered to have been foliar uptake rather than root uptake. The data from Japan compiled from studies following the FDNPP accident were checked to ensure that root uptake of radiocaesium from soil was the main transfer pathway contributing to contamination in fruits. The data from Japan included both field studies and experimental studies [5, 12, 30–32].

Analysis of variance (ANOVA) with Tukey pairwise comparison was used to test the significance of the differences between CR values for different K–G climate classes, soil and plant groups. t-tests were used to test the significance of the differences between comparable CR values in the MODARIA II dataset and TRS 472. Log-transformed data were used in both the ANOVAs and t-tests as environmental data such as CR values typically follow a lognormal distribution [33].

3. Results and discussion

3.1. Differences in fruit CR data between climate classes, soil and plant groups

The MODARIA II dataset contains 214 entries compiled from 34 studies. Twenty countries (Australia, Bangladesh, Brazil, Cuba, Finland, France, Germany, Greece, India, Iraq, Israel, Italy, Japan, Marshall Islands, Nigeria, Sweden, Syria, Turkey, United Kingdom and United States of America) and four K–G climate classes (tropical (A), arid (B), temperate (C) and cold (D)) are represented within the data. The entire MODARIA II dataset of fruit radiocaesium CR values is included in the supplementary material (available online at stacks.iop.org/JRP/42/020511/mmedia).

Table 2 presents the summary CR values derived from the MODARIA II fruit radiocaesium dataset. The table columns are consistent with the TRS 472 format, giving geometric mean (GM) and geometric standard deviation (GSD) if there are three or more dataset entries (N). For $N < 3$, the arithmetic mean (AM) and standard deviation (SD) are given. Minimum and maximum values are also given. The table has been subdivided into K–G climate classes. A total of 39 summary CR values were derived including those for all soil groups. There are some soil and plant groups that are unique to the data for some climate classes. Organic soil is only present in the data for temperate climates, while coral sand soil is exclusive to the data for tropical climates. Non-woody trees are mainly associated with the data for tropical climates, although there is also one datapoint for a temperate (subtropical) location.

The number of available CR values varies between K–G climate classes, with most data originating from temperate climates, including the data reported after the Chernobyl and FDNPP accidents. Statistical comparisons of the MODARIA II fruit radiocaesium dataset were constrained by the relatively small number of datapoints for many of the categories in the other climate classes. Therefore, ANOVA was only conducted on data grouped by a single variable, either K–G climate class, soil group or plant group.

A comparison of CR values (GM) for each K–G climate class is given in figure 1, which does not distinguish the values by soil or plant group. The GM CR value for tropical climates (7.6×10^{-2}) is significantly higher ($p < 0.05$) than those for arid (6.9×10^{-4}), temperate (1.3×10^{-3}) and cold (4.4×10^{-3}) climates. There is no significant difference between the GM CR values for arid, temperate and cold climates.

Figure 2 compares CR values (GM) categorised by soil group without distinguishing by K–G climate class or plant group. The GM CR value related to coral sand (1.1×10^{0}) is significantly higher ($p < 0.05$) than those for clay (1.6×10^{-3}), loam (1.6×10^{-3}), sand (2.6×10^{-3}) and organic (2.4×10^{-2}) soils. The GM CR value for organic soil is significantly higher ($p < 0.05$) than those for clay, loam and sand. There is no significant difference between the GM CR values for the clay, loam and sand soil groups.

Coral sand soil is unique to the tropical climate data in the MODARIA II dataset. The data for this soil group originate from the Marshall Islands, which are a series of coral atolls in the Pacific Ocean that were contaminated by radiocaesium and other radionuclides during past nuclear weapons testing. The characteristics of coral sand soil include: (a) high calcium carbonate concentrations; (b) virtually no clay minerals (which have a high affinity for adsorbing radionuclides including radiocaesium); and (c) low

Table 2. MODARIA II fruit radiocaesium summary CR values categorised by K–G climate class, plant and soil group.

Plant group	Soil group	N	Mean value[a]	GSD/ SD[b]	Min	Max	Reference ID[c]
Tropical (A)							
Herbaceous plants	Loam	3	2.8×10^{-2}	2.0	1.7×10^{-2}	5.9×10^{-2}	19
Woody trees	Clay	2	1.0×10^{-2}	2.6×10^{-3}	8.3×10^{-3}	1.2×10^{-2}	13
	Coral sand	2	6.2×10^{-1}	3.4×10^{-1}	3.7×10^{-1}	8.6×10^{-1}	23, 27
	Loam	1	2.5×10^{-3}	—	—	—	33
	Sand	5	1.1×10^{-2}	6.4	2.1×10^{-3}	8.1×10^{-2}	4, 34
	Unspecified	7	8.3×10^{-2}	4.0	8.0×10^{-3}	7.8×10^{-1}	10, 30, 32
	All	17	3.6×10^{-2}	7.4	2.1×10^{-3}	8.6×10^{-1}	4, 10, 13, 23, 27, 30, 32, 33, 34
Non-woody trees	Clay	2	3.1×10^{-2}	7.1×10^{-4}	3.0×10^{-2}	3.1×10^{-2}	13
	Coral sand	7	1.3×10^{0}	3.6	1.0×10^{-1}	4.0×10^{0}	23, 27
	Sand	2	2.3×10^{-3}	4.4×10^{-4}	2.0×10^{-3}	2.6×10^{-3}	34
	Unspecified	5	1.9×10^{-1}	3.5	5.3×10^{-2}	1.5×10^{0}	10, 30, 32
	All	16	2.0×10^{-1}	11.2	2.0×10^{-3}	4.0×10^{0}	10, 13, 23, 27, 30, 32, 34
Arid (B)							
Herbaceous plants	Unspecified	1	6.0×10^{-4}	—	—	—	21
Woody trees	Loam	4	2.5×10^{-3}	7.8	4.5×10^{-4}	5.0×10^{-2}	1, 18
	Sand	6	3.0×10^{-4}	1.3	2.2×10^{-4}	4.2×10^{-4}	20
	All	10	7.0×10^{-4}	5.1	2.2×10^{-4}	5.0×10^{-2}	1, 18, 20, 21
Temperate (C)							
Herbaceous plants	Clay	1	5.4×10^{-4}	—	—	—	31
	Loam	1	9.0×10^{-4}	—	—	—	8
	Organic	1	6.4×10^{-3}	—	—	—	8
	Sand	1	4.2×10^{-3}	—	—	—	8
	Unspecified	9	1.6×10^{-3}	2.8	4.1×10^{-4}	1.0×10^{-2}	2, 8, 9
	All	13	1.7×10^{-3}	2.8	4.1×10^{-4}	1.0×10^{-2}	2, 8, 9, 31
Shrubs	Loam	4	2.3×10^{-3}	7.8	3.0×10^{-4}	3.5×10^{-2}	14
	Organic	1	1.4×10^{-1}	—	—	—	14
	Unspecified	17	1.7×10^{-3}	2.0	6.0×10^{-4}	5.2×10^{-3}	9
	All	22	2.2×10^{-3}	3.9	3.0×10^{-4}	1.4×10^{-1}	9, 14

(Continued.)

Table 2. (Continued.)

Plant group	Soil group	N	Mean value[a]	GSD/ SD[b]	Min	Max	Reference ID[c]
Woody trees	Clay	8	5.3×10^{-4}	4.3	9.3×10^{-5}	5.2×10^{-3}	28, 31
	Loam	44	1.2×10^{-3}	4.0	6.5×10^{-5}	2.7×10^{-2}	6, 9, 12, 16, 18, 24, 25, 26, 29
	Organic	7	2.3×10^{-2}	2.0	1.0×10^{-2}	7.9×10^{-2}	9
	Sand	10	4.6×10^{-3}	3.8	5.0×10^{-4}	8.0×10^{-2}	3, 9, 28
	Unspecified	27	2.2×10^{-3}	3.6	4.0×10^{-4}	1.3×10^{-1}	2, 9, 10, 11, 15, 17
	All	96	1.9×10^{-3}	4.8	6.5×10^{-5}	1.3×10^{-1}	2, 3, 6, 9, 10, 11, 12, 15, 16, 17, 18, 24, 25, 26, 28, 29, 31
Non-woody trees	Unspecified	1	1.3×10^{-2}	—	—	—	32
Cold (D)							
Herbaceous plants	Unspecified	3	8.0×10^{-3}	3.9	1.8×10^{-3}	2.6×10^{-2}	22
Shrubs	Clay	2	2.2×10^{-3}	1.7×10^{-3}	9.8×10^{-4}	3.3×10^{-3}	7
	Loam	2	3.8×10^{-3}	2.8×10^{-3}	1.8×10^{-3}	5.7×10^{-3}	7
	Unspecified	1	5.4×10^{-3}	—	—	—	22
	All	5	2.8×10^{-3}	2.1	9.8×10^{-4}	5.7×10^{-3}	7, 22
Woody trees	Unspecified	1	7.2×10^{-3}	—	—	—	22

[a] Geometric mean (GM) is reported where $N \geqslant 3$, otherwise the arithmetic mean (AM) is given.
[b] Geometric standard deviation (GSD)/standard deviation (SD).
[c] A publication index is provided in the appendix.

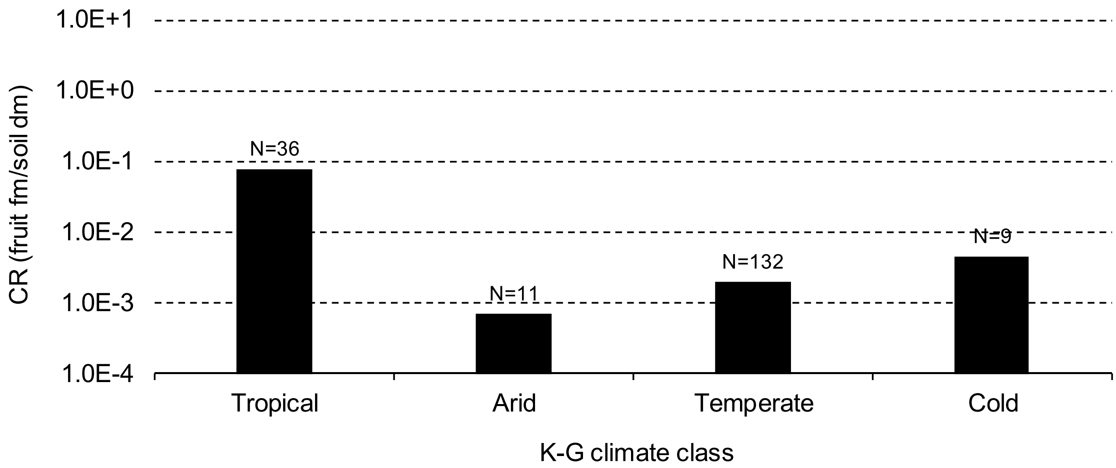

Figure 1. Fruit radiocaesium GM CR values for different K–G climate classes (the value of *N* above each column is the number of MODARIA II dataset entries on which each CR is based).

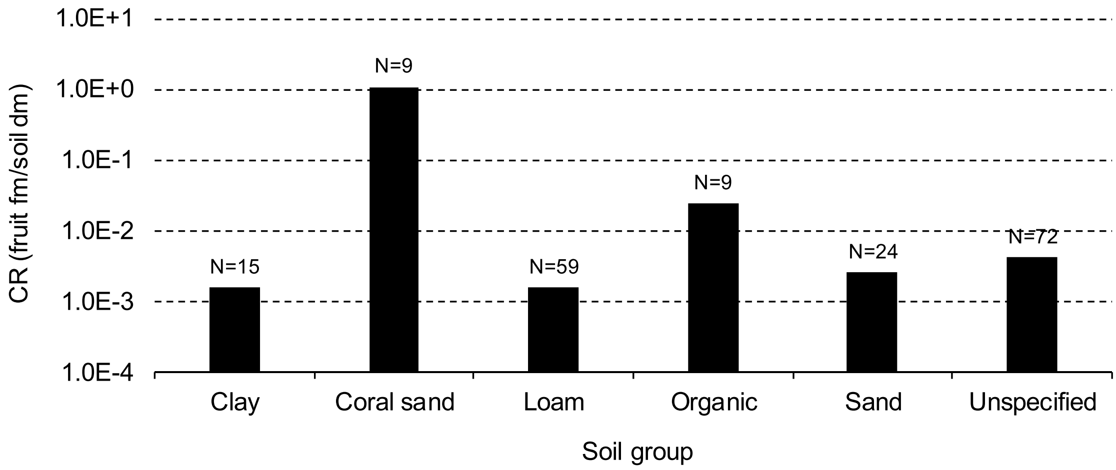

Figure 2. Fruit radiocaesium GM CR values for different soil groups (the value of *N* above each column is the number of MODARIA II dataset entries on which each CR is based).

exchangeable potassium (an analogue and uptake competitor of radiocaesium) [28, 29]. Collectively, these characteristics make radiocaesium more available for root uptake by plants growing on coral sand soil than continental soils [28]. Also, the higher CR values for fruits growing on organic soil compared with clay, loam and sand are consistent with the reported finding that soil organic matter decreases the affinity of clay minerals, thereby reducing their ability to immobilise radiocaesium in soil [34]. This reducing effect of soil organic matter on clay minerals thus outweighs any increase in adsorption of radiocaesium by humic substances in the soil [35, 36].

Figure 3 compares CR values (GM) for the different plant groups without distinguishing by K–G climate class or soil group. The GM CR value for non-woody trees (1.7×10^{-1}) is significantly higher ($p < 0.05$) than those for herbaceous plants (3.1×10^{-3}), shrubs (2.3×10^{-3}) and woody trees (2.6×10^{-3}). There is no significant difference between the GM CR values for herbaceous plants, shrubs and woody trees.

The non-woody trees data in the MODARIA II dataset are exclusive to tropical climates, except for a single datapoint for banana from a temperate (subtropical) location. Almost half of the compiled data for non-woody trees relate to coral sand soil, which has the highest CR values of any soil group due to its unique characteristics (see above). Repeating the ANOVA for plant groups after removing the non-woody trees data relating to coral sand soil showed that the remaining CR values for non-woody trees ($N = 10$) remained significantly higher ($p < 0.05$) than those of the other plant groups.

The highest CR values are for tropical climate, coral sand soil (uniquely tropical data) and non-woody trees (primarily tropical data). The key factors contributing to higher CR values in tropical environments are most likely the specific properties of tropical soils/coral sands. Coral sands (described above) are representative of tropical soils specific to some islands. However, tropical soils are often characterised by

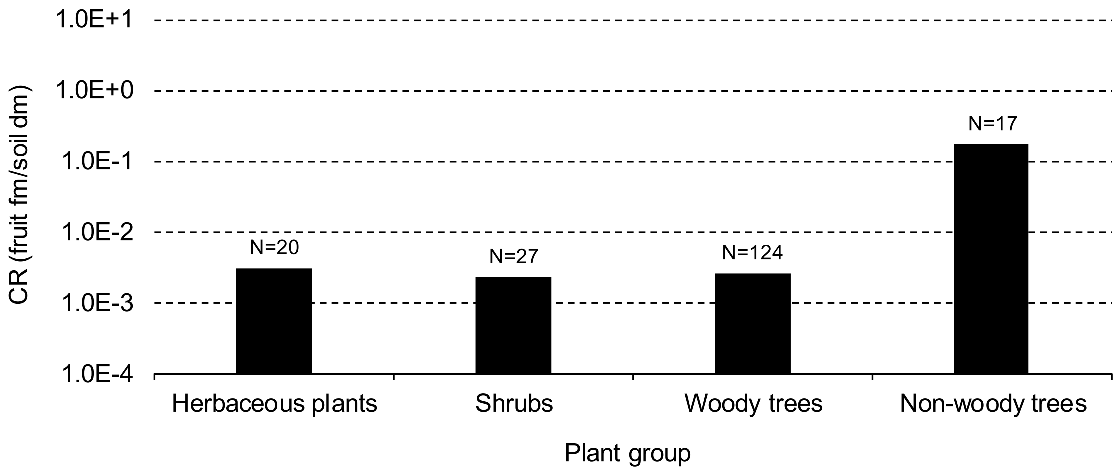

Figure 3. Fruit radiocaesium GM CR values for different plant groups (the value of N above each column is the number of MODARIA II dataset entries on which each CR is based).

intensive deep weathering of clay minerals, which is accompanied by a reduction in the cation exchange capacity [36]. Caesium is very loosely bound in such soils, which results in a high plant availability of radiocaesium and a relatively high uptake of radiocaesium compared with less weathered soils as found in temperate or arid climates. Therefore, both coral sands and deeply weathered tropical soils have a similar behaviour regarding the uptake of radiocaesium by crops. The apparent influence of climate (figure 1) is considered indirect: in tropical climates the CR values are higher because the climate has caused deep weathering of the soil, which results in a high availability of radiocaesium. The apparent influence of plant group (figure 3) is also considered indirect: non-woody trees have higher CR values across all plant groups because they are mainly from tropical climates and grow in tropical soils (either coral sands or deeply weathered soil).

3.2. Comparison of MODARIA II fruit data with TRS 472 temperate and tropical values

This paper focuses on radiocaesium transfer to fruit via root uptake from soil because there has been a substantial increase in the availability of relevant data over the last decade. The increase in data was due to the importance of fruit production in Fukushima Prefecture after the FDNPP accident and the collation of data during MODARIA II, which included a wide variety of fruit CR values for a range of radionuclides in tropical and arid climates.

TRS 472 is an important source of data on radionuclide transfer to crops and animal products, mostly for temperate and, to a lesser extent, tropical climates. The TRS 472 data are used for radiological impact assessments in many countries. Therefore, it is useful to compare the updated CR values in the MODARIA II fruit radiocaesium dataset (table 2) with the original dataset in TRS 472 to identify notable changes in the CR values where there are adequate data to carry out comparisons. With the set of data available it is possible to compare CR values for herbaceous plants, shrubs and woody trees in temperate climates and for all plant groups in tropical climates (TRS 472 does not distinguish between plant groups in tropical climates).

The comparison of CR values (GM) for herbaceous plants in temperate climates (figure 4) shows no changes in the CR values for loam, organic and sandy soils between the MODARIA II dataset and TRS 472 because no new fruit radiocaesium data were compiled in MODARIA II for these soil groups. One value was added during MODARIA II for a new soil group of clay and four values were added to the unspecified soil group. There is no significant difference in the CR value (GM) for all soils between TRS 472 (1.5×10^{-3}) and MODARIA II (1.7×10^{-3}). In TRS 472, the AM (2.9×10^{-3}) rather than the GM is reported for all soils for herbaceous plants. The corrected TRS 472 GM of 1.5×10^{-3} is the value shown in figure 4.

The comparison of CR values (GM) for shrubs in temperate climates (figure 5) shows that the revised values in the MODARIA II dataset are similar to those in TRS 472. One value was added during MODARIA II for a new soil group (organic), two values were added to loam and 15 values were added to the unspecified soil group. There are no CR values for clay soil in the MODARIA II dataset. The clay soil CR values in TRS 472 were from Sweden and were reclassified as cold climate data in the MODARIA II dataset following the K–G climate classification. There is no significant difference in the CR value (GM) for all soils between TRS 472 (2.1×10^{-3}) and MODARIA II (2.2×10^{-3}).

The comparison of CR values (GM) for woody trees in temperate climates (figure 6) shows that a substantial number of new data were added during MODARIA II (including from Fukushima Prefecture

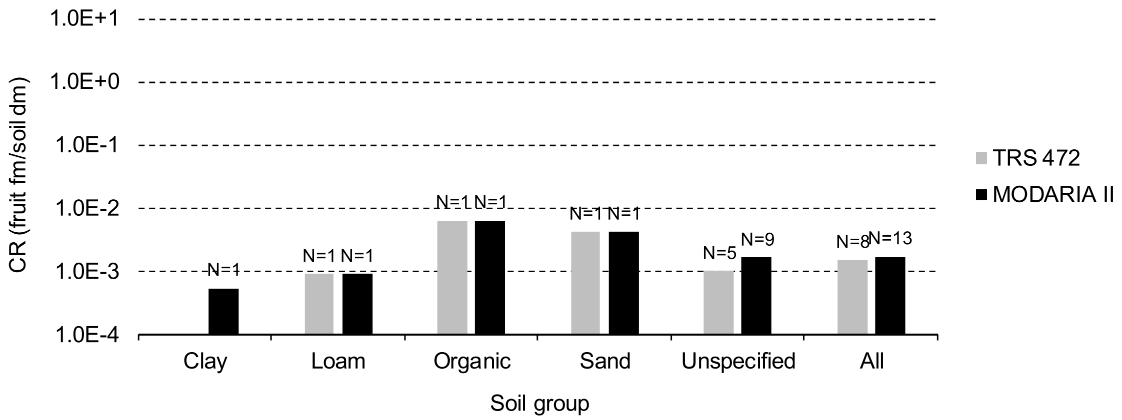

Figure 4. Comparison of fruit radiocaesium GM CR values for herbaceous plants for different soil groups in temperate climates (the value of *N* above each column is the number of dataset entries on which each CR is based).

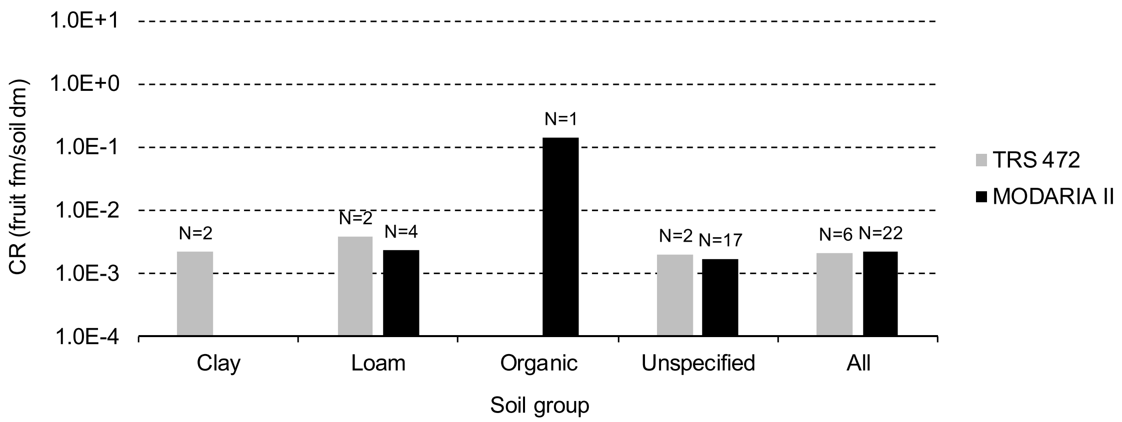

Figure 5. Comparison of fruit radiocaesium GM CR values for shrubs for different soil groups in temperate climates (the value of *N* above each column is the number of dataset entries on which each CR is based).

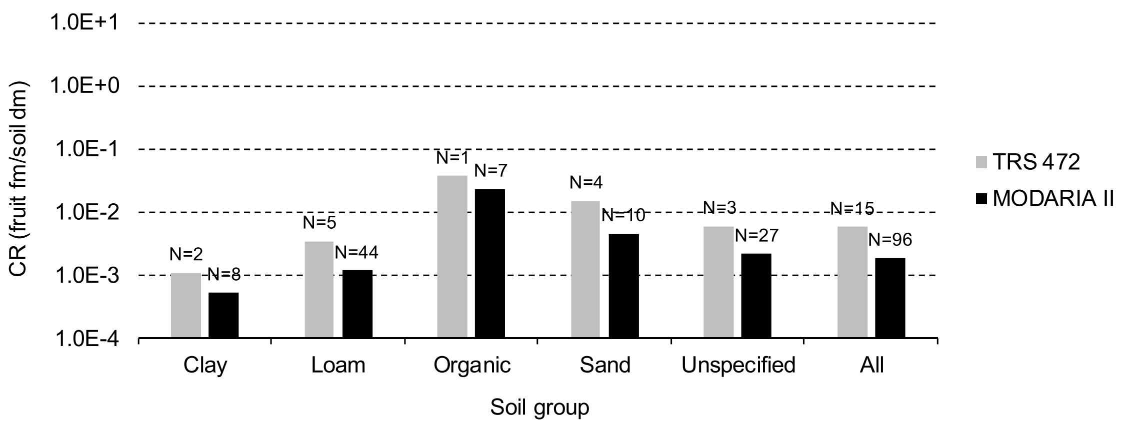

Figure 6. Comparison of fruit radiocaesium GM CR values for woody trees growing on different soil types in temperate climates (the value of *N* above each column is the number of dataset entries on which each CR is based).

after the FDNPP accident) and that the CR values in the MODARIA II dataset are lower than those in TRS 472 across all soil groups. The reduction in CR values between TRS 472 and the enhanced MODARIA II dataset is less than one order of magnitude in all cases. Nevertheless, there is a significant difference ($p < 0.05$) in the CR value (GM) for all soils between TRS 472 (5.8×10^{-3}) and MODARIA II (1.9×10^{-3}).

The temperate climate woody tree data in the enhanced MODARIA II dataset mainly originate from Europe and the United Kingdom (55%) and Japan (36%). By contrast, the data in the original TRS 472 dataset were dominated by Europe and the United Kingdom (∼90%), with no data from Japan or the Asian

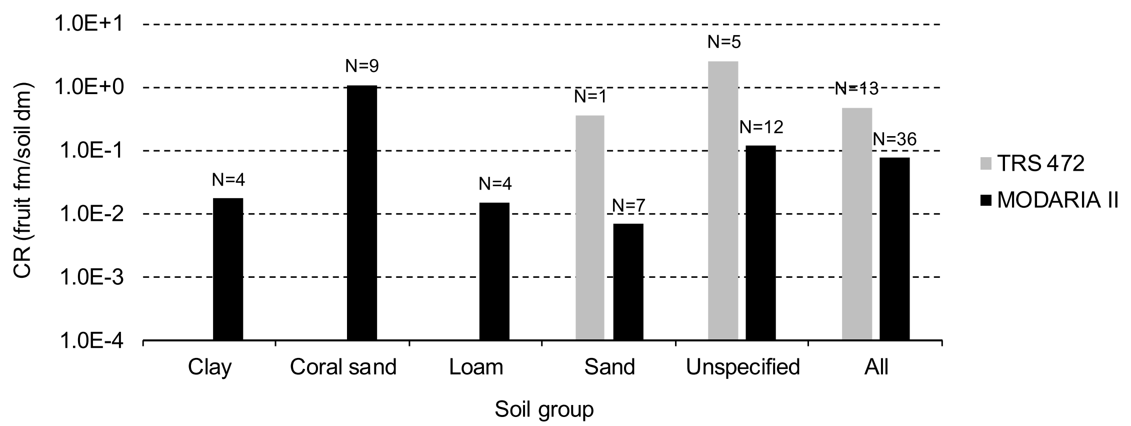

Figure 7. Comparison of fruit radiocaesium GM CR values for different soil groups in tropical climates (the value of *N* above each column is the number of dataset entries on which each CR is based).

region. The lower CR values for temperate climate woody trees in the enhanced MODARIA II dataset perhaps reflect subtle differences in soil type or growing conditions that are specific to Japan. Assessors should consider the possibility of regional variations when using the data, especially if the situation requires a more specific assessment.

The comparison of CR values (GM) for the tropical climate (figure 7), which includes data for additional soil groups (i.e. clay, coral sand and loam), shows that CR values for the sand, unspecified and all soil groups are lower in the MODARIA II dataset than in TRS 472. The reduction is by 1–2 orders of magnitude. However, there is no significant difference in the CR value (GM) for all soils between TRS 472 (4.8×10^{-1}) and MODARIA II (7.6×10^{-2}) due primarily to the large variability for each dataset (GSD is 5.7 in TRS 472 and 9.7 in MODARIA II).

3.3. Factors affecting fruit radiocaesium CR values

Radiocaesium transfer to fruits via root uptake from soil is determined by many environmental variables [37–39]. The three variables analysed in this paper (i.e. climate class, soil group and plant group) are closely interconnected. The climate is responsible for the characteristics of the soil which are the key factor in the soil-to-plant transfer of radiocaesium and is also decisive in the selection of plants suitable for living in those conditions. Analysis of the fruit radiocaesium CR data compiled under MODARIA II confirms soil characteristics to be the main factor in defining the extent of soil-to-plant transfer.

A comparison between CR values (GM) for plant groups under different climatic conditions is shown in figure 8. The data suggest that there are differences for herbaceous plants and woody trees (and possibly also for non-woody trees) grown in different climates. The CR values within each of these three plant groups are highest for tropical climate, most likely due to the specific characteristics of tropical soils (e.g. deep weathering of clay minerals) on radiocaesium uptake by plants. ANOVA on the log-transformed data for woody trees shows that the GM CR value for tropical climate is significantly higher ($p < 0.05$) than those for arid and temperate climates (the single datapoint for cold climate could not be tested). The data for herbaceous plants and non-woody trees are too sparse for statistical testing.

Figure 8 can be used to provide some rough guidance for determining when it might be possible to make assumptions about using CR data from the updated MODARIA II dataset for a specific plant group–climate combination for which there are currently few or no data. For dose assessment purposes, the data in figure 8 suggest that it is difficult to make the assumption that one can generalise the data completely. However, for a particular climate, a generally conservative CR value could be chosen to cover all fruit types for a generic screening dose assessment. If doses from fruit are shown to be important, then either a more specific assumption needs to be made (or a sensitivity analysis conducted) or the CR value used needs to be focused on the fruit production that is important in the affected areas.

For soil to plant transfer of radionuclides, most models use a simple CR value for fruit at harvest and so the predicted activity concentration in fruit for a given activity concentration in soil scales with the CR value. Changes in the fruit radiocaesium CR value may occur over the fruit development period, with a dilution of the radiocaesium activity that has been translocated to the fruit occurring as fruit size increases [12]. In tropical lemon trees, for example, the highest CR values for radiocaesium were observed during the initial stage of fruit growth, they decreased with fruit development and reached the lowest value at maturation [40]. Consideration of the time dependence of fruit radiocaesium CR values may be relevant where fruit are

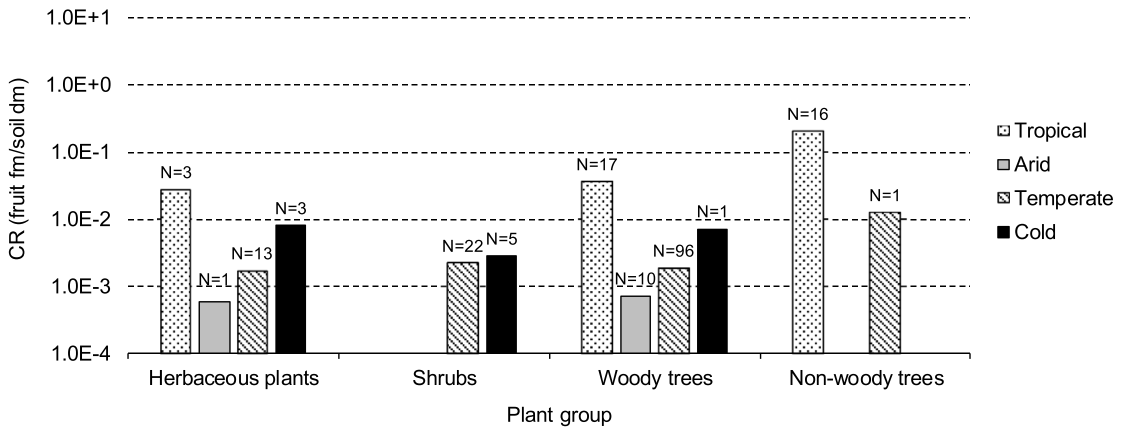

Figure 8. Comparison of fruit plant group CR values for different K–G climate classes (the value of *N* above each column is the number of dataset entries on which each CR is based).

picked, processed or consumed before ripening. For fruits harvested at maturation, knowledge of any time dependence in the CR value is not needed for the purposes of dose assessment.

A plant-related factor that has been identified as potentially affecting the radiocaesium content of fruit and the related CR value is the relative position of the absorbing roots compared with that of the deposited radiocaesium [5, 31]. Radiocaesium in surface soils may be relatively more bioaccessible to shallow-rooted plants such as herbaceous plants and shrubs. Deeper-rooted plants such as woody trees may not be able to take up significant radiocaesium until it moves or mixes down the soil profile.

A specific agricultural practice that can significantly affect soil to fruit transfer of radiocaesium and the related CR value is the application of potassium-rich soil amendments. Potassium is an essential plant nutrient with similar chemistry to caesium and hence suppresses the bioavailability of radiocaesium in the soil. This practice has been used as a countermeasure in areas significantly contaminated by radiocaesium, including Fukushima Prefecture [30, 41, 42], some European countries following the Chernobyl accident [43] and the Marshall Islands [44]. For certain food and feed crops growing in temperate climate soils (Europe and Japan), a reduction in ^{137}Cs uptake by a factor of about 2–5 has been observed after potassium amendment of the soil [42, 43]. A more pronounced effect has been observed for the naturally potassium-poor coral sand soils of the Marshall Islands, where the addition of potassium to the soil resulted in a factor of 20 reduction in fruit ^{137}Cs activity concentrations [44].

3.4. Limitations of the data

Worldwide there is great diversity in the types of fruit-bearing plants that are grown and their specific morphology. The fruit radiocaesium CR values in the MODARIA II dataset cover a limited number of species (table 1) and originate from only 20 countries. Most of the data are from studies conducted in areas that have been affected by sources of radiocaesium arising from nuclear accidents, regulated releases or nuclear weapons test fallout. Hence, the availability of fruit radiocaesium CR data is influenced by the presence of these sources in the environment rather than by areas of high fruit production. A notable exception is Fukushima Prefecture, which is an area of high fruit production in Japan and has contributed a large amount of new data following the FDNPP accident, especially for fruits from woody trees.

Much of the available fruit radiocaesium CR data are linked to either the Chernobyl or FDNPP accidents. Consequently, the data largely relate to fruits grown in temperate climate areas, which were the areas most affected by these sources. There are not many data available for fruits grown in non-temperate climates (e.g. tropical and arid). Review of the FAOSTAT database (www.fao.org/faostat/en/#data) suggests that fruits with high production in mostly tropical countries (e.g. Brazil, India, Indonesia and Philippines, amongst others) include bananas, coconuts, mangoes, papayas and pineapples and those with high production in mostly arid countries (e.g. Algeria, Egypt and Iran, amongst others) include dates and figs. Further research focusing on important fruit types in non-temperate climates would be helpful to identify if any species have strong accumulation capacity for radiocaesium or other radionuclides and which ones might be important for dose assessment.

4. Conclusions

Uptake from soil is an important long-term transfer pathway for radiocaesium contamination of fruits and other crops. This long-term transfer from soil is quantified using CR values. The CR approach is not immediately applicable to scenarios where fruit plants have been contaminated by deposition of radiocaesium on above-ground parts following a nuclear or radiological accident. In such scenarios, translocation of radiocaesium deposited on plant surfaces is likely to be relatively more important than uptake from soil for several years following the deposition event.

The enhanced MODARIA II dataset has considerably expanded the available radiocaesium CR data for fruits, including more types of fruit and soil, specified by K–G climate class. Analysis of the data according to K–G climate class, soil and plant group has identified some similarities and differences. The highest CR values relate to tropical climate, coral sand soil and non-woody trees. These categories are interrelated (all tropical). The properties of tropical soils (both coral sand and deeply weathered soils) promote relatively high uptake of radiocaesium by plants and are considered the main influencing factor for higher CR values in tropical environments.

Further data are needed to be able to carry out an improved statistical analysis of the individual and combined influence of different factors such as climate, plant and soil type on the soil to fruit transfer of radiocaesium and the related CR values. This would support a better understanding of the importance of these factors and provide greater confidence in the fruit radiocaesium CR data used in radiological impact assessment models.

There is a general deficit of fruit radiocaesium CR values for non-temperate climates (e.g. tropical and arid), which are important areas for the worldwide production of certain fruit types. Research focusing on fruits important to non-temperate climates would be helpful to strengthen the existing dataset and to identify if any species have high root uptake of radiocaesium which could make them important for dose assessment.

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ORCID iDs

C Doering https://orcid.org/0000-0001-6178-8952
J Brown https://orcid.org/0000-0001-9626-2619

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