

Chapter 10

Transport of ^{137}Cs into Fruits After External Deposition onto Japanese Persimmon Trees



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10.1 Introduction

The Fukushima Daiichi Nuclear Power Plant (FDNPP) is in Fukushima Prefecture, which is a major area of deciduous fruit production in Japan (Ministry of Agriculture, Forestry and Fisheries 2022). During the FDNPP accident, there was a large release of radiocesium (RCs) into the environment especially in the period 12–14 March 2011.

The transfer factor via soil (CR_{f-s}) is one of the parameters used to quantify the extent of transfer of RCs from soil into the edible parts of crops, defined as an activity concentration ratio on a weight basis. Prior to the Fukushima accident, several studies have been conducted to determine the CR_{f-s} for fruit trees (IAEA (International Atomic Energy Agency) 2020). Another most commonly used parameter to quantify transfer is the aggregated transfer factor (T_{ag}), which is defined as the ratio of RCs activity concentration in edible parts (Bq kg^{-1} , FW or DW) to RCs deposition amount per unit area (Bq m^{-2}). T_{ag} does not necessarily imply that the soil is the source of contamination, as it quantifies the contribution via all migration processes leading to the radioactivity concentration of the fruit. However, there have been no previous reports of T_{ag} quantifying migration when the source is bark deposition.

At the time of the FDNPP accident, most deciduous fruit trees, except Japanese apricot [*Prunus mume* (Sieb.) Sieb. et Zucc.], were in the dormant stage prior to bud burst. Since most deciduous fruit trees had not developed leaves, only the bark of the plant was directly contaminated. Of the released radionuclides, ^{137}Cs and ^{134}Cs were the most important contributors to plant contamination.

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Initial studies in May 2011 reported elevated RCs activity concentrations in leaves and young fruits of peach, of 449 Bq kg⁻¹ FW and 157 Bq kg⁻¹ FW, respectively, at the Fruit Tree Research Center, Fukushima Agricultural Technology Center (FTRC), approximately 65 km northwest of the FDNPP. Absorption of RCs from the roots was initially unlikely as deposited RCs was deposited onto and retained in the upper soil layers of orchard soil where there are few tree roots. Therefore, the data indicated that RCs attached to the surface of the bark may have contributed to fruit contamination (Sato et al. 2019a). Before the FDNPP accident, a small study by Katana et al. (1988) reported that RCs migrate directly into tree tissues from contaminated bark. After the FDNPP accident, several studies also found that ¹³⁷Cs deposited on the aboveground part of deciduous trees, including fruit trees, had migrated into the tree mainly via bark (Tagami et al. 2012; Takata 2013; Kuroda et al. 2013; Sato et al. 2014; Aoki et al. 2017). Consistent with these observations, bark-washing of Japanese persimmon and peach was effective in decreasing the ¹³⁷Cs activity concentration ([¹³⁷Cs]) in fruit in the subsequent year (2012) (Sato et al. 2015a).

Furthermore, the [¹³⁷Cs] in fruits of the Japanese persimmon, which did not have bark washed, was significantly higher than that of trees with washed bark at least for 7 years after the FDNPP accident (Sato et al. 2019b). Decontamination by external washing resulted in a reduction in RCs activity concentration of 29.1% in fruits and 33.2% in leaves in the Japanese persimmon (Sato et al. 2015a). These data indicated that residual ¹³⁷Cs on the bark continued to move to other parts of the unwashed tree for several years after ¹³⁷Cs was deposited. However, prior to this study, there had been no reports that have quantitatively verified the transfer of RCs from externally contaminated bark of dormant branches to fruits.

Dissolved ¹³⁷Cs (termed here as dis-¹³⁷Cs solution) was detected in stemflow more than 4 years after the FDNPP accident (Sato et al. 2017a, b, 2021). An alternative possible pathway for continuing contamination of fruit of the transfer was via stemflow of ¹³⁷Cs from external bark to leaves, which had developed after the FDNPP accident. The observation raised the need to quantify the relative importance of the externally deposited RCs compared with that from contaminated soil uptake over several years after deposition. The leaf-to-fruit transfer rate of RCs has been previously examined in the UK, France, Italy, and Germany after the Chernobyl accident. The reported leaf-to-fruit transfer of ¹³⁴Cs expressed as fraction of the applied or intercepted activity has been highly variable at 1.8–9.6% in grapes (Zehnder et al. 1995; Carini et al. 1996, 1999; Carini and Lombi 1997) and 1–47% in apples (Katana et al. 1988; Carini et al. 1999; Pröhl et al. 2003). The transport of RCs to fruits via leaves in these studies was affected by the following factors: stage of contamination (seasonality), precipitation intensity, age of branch and tree, cultivar and tree species, distance between fruit and the contaminated leaf, dilution effect from growth, and yield.

The translocation of assimilate in fruit trees depends on the relationship between source (leaves) and sink (fruits) (Warren 1972). RCs is an analogue of K and, therefore, behaves in a similar manner in plants. The direction of translocation and distribution of K with various assimilates such as organic acids and sugars (Van

Goor and Van Lune 1980; Possner and Kliewer 1985; Lang 1983; Westwood 1993) is controlled by the sink strength defined by Warren (1972) as: “sink strength = sink size \times sink activity,” which is represented by the growth rate of fruit (Faust 1989). Pröhl et al. (2003) found that the transfer to fruits via leaves was higher in apples after spraying ^{137}Cs solution during the fruit growing stage than at the flowering stage. Sink activity in fruit increases after fruit growing stage, so the transfer of ^{137}Cs is probably also affected by the relationship of source and sink between fruits and leaves.

Fruit load affects the sink-source relationship, and is often modified by the horticultural practice of fruit thinning that adjusts the fruit load using the leaf-fruit ratio as a criterion. Horii et al. (2019) revealed that there was no clear relationship between the leaf-fruit ratio and the [^{137}Cs] in the fruit during the defoliation study. However, there have been no previous studies that have examined the [^{137}Cs] in fruit due to fruit thinning.

Japanese persimmon has been cultivated and consumed for a long time in Japan. Ampo-gaki is a product of astringent persimmon fruit semidried in the sun or in the open air and is an important processed foodstuff produced largely in the northern part of Fukushima Prefecture. The production volume of ampo-gaki in 2010 was the highest recorded in Japan of 1423 t before the FDNPP accident (Ministry of Agriculture, Forestry and Fisheries 2010). Because drying fruit can lead to higher [^{137}Cs], ampo-gaki production has been under voluntary suspension in specific areas designated by Fukushima Prefecture because of the likelihood that [^{137}Cs] will exceed designated standard limits in Japan. Since 2013, an inspection system for [^{137}Cs] in ampo-gaki has been established, and production has resumed in areas designated by Fukushima Prefecture. Japanese persimmon has been, and remains, the most important economically damaged fruit product produced in Fukushima Prefecture after the FDNPP accident.

Japanese persimmon fruits are true fruits with enlarged ovaries. The flower buds are a mixture of the immature shoot structure and flower parts, and the fruit-bearing part is the fruiting mother shoot that grew the previous year. After sprouting, the growing fruiting shoots bear fruit at several leaf axils. Several fruiting shoots grow from a fruiting mother shoot, and several fruiting mother shoots grow from a lateral branch. A group of fruiting mother shoots is formed mainly on the lateral branches that are 2–5 years of age. There is a relatively large fruit load produced on the apical fruiting mother shoot that develops from the apical bud of the 2-year-old lateral branch. In an experiment conducted after the Chernobyl accident by Katana et al. (1988), the positional relationship between fruit and contaminated leaves within the same branch was not considered. It was reported that the [^{137}Cs] in fruits of Japanese persimmon varies widely even within the same lateral branch, but the cause of this variation was not clarified (Horii et al. 2019; Sato et al. 2021).

The surface of the peel of Japanese persimmon fruit lacks aerenchyma, and the respiration of fruit is carried out through a calyx. The calyx of the Japanese persimmon is a homologous organ comprising of leaves and has plenty of stomata and spongy tissues (Watanabe and Hoshi 1981). Since RCs is transported to pulp via

the calyx in the Japanese persimmon (Sekizawa et al. 2016a, b), evaluation of the transfer rate of RCs to fruit via both the leaf and calyx is needed.

The aims of this work were to (1) quantify the transfer rate of ^{137}Cs applied to leaves and calyx into fruit; (2) examine effects of leaf position and fruit load on the transport of ^{137}Cs into fruit; and (3) quantify the transfer rates and aggregated transfer factors of ^{137}Cs applied to apical fruiting mother shoot and 2-year-old lateral branch into fruits before bud burst.

10.2 Materials and Methods

An outline of experiments conducted from 2016 to 2021 is shown in Table 10.1.

10.2.1 Preparation of ^{137}Cs Solution

For Experiment 1 (EXP. 1), moss samples of *Thuidium cymbifolium* (Dozy & Molk.) Dozy & Molk., collected from the Yamakiya area in the town of Kawamata approximately 50 km northwest of the FDNPP in May 2015, were used for preparing a ^{137}Cs solution. After boiling approximately 200 g of moss with 1.5 L of distilled water for 15 min, the moss solution was filtrated through a pulp sheet (JK Wiper, NIPPON PAPER CRECIA CO., Ltd., Tokyo) laid onto a stainless-steel net, and centrifuged at 3500 rpm. The supernatant was filtered through a 0.45 μm membrane filter (cellulose ester mixed type, ADNANTEC A045A047A, Toyo Roshi Kaisha, Ltd., Tokyo) under suction. The ^{137}Cs solution was reduced in volume to approximately 350 mL by heating and then subjected to high-pressure sterilization treatment in an autoclave (SX-700, TOMY SEIKO CO., Ltd., Tokyo) at 120 °C for 20 min to obtain a final solution containing 2.2 Bq mL⁻¹ of dis- ^{137}Cs . For EXP. 2 and EXP. 3, moss samples of *Plagiothecium nemorale* (Brid.) Z. Iwats.; *P. roseanum* Schimp. in the Nagadoro area of Iitate village located about 40 km northwest from the FDNPP and of *Thuidium cymbifolium* (Dozy & Molk.) Dozy & Molk. in the same site as EXP. 1 were collected in July 2016 and May 2017. The moss was used to prepare the experimental dis- ^{137}Cs solution as described above producing 1.8 Bq mL⁻¹ of dis- ^{137}Cs solution. For EXP. 4, moss samples of *Pylaisiadelpha tenuirostris* (Buch et Schimp.) W.R. Buch. in the Nagadoro area of Iitate village were collected in May 2017. The moss was used to prepare the experimental dis- ^{137}Cs solution as described above producing 7.0 for 2020 and 7.5 for 2021 Bq mL⁻¹ of dis- ^{137}Cs solution. In Experiments 1, 2, and 3, epiphytic moss growing on rock was used, whereas epiphytic moss on bark was used in Experiment 4.

Table 10.1 Outline of the experimental plan and the results related to the TR_f and the T_{ag}^{f-b} into mature fruit

Experiment no./year	Cultivar	Comparative treatment				Replicates (shoot/branch)	Application days	Amount of applied ¹³⁷ Cs (Bq per replicate)	TR_f^a (%)	$T_{ag}^{f-b} \times 10^{-4}$ (m ² kg ⁻¹ DW)
		Application Stage	Applied organ	Applied position						
1/2016	Hachiya	Young fruit	Calyx	Front side of a calyx	3	24 June–1 July	12.3	14.9 ± 4.7		
		Fruit growing	Calyx	Front side of a calyx	4	1–10 August	21.1	10.3 ± 4.6		
		Young fruit	Leaf	Adjacent to fruit on a short fruiting shoot	2	24 June–1 July	25.0	10.2 ± 3.2		
		Fruit growing	Leaf	Adjacent to fruit on a short fruiting shoot	3	1–10 August	15.9	16.4 ± 5.0		
2/2017	Hiratanenashi	Young fruit	Leaf	Adjacent to fruit on a long fruiting shoot	4	26–30 June	12.5	8.4 ± 2.6		
			Leaf	Middle part in a long fruiting shoot	4			2.7 ± 1.2		
			Leaf	Top part in a long fruiting shoot	4			2.0 ± 0.8		
			Leaf	Adjacent to fruit on a short fruiting shoot	6			8.8 ± 4.3		
3/2018	Hiratanenashi	Fruit growing	Leaf	All leaves on the central fruiting shoot on the fruiting mother shoot with thinning or with no thinning	4	July 31–2 August	7.6	17.1 ± 6.1		
				Adjacent to fruit on a short fruiting shoot	3			10.0 ± 1.8		
4/2020	Hiratanenashi	Dormancy	Shoot	Front side of an apical fruiting mother shoot with thinning	8	3 and 6 April	13.3	1.3 ± 0.6	15.2 ± 6.9	
			Branch	Front side of a 2-year-old lateral branch with thinning	8			0.89 ± 0.35	9.1 ± 8.8	
4/2021			Shoot	Front side of an apical fruiting mother shoot with no thinning	4	7 April	13.1	3.2 ± 1.8	8.0 ± 4.5	

^aArithmetic mean ± standard deviation

10.2.2 Measurement of the Amount of ^{137}Cs Applied to Various Organs

The [^{137}Cs] in several treated organs (i.e., calyx, leaf, shoot) collected immediately after treatment was measured, and the retained ratio (RR) was calculated using Eq. (10.1). The amount of ^{137}Cs (Bq) in individual treated organ was calculated using Eq. (10.2):

$$RR = w_{\text{so}} \times C_{\text{so}} \times (s_{\text{g}} \times v_{\text{s}} \times C_{\text{s}})^{-1}, \quad (10.1)$$

where w_{so} (kg DW) is total weight of the contaminated organs, C_{so} (Bq kg^{-1} DW) is the [^{137}Cs] in the contaminated organs, s_{g} ($= 1.00 \text{ g mL}^{-1}$) is the specific gravity of the applied dis- ^{137}Cs solution, v_{s} (mL) is the volume of the applied dis- ^{137}Cs solution, C_{s} (Bq g^{-1}) is the [^{137}Cs] in the dis- ^{137}Cs solution.

$$AS_{\text{io}} = RR \times s_{\text{g}} \times v_{\text{s}} \times C_{\text{s}}, \quad (10.2)$$

where AS_{io} is the amount of ^{137}Cs in individual contaminated organs (Bq organ^{-1}), RR is the retained ratio, v_{s} (mL) is the volume of the applied dis- ^{137}Cs solution, C_{s} (Bq g^{-1}) is the [^{137}Cs] in the dis- ^{137}Cs solution.

10.2.3 Transport into Japanese Persimmon Fruits of ^{137}Cs Applied on Calyx and Leaves (EXP. 1)

10.2.3.1 Plant Material and Treatments

The experiments were conducted using two 12-year-old ‘‘Hachiya’’ Japanese persimmon (*Diospyros kaki* Thunb.) trees planted at the FTRC. Fruit bearing shoots less than about 20 cm in length were selected for the ^{137}Cs application treatment. The experiments were performed both at the young and the growing stage of fruits. In 2016, the fruit young stage was June 24–July 1 (23–31 days after full blossom) and the fruit growing stage was August 1–15 (61–75 days after full blossom). To compare the amount of ^{137}Cs transported to fruit from the calyx or from the leaves, the dis- ^{137}Cs solution was applied onto either the front side of the calyx or onto two adjacent leaves using a bottle with a plastic brush (Fig. 10.1). A cellulose cloth was placed onto the calyx to prevent contamination by ^{137}Cs during application onto the adjacent leaves, which was repeated 1–3 times per day. After the treatment, the applied solution was left to dry naturally, and the fruits were then wrapped within a net bag. To calculate the RR , the [^{137}Cs] was measured in three sets of contaminated leaves collected immediately after each treatment and in 5 and 6 contaminated calyxes on June 27 and July 1, respectively, for the fruit young treatment, and in 3 contaminated calyxes on August 1 for the fruit growing stage treatment.



Fig. 10.1 Procedure to contaminate the plants by applying the $\text{dis-}^{137}\text{Cs}$ solution to the calyx or leaves of the Japanese persimmon “Hachiya” in EXP. 1 conducted in 2016. A sheet of cellulose cloth was placed beneath the calyx to prevent adhesion of the treatment solution to the calyx during the leaf contamination process. The $\text{dis-}^{137}\text{Cs}$ solution was applied on the surface of the front side of calyx and onto two leaves adjacent to the fruit using a bottle with a plastic brush

There were losses of contaminated fruit, commonly called June drop, caused by factors such as pollination and lack of sunshine (Sobashima and Takagi 1968; Kitajima et al. 1987, 1990; Chauhan 2014). During the period from the start of July to mid-August, the young unripe fruits, which had dropped into the net, were collected (on July 4 and 11) and the ^{137}Cs was measured for both treatments (calyx and leaf contamination).

10.2.3.2 Sample Preparation

Contaminated leaves and mature fruits were collected on October 26 and the ^{137}Cs in leaves and fruit was measured. Fruit was separated into calyx, peel, and pulp. On July 27 and October 31, respectively, 7 and 6 uncontaminated fruits were also sampled to measure the ^{137}Cs for control of the young fruit and the mature fruit. The ^{137}Cs was measured for each part of the combined control fruit sample in a similar manner to that for contaminated fruits.

10.2.4 Effects of Leaf Position on the Transport into Fruit of ^{137}Cs Applied on Leaves (EXP. 2)

10.2.4.1 Plant Material and Treatments

The experiments were conducted using three 13-year-old “Hiratanenashi” Japanese persimmon trees planted at FTRC. The effects of the distance between leaves and fruit on leaf to fruit transport of ^{137}Cs were examined. An outline of the treatments is shown in Table 10.1 and Fig 10.2. From June 26th to June 30th during the juvenile period, 20.3 Bq of ^{137}Cs was applied to 2 leaves as explained below. Twelve fruiting shoots that were longer than 20 cm (long-fruited shoots) and bearing one fruit were selected. Two leaves were contaminated from each of the three positions: adjacent to



Fig. 10.2 The treatment of Japanese persimmon “Hiratanenashi” cultivar in EXP. 2 conducted in 2017. The $\text{dis-}^{137}\text{Cs}$ solution was applied on the surface of the front side of two leaves from the adjacent to fruit, middle and top part of the long fruiting shoots (>25 cm length) and two leaves adjacent to fruit on the short fruiting shoot (<15 cm length) using a bottle with a plastic brush

the fruit, at the middle node, and at the apical node. Similarly, six short-fruiting shoots (less than 20 cm in length) were selected, where two leaves adjacent to the fruit were contaminated. The ^{137}Cs solution was applied over the surface of the front side of leaves using the same method as in EXP. 1. The $[^{137}\text{Cs}]$ in six treated leaves collected within a few seconds after treatment was measured, and the RR was calculated.

10.2.4.2 Sample Preparation

Samples of the Japanese persimmon were collected on October 18. Each replicate of fruit and contaminated leaves were prepared individually for each treatment position group. Leaves that had not been contaminated from each long fruiting shoot were collected and subdivided into the upper and the lower leaf from the node of treated leaves.

10.2.5 Effects of Fruit Load on the Transport into Fruit of ^{137}Cs Applied on Leaves (EXP. 3)

10.2.5.1 Plant Material and Treatments

The experiments were conducted using a 15-year-old “Hiratanenashi” Japanese persimmon tree planted at FTRC. Eight fruiting mother shoots with 5 consecutive

fruiting shoots longer than 20 cm (long fruiting shoots) bearing one fruit were selected, and comparative treatments by fruit load were applied as follows:

Four “No fruit thinning” group where each of five consecutive fruiting shoots bears one fruit (Fig. 10.3a).

Four “Fruit thinning” group where fruits on the adjacent shoots of the central one were picked off just before the contamination treatment took place on July 31 (Fig. 10.3b).

Three short fruiting-shoots (less than 20 cm) developed on other lateral branches were selected to compare with the above-mentioned long fruiting shoot groups. Replicates were made on four fruiting mother shoots.

Dis- ^{137}Cs solution was applied to all leaf surfaces of the central (among five) fruiting shoots and of the short fruiting shoots during the period from July 31 to August 2. The total volume of applied dis- ^{137}Cs solution was 12 mL. The [^{137}Cs] in leaves of three treated fruiting shoots collected within a few seconds after treatment was measured, and the *RR* was calculated.

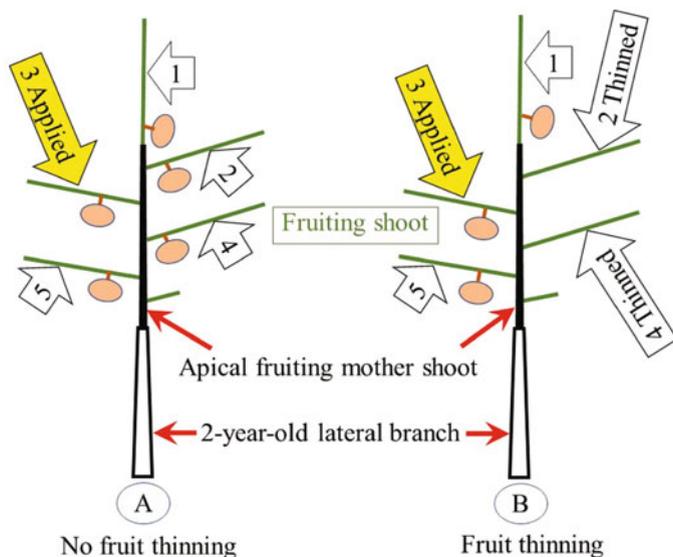


Fig. 10.3 The treatment of Japanese persimmon “Hiratanenashi” cultivar in EXP. 3 conducted in 2018. Eight fruiting mother shoots with 5 “No fruit thinning” shoots longer than 20 cm (long fruiting shoots) that bear one fruit were selected. Prior to applying dis- ^{137}Cs solution, the comparative group was set as follows. “No fruit thinning” group (a): One fruit was set on each of the five “No fruit thinning” shoots. “Fruit thinning” group (b): Fruits on the upper and lower adjacent shoots of the central shoot among the five consecutive shoots were thinned. Dis- ^{137}Cs solution was applied to all leaf surfaces of the central fruiting shoots among five fruiting shoots and the short fruiting shoots

10.2.5.2 Sample Preparation

Fruits, leaves, and wood with bark of fruiting shoots and fruiting mother shoots were collected on October 22. Same organs were also collected from uncontaminated lateral branches in the same tree to use as a control.

10.2.6 *The Transfer Rate and Aggregated Transfer Factors into Fruits of ^{137}Cs Applied on Fruiting Mother Shoots Before Sprouting (EXP. 4)*

10.2.6.1 Plant Material and Treatments

The experiments were conducted using a 17-year-old “Hiratanenashi” Japanese persimmon tree planted at FTRC. Eight 2-year-old lateral branches, which had several fruiting mother shoots, were selected before sprouting for treatment. In 2020, the apical fruiting mother shoots and their previous year’s branches (2-year-old lateral branch) were selected for application of the dis- ^{137}Cs solution. In 2021, only apical fruiting mother shoots were selected. The dis- ^{137}Cs solution was applied to the front side of the apical fruiting mother shoots and of the 2-year-old branches using a polyamide brush (Fig. 10.4). The [^{137}Cs] was measured in two treated shoots or branches that had been collected a few seconds after treatment, and the *RR* was calculated. In 2020, 30 days after full blossom the number of fruit set was adjusted to provide a leaf-fruit ratio of 25 leaves per fruit on July 2. No fruit thinning was carried out in 2021.

10.2.6.2 Calculation of the [^{137}Cs] per Unit Area of Contaminated Fruiting Mother Shoot

Before application of the dis- ^{137}Cs solution, the length and thickness of the fruiting mother shoot or 2-year-old lateral branch for experiment were measured, and the [^{137}Cs] per unit area of shoots and branches (A_b) was calculated as follows:

$$A_b = AS_{\text{io}} \times (0.5 \times \pi \times W \times L)^{-1}, \quad (10.3)$$

where A_b is the amount of ^{137}Cs per unit area of the contaminated shoots and branches (Bq m^{-2}), AS_{io} is the amount of ^{137}Cs in the contaminated shoots and branches (Bq shoot^{-1}), W is the thickness of the contaminated shoots and branches (m), L is the length of the contaminated shoots and branches (m).

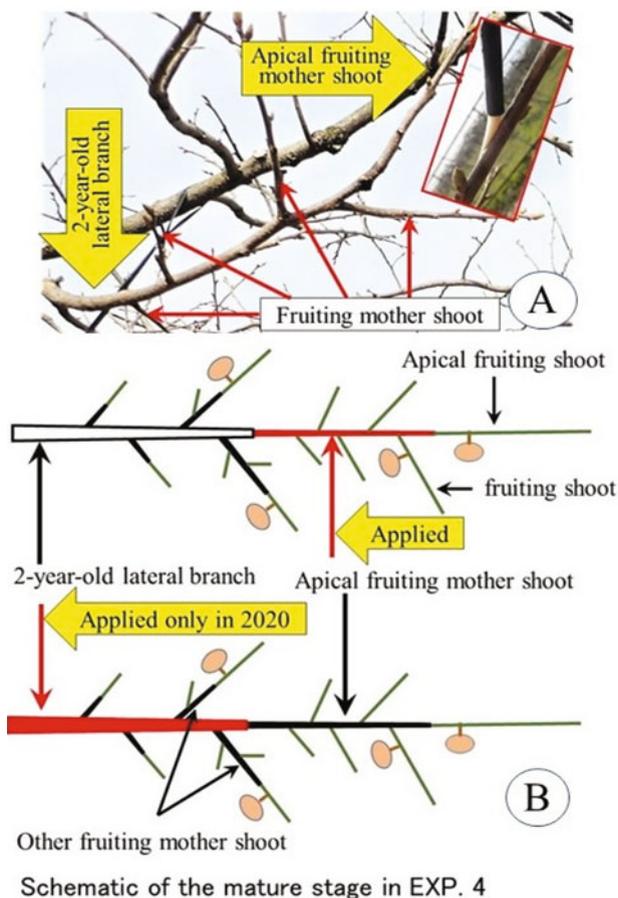


Fig. 10.4 The treatment (a) and schematic of the mature stage (b) of Japanese persimmon “Hiratanenashi” cultivar in EXP. 4 conducted in 2020 and 2021. Before sprouting in the year of 2020 and 2021, dis- ^{137}Cs solution was applied to the front side of the apical fruiting mother shoot and 2-year-old branches (only in 2021) using a polyamide brush (a), whereas only apical fruiting mother shoots were applied in 2021

10.2.6.3 Sample Preparation

In 2020, thinned young fruits and mature fruits were collected from the contaminated or uncontaminated apical fruiting mother shoot and the other fruiting mother shoots on 2-year-old branches on July 2 and October 14, respectively. Mature fruits were subdivided into calyx and pulp with skin.

In 2021, on June 25, at the young fruit stage, the contaminated apical fruiting mother shoots and the uncontaminated fruiting mother shoot adjacent to the apical one were collected and divided into wood with bark, shoots, leaves, and young fruits. The contaminated fruiting mother shoots were further subdivided into bark

and wood. During the maturity period, the contaminated fruiting mother shoots were collected on October 11 and divided into organs in the same way as in 2020. The replicated samples were combined and then the [^{137}Cs] was measured.

10.2.7 Radiocesium Measurements

After freeze-drying for at least 72 h, all samples from EXP. 1 to EXP. 4 were placed into a 100-mL polypropylene container (U-8 pots) to measure [^{137}Cs]. The [^{137}Cs] in the samples of EXP1, EXP2, EXP4 was measured using a germanium detector (GEM40-76, Seiko EG & G ORTEC, Tokyo, Japan) at Fukushima University. Gamma-ray emissions at 662 keV were measured for 43,200–200,000 s. For the pulse-height analysis, a multichannel analyzer (MCA7, Seiko EG & G ORTEC) was used together with the spectrum analysis software (Gamma Studio, Seiko EG & G ORTEC). The [^{137}Cs] and [^{40}K] in the samples of EXP3 were measured with a germanium detector at the Foundation for Promotion of Material Science and Technology of Japan. Decay correction was not applied as the ^{137}Cs measurement was conducted within 2 weeks of sampling.

10.2.8 Transfer of ^{137}Cs Applied on the Dormant Fruiting Mother Shoot into Organs and Measurement of the Aggregated Transfer Factors of ^{137}Cs into Fruit

The contaminated ^{137}Cs amount (AS , Bq) in each sample due to the application of dis- ^{137}Cs solution was calculated using the following equations:

$$AS_i = w_i \times (C_i - C_0) \div 1000, \quad (10.4)$$

where the subscript i represents the type of the organ (e.g., fruit, leaf, calyx, peel, pulp, bark and wood) to be examined, w_i (g DW) is weight of i , C_i (Bq kg^{-1} DW) is the [^{137}Cs] in i , C_0 is the [^{137}Cs] in control of i .

The transfer rate of ^{137}Cs to fruit via contaminated organs (TR_f , %) was calculated using the following equations:

$$TR_f = 100 \times AS_f \div (RR \times AP), \quad (10.5)$$

where AS_f is the amount of ^{137}Cs in fruit (Bq fruit^{-1}), RR is the retained ratio, AP is the amount of applied ^{137}Cs (Bq organ^{-1}).

Based on the equations above, TR_f represents the percentage of ^{137}Cs transported into fruit from the leaves, calyx, or dormant fruiting mother shoots (on which it was deposited).

The aggregated transfer factors of ^{137}Cs applied on the dormant fruiting mother shoot to fruit were calculated using the following equations:

$$T_{ag}^{f-b} = (C_f - C_0)A_b^{-1}, \quad (10.6)$$

where T_{ag}^{f-b} ($\text{m}^2 \text{kg}^{-1}$) is the aggregated transfer factors into fruit of ^{137}Cs via the dormant fruiting mother shoot, C_f ($\text{Bq kg}^{-1} \text{DW}$) is the [^{137}Cs] in the mature fruit on the contaminated dormant fruiting mother shoot, C_0 is the [^{137}Cs] in control of mature fruit, A_b is the amount of ^{137}Cs per unit area of the contaminated shoots and branches (Bq m^{-2}).

10.2.9 Data Analysis

Analysis of variance (ANOVA) with Tukey pairwise comparison and t -tests were used to test the significance of the differences between comparable [^{137}Cs], TR_f and T_{ag}^{f-b} values. Log-transformed data were used in both the ANOVAs and t -tests.

10.3 Results

10.3.1 Transfer of ^{137}Cs Applied on Calyx and Leaves at the Young Fruit Stage and the Fruit Growing Stage into Dropped Fruit and Mature Fruit of Japanese Persimmon “Hachiya” (EXP. 1)

During the period from the start of July to mid-August, some young unripe fruit had dropped from the tree, so only 2–4 fruits in each treatment remained on the tree up to the harvest time. The TR_f of ^{137}Cs into fruit that had naturally dropped after contamination at the young fruit period was significantly higher due to contamination of the calyx than that for contamination of leaves for both sampling occasions (Table 10.2).

The TR_f of ^{137}Cs derived from EXP. 1 for mature fruit are shown in Table 10.3. The [^{137}Cs] ($\text{Bq kg}^{-1} \text{DW}$) measured in the control collected on October 26 were as follows: pulp 5.92, peel 7.20, calyx 10.1 and leaf 10.3 Bq kg^{-1} . The TR_f via calyx was higher after contamination at the young fruit stage, whereas the TR_f via leaves showed the opposite trend. Nevertheless, the TR_f were not significantly different (by ANOVA) between organs, or the stage of contamination. However, ANOVA indicated that there was a possibility of the interaction between contaminated period and organ (0.069 of P value by ANOVA).

Table 10.2 Transfer of ^{137}Cs applied onto calyx and leaf during the young fruit stage into Japanese persimmon fruit that had dropped naturally (June drop) at two collecting days

Application days	Applied organ	Replicates (shoot)	Collecting days	Weight of fruit (pulp with peel) (g FW)	Dry matter		Amount of ^{137}Cs (Bq) ^a			TR_f
					Pulp with peel (%)	Pulp with peel (%)	Pulp with peel	Calyx	Leaf	
24 June–1 July	Calyx	2	4-Jul	7.0 ± 0.3	16.6 ± 0.1	0.29 ± 0.12	3.0 ± 3.0	–	2.47 ± 0.71	
	Leaf	3	4-Jul	7.2 ± 2.0	16.8 ± 0.3	0.06 ± 0.04	0.05 ± 0.03	3.7 ± 1.2	0.23 ± 0.17	
	Calyx	3	11-Jul	10.3 ± 2.4	15.6 ± 0.7	0.33 ± 0.03	1.4 ± 0.26	–	2.61 ± 0.21	
	Leaf	4	11-Jul	9.0 ± 2.5	17.8 ± 4.2	0.24 ± 0.19	0.12 ± 0.03	3.8 ± 1.0	0.96 ± 0.72	
<i>P</i> value by ANOVA	Applied organ								0.003	
	Collecting days								NS	
	Interaction								NS	

^aArithmetic mean ± standard deviation**Table 10.3** Transfer of ^{137}Cs administered via calyx and leaves to mature Japanese persimmon fruit at two different growth stages

Application days	Applied organ	Replicate (shoot)	Weight of fruit (pulp with peel) (g FW)	Dry matter		Amount of ^{137}Cs (Bq) ^b			TR_f
				Pulp with peel (%)	Pulp with peel (%)	Pulp with peel	Calyx	Leaf	
24 June–1 July	Calyx	3	291 ± 31.5	17.9 ± 0.4	2.0 ± 0.6	0.7 ± 0.3	–	14.9 ± 4.7	
	Leaf	2	306 ± 36.3	19.3 ± 0.8	2.5 ± 0.7	0.1 ± 0.0	0.3 ± 0.0	10.2 ± 3.2	
	Calyx	4	293 ± 25.4	18.3 ± 0.9	2.2 ± 1.0	1.1 ± 0.4	–	10.3 ± 4.6	
<i>P</i> value by ANOVA	Leaf	3	358 ± 73.7	18.9 ± 0.9	2.6 ± 0.8	0.3 ± 0.1	0.5 ± 0.2	16.4 ± 5.0	
	Applied organ							NS	
	Applied days							NS	
	Interaction							NS (0.069)	

^aCollected on 26 October^bArithmetic mean ± standard deviation

10.3.2 Effects of the Position Where ^{137}Cs Was Applied onto Leaves on the Transfer into Japanese Persimmon Fruit (EXP. 2)

The result of EXP. 2 is shown in Table 10.4. ^{137}Cs was not detected in the uncontaminated leaves of each treatment. The TR_f of the pulp with peel resulting from contamination of the leaves adjacent to fruit both on the long and on the short fruiting shoot showed the same trend as the [^{137}Cs]. They were significantly higher than those from contamination of the leaves at the middle and top part on a long fruiting shoot (0.01 of P value by ANOVA).

10.3.3 Effects of Fruit Load on the Transfer of ^{137}Cs Applied onto Leaves into Persimmon Fruit (EXP. 3)

The leaf to fruit ratio of “No fruit thinning” was significantly lower than that of the “Fruit thinning” (Table 10.5). The [^{137}Cs] in fruit and the TR_f into fruit of the “Fruit thinning” were higher than that of the “No fruit thinning” (0.02 and 0.055 of P value by t -test, respectively), and the TR_f in short fruiting shoots was an intermediate value. There was no significant difference in fruit weight between both groups. The TR_f of ^{137}Cs into the fruit on the uncontaminated fruiting shoots was less than 2% (Table 10.6). Values of the TR_f of the fruit two nodes below and of the sum of TR_f of the five fruiting shoots in “Fruit thinning” were, respectively, higher than the corresponding TR_f in “No fruit thinning.” There was a significant correlation between the amount of ^{137}Cs and ^{40}K as well as of their concentration in the fruit on the contaminated fruiting shoot. The amount of ^{137}Cs as well as ^{40}K in fruits tended to be higher in the “Fruit thinning” (Fig. 10.5). The TR_f of the ^{137}Cs into wood with bark of 2-year-old lateral branch in the “No fruit thinning” group was $1.54 \pm 0.15\%$ (mean \pm standard deviation, SD), which was significantly higher than that in the “Fruit thinning” group of $0.30 \pm 0.06\%$. Conversely there was no significant difference in the TR_f into wood with bark of the five fruiting shoots in the “No fruit thinning” and the “Fruit thinning” group, which were $1.18 \pm 0.46\%$ and $1.36 \pm 0.41\%$, respectively.

10.3.4 Transfer of ^{137}Cs Applied on the Dormant Fruiting Mother Shoot into Fruit (EXP. 4)

The leaf to fruit ratio for the 2-year-old branch was 28.6 ± 7.2 where the fruit thinning was applied in 2020 and for the apical fruiting mother shoot was 28.8 ± 8.1 in 2020 and 6.5 ± 3.4 in 2021. A_b was 5.2 ± 4.3 and 4.8 ± 2.3 kBq m^{-2} of branch in

Table 10.4 Concentration, amount, and transfer of ^{137}Cs into Japanese persimmon fruit from leaves contaminated in different positions relative to the fruit

Treatment ^c	Replicate (shoot)	Dry matter		[^{137}Cs]		Amount of ^{137}Cs (Bq) ^f		TR_f
		Pulp with peel (%)	Pulp with peel (Bq kg ⁻¹ DW)	Pulp with peel ^d (Bq kg ⁻¹ DW)	Pulp with peel	Calyx ^e	Contaminated leaves	
Position of spiked leaves								
Adjacent to fruit on a long shoot	4	16.9 ± 0.5	36.5 ^a ± 10.3	1.1 ^a ± 0.3	0.06	0.46 ± 0.5	8.4 ^a ± 2.6	
Middle part in a long shoot	4	17.3 ± 0.5	12.1 ^b ± 5.6	0.3 ^b ± 0.1	0.02	0.21 ± 0.03	2.7 ^b ± 1.2	
Top part in a long shoot	4	16.9 ± 0.4	9.6 ^b ± 4.1	0.2 ^b ± 0.1	0.02	0.29 ± 0.1	2.0 ^b ± 0.8	
Adjacent to fruit on a short shoot	6	16.9 ± 0.6	41.4 ^a ± 24.0	1.1 ^a ± 0.5	0.09	0.30 ± 0.3	8.8 ^a ± 4.3	
<i>P</i> value by ANOVA			0.01	0.004			0.00008	

^c12.5 Bq of ^{137}Cs was retained after applying 20.3 Bq of ^{137}Cs onto two leaves

^dDifferent letters indicate a significant difference at $P \leq 0.05$ by Tukey's test

^eMeasured by combining samples into one sample for the treatment

^fArithmetic mean ± standard deviation

Table 10.5 Leaf to fruit ratio on the fruiting mother shoot and [¹³⁷Cs] of the mature fruit on the contaminated fruiting shoot

Treatment	Replicate (branch)	Fruiting mother shoot			Pulp with peel of fruit on contaminated fruiting shoot			
		Number of fruit	Number of leaf	Leaf to fruit ratio	Number of leaf	Weight (g FW)	Dry matter (%)	[¹³⁷ Cs] (Bq kg ⁻¹ DW)
No fruit thinning	1	5	33	6.6	7	238	19.9	22.1
	2	5	37	7.4	9	184	20.2	19.5
	3	5	41	8.2	8	213	20.6	22.2
	4	5	29	5.8	7	236	17.8	19.9
	Mean ± SD ^a		35.0 ± 5.2	7.0 ± 1.0	7.8 ± 1.0	218 ± 25	19.6 ± 1.2	20.9 ± 1.4
Fruit thinning	1	3	47	15.7	5	184	19.4	24.6
	2	3	33	11.0	6	231	18.0	30.3
	3	3	27	9.0	9	252	18.2	43.3
	4	3	35	11.7	7	255	18.0	35.4
	Mean ± SD		35.5 ± 8.4	11.8 ± 2.8	6.8 ± 1.7	230 ± 33	18.4 ± 0.7	33.4 ± 7.9
<i>P</i> value by <i>t</i> -test			NS	0.02	NS	NS	NS	0.02

^aArithmetic mean ± standard deviation

Table 10.6 TR_f of ^{137}Cs into fruit for “No fruit thinning” and “Fruit thinning” in contaminated shoots and into fruits borne by branches one or two nodes away from the contaminated central one

Treatment	Replicate	TR_f of pulp with peel (%)						Short fruiting shoot
	(Branch)	Long fruiting mother shoot						
		Position of fruiting shoot						
		2 Nodes above	1 Node above	Applied	1 Node below	2 Nodes below	Total	
No fruit thinning	1	0.6	ND	11.8	0.4	0.0	12.8	17.8
	2	0.6	ND	8.0	1.0	0.4	10.0	8.6
	3	ND	ND	11.1	0.3	ND	11.4	11.8
	4	ND	0.1	9.1	2.1	–	11.3	
	Mean \pm SD ^a	0.29 \pm 0.34	0.08 \pm 0.05	10.0 \pm 1.8	0.93 \pm 0.86	0.15 \pm 0.25	11.4 \pm 1.2	12.8 \pm 4.7
Fruit thinning	1	2.6		10.1		0.6	13.3	
	2	0.8		14.7		1.6	17.1	
	3	0.9		24.1		2.0	27.0	
	4	0.2		19.5		1.9	21.6	
	Mean \pm SD	1.13 \pm 1.05		17.1 \pm 6.1		1.53 \pm 0.63	19.7 \pm 5.9	
<i>P</i> value by <i>t</i> -test		–		NS (0.055)		0.017	0.017	

^aArithmetic mean \pm standard deviation

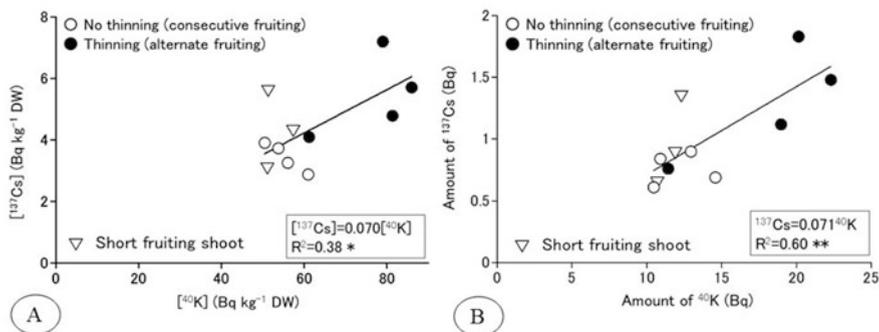


Fig. 10.5 Relationship between ^{137}Cs and ^{40}K (a), and the amount of ^{137}Cs and ^{40}K (b) in fruit on the fruiting shoot contaminated dis- ^{137}Cs . * and ** indicate a significant correlation at $P \leq 0.05$ and 0.01 by ANOVA

2020 and 2021, respectively. The TR_f of ^{137}Cs for fruit on the contaminated apical fruiting mother shoot at young and mature stage was $0.64 \pm 0.27\%$ and $1.3 \pm 0.6\%$ in 2020, which was significantly higher than that of ^{137}Cs into fruit on the uncontaminated 2-year-old lateral branch, which was $0.30 \pm 0.27\%$ and $0.29 \pm 0.22\%$ (Fig. 10.6a). In contrast, there was no significant difference in the

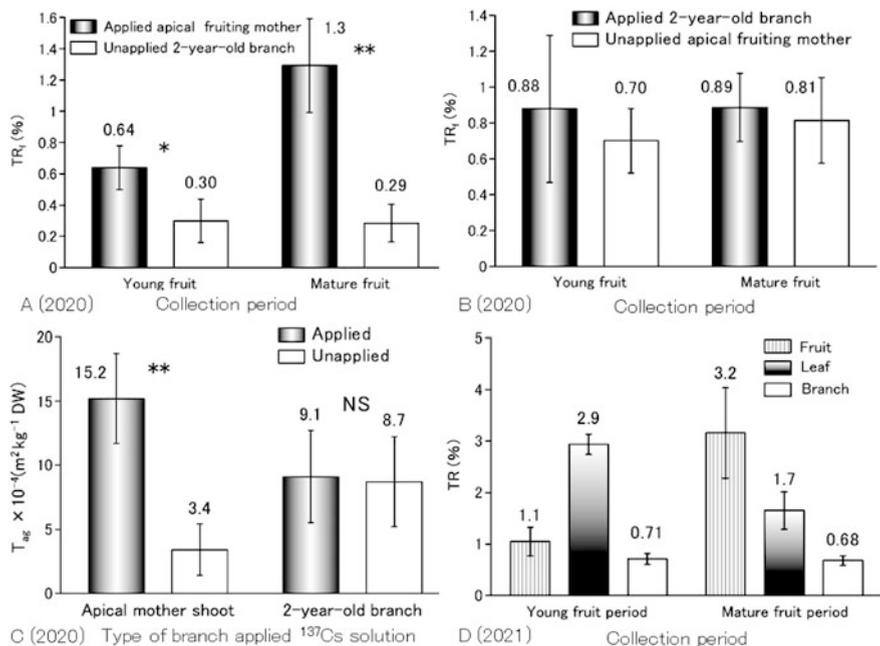


Fig. 10.6 TR_f of ¹³⁷Cs applied on the apical fruiting mother shoot (a) and the 2-year-old lateral branch (b), T_{ag} via the fruiting mother shoot and 2-year-old lateral branch contaminated dis-¹³⁷Cs before sprouting in 2020 (c) and TR of ¹³⁷Cs into leaf, fruit and branch on and of the contaminated apical fruiting mother shoot in 2021 (d). The TR into branch in (d) was combined both TR of the shoot, of which was bark and wood, and of the wood of the contaminated apical fruiting mother shoot except for bark on which surface remains the contaminated ¹³⁷Cs. In graph C “Unapplied” at the label of “Apical mother shoot” and “2-year-old branch” represent fruiting mother shoots other than “Apical mother shoot” and an apical fruiting mother shoot. In graph D, “branch” represents the TR except for bark of contaminated branch/shoot. * and ** indicate a significant correlation at $P \leq 0.05$ and 0.01 by ANOVA. Vertical bar represents arithmetic standard deviation

TR_f of the fruit from the contaminated 2-year-old lateral branch between the uncontaminated apical fruiting mother shoot and the other fruiting mother shoot at young and mature period in 2020 (Fig. 10.6b). The T_{ag}^{f-b} of the mature fruit on the contaminated apical fruiting mother shoot was significantly higher than that in fruit on the corresponding uncontaminated fruiting mother shoots, whereas there was no significant difference in the T_{ag}^{f-b} of the mature fruit on the apical fruiting mother shoot and other fruiting mother shoots on the contaminated 2-year-old branch (Fig. 10.6c). In 2021, the TR_f of ¹³⁷Cs for mature fruit on the contaminated apical fruiting mother shoot was $3.16 \pm 1.75\%$, which was higher than $1.05 \pm 0.56\%$ for young fruits (Fig. 10.6d). The T_{ag}^{f-b} of the mature fruit was $8.0 \pm 4.5 \times 10^{-4} m^2 kg^{-1} DW$. The TR_f of ¹³⁷Cs for the mature fruit via the contaminated apical fruiting mother shoot was significantly higher in 2021 than in 2020 (0.025 P value by t -test).

10.4 Discussion

Because RCs was deposited directly onto fruit tree surfaces (Sato et al. 2015b), it was important to evaluate how much RCs was transferred via leaves to fruits after bud burst after the FDNPP accident.

The calyx of Japanese persimmon is larger than that of other fruit trees and plays an important role in fruit enlargement as the respiratory organ of fruit. Calyx lobes fall during the young fruit stage. The shape of the calyx resembles a dish after the fruit growing stage, because the calyx lobes become erect, so RCs in raindrops intercepted by leaves and branches would tend to accumulate in/on the calyx (Fig. 10.7). Previous studies on the transfer of dis-¹³⁷Cs from cotton contaminated with ¹³⁷Cs solution onto the calyx of mature Japanese persimmon fruit (cultivar ‘Hiratanenashi’) reported that TR_f were 2.3% in the “Immature period” during 7–40 days after full blossom and 16.9% in the “Mature period” during 41 days after full blossom to harvest (Sekizawa et al. 2016a, b). The data derived from this study are not consistent with these findings (Table 10.1) because of differences in the method applied and the period during which the contamination occurred. In this study, the contamination period was 23–31 days after full blossom in the young fruit stage and 61–75 days after full blossom in the fruit growing stage. These time periods were shorter than that of Sekizawa et al. and the contamination method involved direct application of ¹³⁷Cs, whereas Sekizawa et al. used an indirect treatment via cotton. Before 20 days after full blossom most calyx lobes fall, during which dis-¹³⁷Cs from cotton may have been lost from the calyx. Such losses may explain why TR_f in the “Immature period” on the experiment of Sekizawa et al. was



Fig. 10.7 Stemflow stayed on the calyx of “Hachiya” persimmon

lower than that reported in this study. Anyway, further studies are needed to clarify the transfer of ^{137}Cs into fruit via calyx.

The TR_f of ^{137}Cs from contaminated calyx and leaves in the young fruit stage into fruit that had dropped naturally in EXP. 1 was less than 3% (Table 10.2), whereas the TR_f into mature fruit was three fold higher at >10% (Tables 10.1 and 10.3). In EXP. 4, the TR_f of ^{137}Cs from contaminated apical fruiting mother shoots into fruit before sprouting increased from the young fruit to the mature fruit, whereas for leaves, it decreased during the same period (Fig. 10.6d). Therefore, the data indicates that translocation of ^{137}Cs to fruit via the leaves and bark consistently increases after the fruit growing stage. The TR_f of ^{137}Cs from contaminated leaves in the young fruit stage in Japanese persimmon was lower than that reported for fruit after the fruit growing stage (Table 10.1).

These results are corroborated by studies of Pröhl et al. (2003) who found that the transfer rate to fruits via leaves in apples was higher after spraying a ^{137}Cs solution during the fruit growing stage than at the young fruit stage. Other previous data also shows that for grape, the translocation of ^{137}Cs absorbed from the aboveground part of the tree to fruits increased after the fruit growing period (Madoz-Escande et al. 2002). Furthermore, Davies et al. (2006) showed that two potassium transporters in grape are expressed most highly in the berry skin during the pre-véraison period (a stage at which berries begin to soften and change color). Overall, these studies indicate that the TR_f of ^{137}Cs in fruit due to deposition onto leaves is affected by the time at which contamination occurs, and that the extent of accumulation (sink strength) of ^{137}Cs increases after the fruit growing stage. These results are consistent with other relevant data, which showed that translocation of photosynthetic products from leaves to fruits accelerated after the fruit growing stage (Pavel and DeJong 1995; Yamamoto 2001; Zhang et al. 2005; Beshir et al. 2017).

There was a significant correlation between ^{40}K and ^{137}Cs in the mature fruit in EXP. 3. Moreover, the correlation was higher for the total Bq amount than for activity concentration. Amount represents sink strength and activity concentration represents sink activity (Fig. 10.5). K, an analogue of Cs, promotes the translocation of photosynthetic products from leaves to fruit (Eplon et al. 2015), which explains why the TR_f of ^{137}Cs in fruit via leaf also increased after the fruit growing period.

The effect of the distance between fruit and the leaves as the source of ^{137}Cs was shown in the experiment with Japanese persimmon “Hiratanenashi,” where the TR_f after contamination of the leaves adjacent to the fruit was much higher than that after contamination of leaves located further away at the top of the long shoot (Table 10.4). These observations indicate that the relationship between supply and demand of photosynthetic products on the fruiting shoot influenced the sink and source relationship of ^{137}Cs between leaf and fruit. Katana et al. (1988) placed a ^{134}Cs solution onto leaves at the top of the apple branch. Consequently, 19–42% of ^{134}Cs administered was transferred to fruit on the same contaminated branch, whereas a small amount of ^{134}Cs (at 0.01–0.4%) was detected in fruit at the base of the 25 cm length lower branch. They concluded that the relationship between the contaminated leaves and fruit had a tendency that the transport of radiocesium

deposited on the leaves to the fruits is restricted within the branches on which contaminated leaves are growing, and it is difficult to migrate into the fruits on the different branches. Carini et al. (1999) compared the transfer of ^{134}Cs from contaminated leaves to fruits between contaminated branches and uncontaminated branches in grapes, apples, and pears. The transfer factor of ^{134}Cs in fruit of the contaminated branch, which was defined by fruit concentration ($\text{Bq kg}^{-1} \text{ DW}$) divided by Bq administered per plant, was 1.33, 5.11 and 0.69; this was significantly higher than that of the uncontaminated branch of 0.098, 0.1 and not detected for grapes, apples, and pears, respectively. These data showed that there was a close relationship between source and sink for ^{134}Cs on the contaminated branch.

At the time of the FDNPP accident, the Japanese persimmon was in the dormant stage prior to bud burst and ^{137}Cs on the contaminated bark of the aboveground part of the fruit tree migrated directly into the tree. After bud burst, Sato et al. (2021) reported that leaves were also contaminated with ^{137}Cs via raindrops in the canopy during or after rainfall. K^+ is readily absorbed by leaves (Franke 1967; Schönherr and Lubert 2001) and McFarlane (1974) reported that Cs^+ penetrates through the cuticle more easily than K^+ . K^+ penetrates through the fine pores in the cuticle on the leaf surface, thereby reaching parenchyma cells and is then transported via the vascular system. K plays a key role in elevating the translocation of assimilates from leaves to fruit after the fruit growing period (Eplon et al. 2015). Conversely, K leaches through the cuticle easily from leaves due to rainfall (Tukey and Mecklenburg 1964; Mecklenburg and Tukey 1964; Potter et al. 1991), which probably also occurs for radiocesium.

In this study, the effect of the fruit load on TR_f differed depending on which organ was contaminated. In EXP. 3, ^{137}Cs administration onto leaves of fruiting shoots that had been subjected to fruit thinning just before the contamination treatment on July 31 resulted in a higher value of the TR_f than when thinning was not applied. Similarly, a higher amount of ^{40}K was translocated into fruits on the contaminated long fruiting shoot in the “Fruit thinning” scenario (showing that the sink activity and strength of these fruits works effectively) compared with the “No fruit thinning” shoot. The difference indicates that the accumulation by these fruits was suppressed possibly by competition with other fruits on the uncontaminated shoots that had developed on the same mother shoot.

In EXP. 4, the administration of ^{137}Cs to a dormant apical fruiting mother shoot without fruit thinning resulted in a higher TR_f than that in the year with fruit thinning. The number of fruits per shoot in the experiment in 2021 was approximately four times higher than that of the experiment in 2020. The difference in fruit load between the experimental years in EXP. 4 is larger than that between the treatments in EXP. 3. This suggests that the higher TR_f in the experiment without fruit thinning was due to the different mass of the fruits. Conversely, there was a significantly higher [^{137}Cs] in EXP. 3 (Table 10.5) and T_{ag}^{f-b} in EXP. 4 (Fig. 10.6c, d) in the experiment with fruit thinning. These initial data indicate that refraining from heavy fruit

thinning may be a useful remediation option that could reduce the [^{137}Cs] in Japanese persimmon fruits.

In EXP. 4 conducted using the same leaf to fruit ratio, the transfer of contaminated ^{137}Cs was compared between fruits on the apical fruiting mother shoot and the other fruiting mother shoots developed from the same 2-year-old lateral branch. When dis- ^{137}Cs solution was applied to the apical fruiting mother shoot, the TR_f of the combined mature fruits collected from the other fruiting mother shoots was less than a quarter of that for the fruit on the contaminated apical mother shoot (Fig. 10.6a). In contrast, when dis- ^{137}Cs solution was applied to the 2-year-old lateral branches, the TR_f and the T_{ag}^{f-b} into fruit were similar between the fruit on the apical fruiting mother shoot and the other fruiting mother shoots (Fig. 10.6b, c).

These results indicate that the transfer of ^{137}Cs to fruits grown on fruiting mother shoots developed from the same contaminated 2-year-old lateral branch is similar, whereas the transfer of ^{137}Cs from a contaminated apical fruiting mother shoot to fruits grown on the other shoots developed from the same 2-year-old lateral branch is limited. Furthermore, [^{137}Cs] of fruit on the contaminated fruiting shoot in the fruit thinning was higher than that with no fruit thinning in EXP. 3 (Table 10.6), and T_{ag}^{f-b} in 2020 when the fruit was thinned was higher than that in 2021 where the fruit was not thinned in EXP. 4. These data are consistent with the experimental results assuming that the transfer of ^{137}Cs is controlled by the sink activity of fruits.

T_{ag}^{f-b} values derived in EXP. 4 were of the order of magnitude of the $10^{-4} \text{ m}^2 \text{ kg}^{-1}$ DW. Unfortunately, there are no previous data reported for Japanese persimmon after the Chernobyl accident, and only a few data for T_{ag} in fruit after the FDNPP accident. Renaud and Gonze (2014) reported T_{ag} ($\text{m}^2 \text{ kg}^{-1}$ FW), which vary in a range of 10^{-4} to $10^{-3} \text{ m}^2 \text{ kg}^{-1}$ FW. For persimmon T_{ag} values of $9.7 \times 10^{-4} \text{ m}^2 \text{ kg}^{-1}$ FW was previously reported by Tagami and Uchida (2014). The value of $15.2 \times 10^{-4} \text{ m}^2 \text{ kg}^{-1}$ DW of T_{ag}^{f-b} in EXP. 4 is the equivalent of $2.4 \times 10^{-4} \text{ m}^2 \text{ kg}^{-1}$ FW of T_{ag}^{f-b} . Although the leaf area of the contaminated leaves was not measured in EXP. 3, the T_{ag} into fruit via leaves calculated assuming a leaf area of 72 cm^2 (Fujimoto and Tomita 2000) was $10^{-3} \text{ m}^2 \text{ kg}^{-1}$ FW. Therefore, T_{ag} into fruit via dormant branches can be tentatively estimated to be one order of magnitude lower than T_{ag} into fruit via leaves.

This study has shown that T_{ag}^{f-b} for the fruit on the apical mother shoot were approximately twice as high as for fruits on other fruiting mother shoots developed on the same 2-year-old branch contaminated during dormancy. However, similar experiments on fruiting mother shoots on 2-year-old branches other than apical fruiting mother shoots have not yet been conducted. The currently available data suggest that fruit load is likely to be one of the main factors affecting variation in the extent of [^{137}Cs] transfer into fruits within the same lateral branch.

To our knowledge, this was the first reported study that has quantified the transport of ^{137}Cs into fruit via the dormant lateral branch. Further studies are needed to clarify the dynamics of ^{137}Cs inward migration into deciduous fruit trees that have been externally contaminated during dormancy and other growth phases.

10.5 Limitations

The dis-¹³⁷Cs solution used in EXP. 4 contained up to approximately 0.06 Bq mL⁻¹ of ⁴⁰K (0.2% as natural K), but no ⁴⁰K was detected in the dis-¹³⁷Cs solution used epiphytic moss growing on rock. Natural K is present on leaves and bark surfaces by leaching, and inward-migration of RCs from the tissue surface is a physical permeation phenomenon, so inward-migration of dis-¹³⁷Cs likely is not affected by K in the applied solution unlike absorption via the roots. No significant differences in ⁴⁰K activity concentrations in organs between of the control group and the experimental group were found on each sampling date, whereas a considerable amount of applied ¹³⁷Cs was detected in each experiment of this study. While K in the applied dis-¹³⁷Cs seems to have negligible relevance to the result in each experiment, utilizing the parameter calculated in EXP. 4 needs to take into account the precondition which is the experiment using the dis-¹³⁷Cs solution contained up to 0.2% as natural K.

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