# Chapter 11
# Translocation of Radiocesium in Fruit Trees

**Daisuke Takata**

**Abstract** We report our findings on the translocation and distribution of radiocesium inside fruit trees after radiocesium (Cs) was released by the accident at the Fukushima Daiichi Nuclear Power Plant.

We examined the differences in the rooting depth of grapes and figs and the translocation of radiocesium from the soil to the plants. Much of the radiocesium fallout from the nuclear accident remained on the surface soil layer; however, in environments such as orchards, radiocesium translocates more easily to aboveground parts of trees with shallower roots than of those with deeper roots. It was observed that if the old branches were the source of radiocesium, translocation occurred to both the new aboveground organs, such as leaves and fruits, and the underground parts, including pioneer roots. It was clarified that translocation from old organs contributed a much higher proportion of accumulated radiocesium to fruits than that from the soil. We reported that immediately after the accident, radiocesium that accumulated on the bark quickly infiltrated inside the trees. However, several months after the accident, it is possible that a decreased proportion translocated from the outer bark to the internal parts of trees, such as the wood. The translocation of radiocesium and potassium (K) into fruits and leaves may show some differences. Explaining the behavior of radiocesium translocation in perennial crops using K as an index is even more difficult than that in annual crops. To predict the radiocesium concentrations in the harvested fruits, the concentrations in the thinned fruits and the harvested fruits were compared. The results showed that there is a strong correlation between the two. However, since some trees were outliers, predictions must be made carefully.

**Keywords** Fig • Fruit tree • Grapes • Peach • Radiocesium

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## 11.1 Introduction

Major fruit production in Fukushima Prefecture in 2013 was cultivated over 5762 ha and produced a crop yield of 84,060 t; in terms of cultivation area, Fukushima ranked 9th in Japan (Ministry of Agriculture, Forestry and Fisheries, Japan (MAFF)). When itemized, the crop yield of peaches ranked 2nd (share 23 %, 124,700 t, 2013). This shows that, even after the nuclear accident, Fukushima was still a major producer of fruits in Japan (Table 11.1). Many crops did not suffer significant reductions to their growing area and yield; however, the shipment volume of persimmons decreased to 1/3 in the year of the accident, and has not changed much since then (Table 11.2). However, even crops that did not suffer decreased shipping volumes were significantly impacted. For example, there was an increased shipment of crops, such as peaches through agricultural cooperatives, to the market during the year of the accident. The following factors are believed to have contributed. Sales were poor due to the consumers' concerns over radiocesium, indicating that direct sales and orchard sales to tourists decreased. As a response to consumer reactions, producers changed the sales policy. Together, these factors led to an increase in the stock volume; thus, in the year of the accident, the wholesale price

**Table 11.1** Shipments, crop yields and cultivated area of Fukushima Prefecture in 2013 (from Ministry of Agriculture, Forestry and Fisheries, Japan 2013)

| Fruit trees | Ranked | Cultivated area (ha) | Crop yields (t) | Shipments (t) |
|---|---|---|---|---|
| Peach | 2nd | 1780 | 29,300 | 27,100 |
| Apple | 6th | 1380 | 26,800 | 23,500 |
| Persimmon | 5th | 1340 | 3790 | 3790 |
| Japanese pear | 4th | 974 | 19,800 | 18,300 |
| Grapes | 13th | 288 | 2960 | 2960 |

**Table 11.2** Changes in shipments and crop yields and cultivated area of peach and persimmon in Fukushima Prefecture (from Ministry of Agriculture, Forestry and Fisheries, Japan 2013)

| | Peach | | | Persimmon | | |
|---|---|---|---|---|---|---|
| Year | Cultivated area (ha) | Crop yields (t) | Shipments (t) | Cultivated area (ha) | Crop yields (t) | Shipments (t) |
| 1990 | 2610 | 40,200 | 37,600 | 1350 | 10,200 | 8270 |
| 2000 | 1800 | 31,500 | 29,400 | 1420 | 11,000 | 8670 |
| 2004 | 1750 | 30,700 | 28,400 | 1430 | 13,500 | 11,200 |
| 2008 | 1790 | 31,800 | 29,400 | 1420 | 16,100 | 13,500 |
| 2009 | 1790 | 30,100 | 27,900 | 1410 | 13,600 | 11,300 |
| 2010 | 1780 | 28,200 | 26,200 | 1400 | 14,000 | 12,000 |
| 2011[a] | 1780 | 29,000 | 26,500 | 1390 | 4550 | 3540 |
| 2012 | 1780 | 27,500 | 25,200 | 1350 | 4480 | 3390 |
| 2013 | 1780 | 29,300 | 27,100 | 1350 | 4890 | 3790 |
| 2013 in Japan | 10,700 | 124,700 | 114,100 | 22,300 | 214,000 | 177,400 |

[a]Accident year

**Table 11.3** Stock volume, Market share and wholesale price of monthly Fukushima Prefecture peach in Tokyo metropolitan central wholesale market (from Monthly report of Tokyo metropolitan central wholesale market, 2013)

| | August | | | September | | | August–November Total/average | | |
|---|---|---|---|---|---|---|---|---|---|
| Year | Stock volume (t) | Market share (%) | Wholesale price (Yen/kg) | Stock volume (t) | Market share (%) | Wholesale price (Yen/kg) | Stock volume (t) | Market share (%) | Wholesale price (Yen/kg) |
| 2008 | 2837 | 43.0 | 359 | 755 | 45.2 | 408 | 3599 | 43.3 | 369 |
| 2009 | 2751 | 48.5 | 384 | 537 | 43.3 | 411 | 3294 | 47.5 | 389 |
| 2010 | 2421 | 42.5 | 439 | 868 | 41.9 | 481 | 3309 | 42.2 | 450 |
| 2011[a] | 4631 | 54.1 | 196 | 786 | 38.3 | 300 | 5433 | 50.9 | 211 |
| 2012 | 2834 | 48.4 | 344 | 998 | 42.0 | 364 | 3881 | 46.3 | 350 |
| 2013 | 3916 | 61.5 | 342 | 622 | 36.7 | 421 | 4574 | 56.0 | 353 |

[a]Accident year

dropped when compared to the previous year (Table 11.3). However, the stock volume returned to the pre-accident value in the following year, leading to a certain level of recovery in the wholesale price. Prices have shown some stability in the years following the accident.

However, compared to other crops, such as rice, there have not been many studies conducted on radiocesium translocation in fruit trees since the nuclear accident. Thus, there are still many factors that need to be determined. In a previous publication (Takata 2013), the impact of radiocesium on the translocation and distribution inside fruit trees was investigated. The behavior of radiocesium inside fruit trees after the nuclear accident differed to that found after the Chernobyl accident. It was thought that significant effects occurred because at the time of the accident many deciduous fruit trees had not yet flowered or begun producing leaves. Although the accident occurred prior to the growth of leaves and fruits, radiocesium was detected in fruits at the time of harvest. In the year of the accident, the contribution of radiocesium fallout in soil to translocation from the roots was much lower than from aboveground parts. Therefore, we considered the possibility that radiocesium adhered to aboveground organs, such as the trunk and primary scaffold limbs, translocated to the inside of trees via direct deposition on old organs in aboveground parts. Translocation pathways to fruits are most likely due to translocation from old aboveground organs and absorption from the soil through the roots. However, the relative contribution of these two pathways is unclear. In addition, in single annual crops, the behaviors of radiocesium and K showed a strong relationship. Thus, the behavior of K can be a measure of translocation; therefore, application of K to reduce translocation is being undertaken. However, it is difficult to examine all the radiocesium behaviors in relation to K in perennial fruit trees, particularly when radiocesium is already present inside the trees.

In this chapter, we focus on the report from the previous publication in order to discuss the relationship between radiocesium and K in terms of the behavior of radiocesium inside the trees and in orchards.

## 11.2 Pathways of Radiocesium in Fruit Trees

### *11.2.1 Absorption from Soil*

As the distribution of radiocesium in soil after nuclear accident was defined, it became clear that there was a large proportion of radiocesium in the surface layer of soil in orchards (Takata et al. 2012c, d). We demonstrated that, even in this condition, the amount of radiocesium translocated from the soil to mature peach trees in the year of the accident was minimal compared to the amount directly absorbed from aboveground parts (Takata et al. 2012b). The survey of transfer factors of fruit trees, conducted after the Chernobyl accident, showed that this does not mean that there is no translocation from the soil in orchards (IAEA 2003). Furthermore, it is possible that a large amount of radiocesium may be absorbed from the soil surrounding small (young and recently transplanted) trees, with a rapid increase in dry matter.

Among the tests to determine the transfer factors affected by the Chernobyl accident, a survey of the planting area was conducted in undisturbed areas, while reproduction tests in pots were conducted in soil with uniform radiocesium concentrations. The differences in the conditions may be the cause for the large discrepancy in transfer factors, even in the same tree species. In vegetable cultivation, radiocesium adhering to the soil surface is stirred during tilling (Oshita et al. 2013). However, orchard soil is not tilled, so it is thought that homogenization with the lower soil layer does not occur. In fruit trees, the distribution of roots with depth varies depending on the tree species, variety, and rootstock variety. Therefore, it is important to clarify the level of radiocesium translocation to fruit trees taking into consideration the variations in root distribution and heterogeneity of the soil pollutant. However, no such report is available. Therefore, we investigated translocation of radiocesium inside fruiting trees, shallow-rooted figs and deep-rooted grapes, located in an area where radiocesium was present only in the soil surface or in the lower soil layer, and we compared the organ volume distribution with naturally-occurring $^{40}$K.

We tested 3-year-old 'Campbell Early' and 'Muscat Bailey A' grapes (*Vitis. spp*.), and 2-year-old 'Houraishi' figs (*Ficus carica* L.) in 4.0 L pots. These plants had been cultivated in a closed, environmentally controlled greenhouse before the nuclear accident. In March 2012, the trees were replanted into 7.0 L pots, and the radiocesium concentrations in the soil were adjusted. To adjust the radiocesium concentration in the soil, we used orchard soil (sandy loam) from Date, Fukushima Prefecture, and Tokyo, and uncontaminated commercial soil (Akadama soil and mulch). For example, for 'Campbell Early,' sections with a uniform concentration

**Table 11.4** $^{137}$Cs concentration in pot soil (from Takata et al. 2013b)

| | Soil $^{137}$Cs concentration (Bq/kg – Dry weight) | | | Soil $^{137}$Cs content |
|---|---|---|---|---|
| Cultivar | 0–5 cm depth | 5–15 cm depth | Homogeneous | (Bq/pot) |
| Grapes | | | | |
| Campbell early | | | | |
| 0–5+ | 833.9 ± 1.9 | 4.7 ± 0.0 | 258.8 ± 1.8 | 655.3 |
| 5–15+ | 2.0 ± 0.0 | 938.7 ± 1.7 | 618.8 ± 0.0 | 1543.6 |
| Homogeneous | 576.4 ± 7.1 | 609.1 ± 0.7 | 592.2 ± 5.8 | 1665.1 |
| Muscat bailey A | | | | |
| 0–5++ | 1006.5 ± 0.8 | 2.0 ± 0.0 | 293.4 ± 18.7 | 765.9 |
| 0–5+ | 467.4 ± 1.1 | 2.0 ± 0.0 | 154.2 ± 9.9 | 390.3 |
| 5–15+ | 2.1 ± 0.2 | 483.5 ± 0.1 | 307.5 ± 10.0 | 746.7 |
| Fig | | | | |
| Houraishi | | | | |
| 0–5+ | 4068.6 ± 131.1 | 3.9 ± 0.6 | 1450.3 ± 51.5 | 3521.4 |
| 5–15+ | 1.5 ± 0.6 | 4208.1 ± 138.2 | 2818.4 ± 103.0 | 6355.4 |

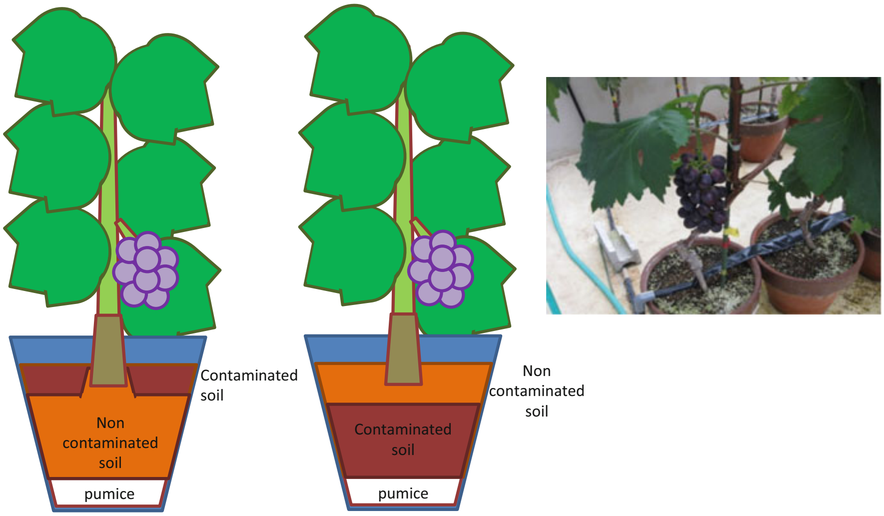


**Fig. 11.1** Test of heterogeneity of $^{137}$Cs concentration in pot soil. *Left*: 0–5+, *right*: 5–15+, Photograph: the image of potted grape tree

were established: a high concentration of radiocesium in the soil 0–5 cm (surface layer; 0–5+), and the 5–15 cm (lower layer; 5–15+) (Table 11.4, Fig. 11.1). At 5 cm, where the concentration changed, three layers of water-soluble packaging paper were placed to delineate the boundary. Similar treatment sections were established for the 'Muscat Bailey A' grape and 'Houraishi' fig. The concentration of $^{40}$K in the soil was about 300 Bq/kg DW. After cultivation, the trees were divided into fruits, leaves, shoots, old branches (1–3-year-old branches, including rootstock), and roots. The dry weight was measured and concentrations of $^{137}$Cs and $^{40}$K were measured. In the two varieties of grapes and figs, the dry weight of roots from 0 to 5 cm was lower than that from 5 to 15 cm (Table 11.5). The proportion of 0–5 cm roots was higher in figs than in grapes (Fig. 11.2). The weight of the 0–5 cm pioneer roots of grapes was less than that from 5 to 15 cm. However, for figs, it was higher than that for 5–15 cm roots. Based on these results, we conclude that fig roots grew more vigorously at shallower depths than grape roots, so these plants would be suitable for comparing the effect of root distribution with depth on radiocesium uptake.

After converting the concentration of $^{137}$Cs in fruits to per fresh weight (Bq/kg FW), the value was divided by the concentration in the soil (Bq/kg DW) to obtain the transfer factor. The $^{137}$Cs concentration in the soil was obtained by homogenizing the soil from 0 to 5 and 5 to 15 cm depths unless the soil was uniformly contaminated. In addition, the pioneer root weight was obtained by subtracting the root weight of individual roots, which were dissected separately prior to the test, from the root weight after cultivation (Table 11.6). Concentrations of $^{137}$Cs in the fruits of grapes and transfer factors were higher in 5–15+ than in 0–5+, and it was

**Table 11.5** Root weight in each depth of grape vine and fig trees (from Takata et al. 2013b)

| | Total root weight (gDW) | | New root weight (gDW)[a] | |
|---|---|---|---|---|
| Cultivar | 0–5 cm depth | 5–15 cm depth | 0–5 cm depth | 5–15 cm depth |
| Grapes | | | | |
| Campbell early | | | | |
| 0–5+ | 7.65 | 25.05 | 3.85 | 5.18 |
| 5–15+ | 7.92 | 26.27 | 3.87 | 5.23 |
| Homogeneous | 7.68 | 26.88 | 2.73 | 4.85 |
| Muscat bailey A | | | | |
| 0–5++ | 7.48 | 26.75 | 2.53 | 3.35 |
| 0–5+ | 7.63 | 27.23 | 2.60 | 2.73 |
| 5–15+ | 7.95 | 26.80 | 2.73 | 3.58 |
| Fig | | | | |
| Houraishi | | | | |
| 0–5+ | 15.43 | 24.75 | 7.20 | 5.55 |
| 5–15+ | 14.93 | 24.40 | 7.18 | 4.35 |

[a]New root weight = root weight after harvest – root weight before budbreak

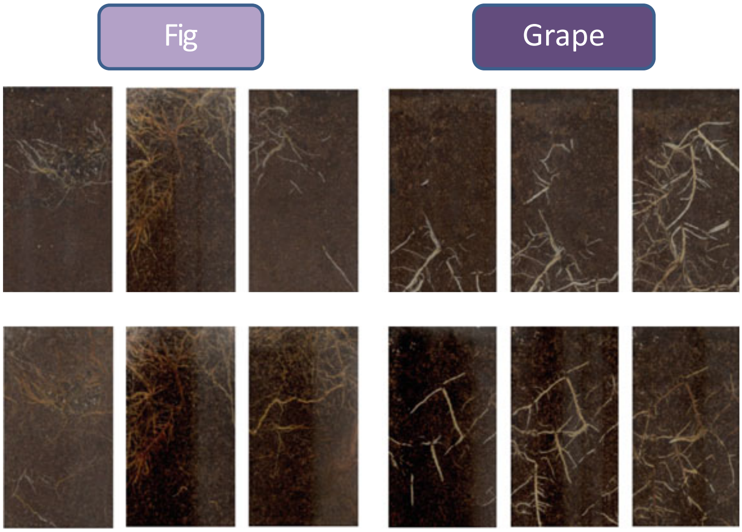


**Fig. 11.2** Rooting of acrylic potted grape vine and fig trees. Roots of fig spread only upper part, and roots of grape spread all around

thought that $^{137}Cs$ translocation to new organs, such as fruits, derived more $^{137}Cs$ from the lower soil layer. In the 5–15+ section of 'Campbell Early' the concentration of $^{137}Cs$ in the roots was high in the lower soil layer with a high $^{137}Cs$ concentration. However, in other treatment sections, the concentrations in the roots were not necessarily high in soil layers with high concentrations. This indicates that the $^{137}Cs$ absorbed by the roots was also accumulated in the pioneer

**Table 11.6** $^{137}Cs$ concentration in each organ and TF of grape vine and fig trees (from Takata et al. 2013b)

| | $^{137}Cs$ (Bq/kg – Dry weight) | | | | | | |
|---|---|---|---|---|---|---|---|
| Cultivar | Fruit | Leaf | Shoot | Old branch | Root at 0–5 | Root at 5–15 | TF[a] |
| Grapes | | | | | | | |
| Campbell early | | | | | | | |
| 0–5+ | 1.9 ± 0.1 | 3.5 ± 0.5 | 2.0 ± 0.5 | 5.2 ± 1.4 | 6.4 ± 0.9 | 6.1 ± 1.0 | 1.68E-03 |
| 5–15+ | 10.6 ± 0.4 | 9.7 ± 0.6 | 4.2 ± 0.6 | 5.9 ± 1.7 | 6.6 ± 0.9 | 11.1 ± 1.1 | 3.97E-03 |
| Homogeneous | 6.8 ± 0.2 | 3.7 ± 0.5 | 3.8 ± 0.6 | 5.7 ± 1.3 | 9.1 ± 1.1 | 9.1 ± 1.0 | 2.67E-03 |
| Muscat bailey A | | | | | | | |
| 0–5++ | 3.7 ± 1.1 | 8.4 ± 0.3 | 3.2 ± 0.2 | 7.2 ± 1.9 | 19.0 ± 1.8 | 17.5 ± 2.0 | 2.93E-03 |
| 0–5+ | 2.9 ± 0.9 | 6.5 ± 1.6 | 2.4 ± 0.2 | 5.8 ± 1.7 | 14.4 ± 2.1 | 13.5 ± 1.3 | 4.39E-03 |
| 5–15+ | 7.5 ± 1.0 | 8.1 ± 0.3 | 3.9 ± 0.3 | 7.6 ± 2.1 | 13.3 ± 1.6 | 16.1 ± 1.7 | 5.67E-03 |
| Fig | | | | | | | |
| Houraishi | | | | | | | |
| 0–5+ | 234.2 ± 23.3 | 195.6 ± 19.2 | 100.2 ± 1.2 | 48.0 ± 3.5 | 78.9 ± 5.8 | 41.5 ± 3.4 | 2.66E-02 |
| 5–15+ | 121.1 ± 9.5 | 124.4 ± 9.0 | 50.3 ± 10.0 | 21.0 ± 2.2 | 39.3 ± 3.9 | 62.0 ± 6.4 | 7.08E-03 |

[a]TF = (fruit Bq/kgFW)/(soil Bq/kgDW)

roots at different depths. This can occur in orchards, indicating that radiocesium present in the surface soil layer was absorbed by roots in the surface layer, and was translocated to roots in the lower layer. The proportion is unclear, so the rate at which this occurs is unknown. However, it is likely that this increases the concentration of radiocesium in the lower soil layer.

When contamination was either limited to the lower soil layer or was spread uniform, the problem was not substantial, because in the current situation, the contamination was limited to the surface soil layer. On the other hand, this could be a problem during planting or transplanting. For example, at the time of transplanting, by developing the planting area using soils from other locations without removing the contaminated surface, there is a risk of contaminating the lower soil layer. Fruit trees with deep roots can develop high transfer factors when the lower soil layers are contaminated; therefore, absorption from the soil may pose a critical problem compared to the situation when only the surface layer is contaminated. On the contrary, there are reports indicating that the transfer factors were high when only the surface soil layer had high concentrations compared to when the soil is homogenized. A previous report (IAEA 2003) using pots demonstrated that transfer factors in the same tree species were higher under uniform concentrations compared with the actual planting area. The issue must be sufficiently examined.

Transfer factors in the 0–5+ section for figs were similar to the values reported after the Chernobyl accident (Marouf et al. 1992). However, the values were larger than those for the two varieties of grapes. We believe that our test can reproduce the results of obtained by examining the actual planting areas, because it reproduces the significant contamination levels in the surface soil layer. On the other hand, the concentration of $^{137}$Cs in new organs in the 5–15+ section was lower than that in the 0–5+ section (Table 11.4). Since such variation was noted in the 0–5+ section of figs, although the total $^{137}$Cs volume in the soil was lower than that in the 5–15+ section, it is thought that in figs the ratio of $^{137}$Cs translocated to new organs, such as fruits, was derived from the $^{137}$Cs present in the surface soil layer which was high. This is also evident from the transfer factors. Transfer factors for the 5–15+ section had values one order of magnitude lower than the 0–5+ section. It is believed that the following aspects are related to the differences in the transfer factors of figs caused by the differences in the depth of the contaminated soil: (1) the distribution of fig roots was shallow, (2) the weight of roots in the surface layer was higher than that for grapes, and (3) the weight of pioneer roots was high (Table 11.5). In other words, the amount of rooting of pioneer roots, which play a major role in element absorption in the soil, was low in the lower soil layer, and high in the surface soil layer, leading to the different absorption of $^{137}$Cs.

The changes in $^{137}$Cs and $^{40}$K were calculated in the organs of two varieties of grapes. These were obtained by multiplying the nuclide concentration by the organ volume to find the content per organ, then subtracting the pre-test (pre-sprouting) nuclide content from that value. In this test, each test subject was cultivated in a closed space before the accident, and had not been exposed to the fallout. In addition, $^{137}$Cs was measured after homogenizing all the parts in another sample under the same conditions prior to the test, and the results were below the detection limit. Therefore, the $^{137}$Cs content prior to the test was assumed to be 0. The

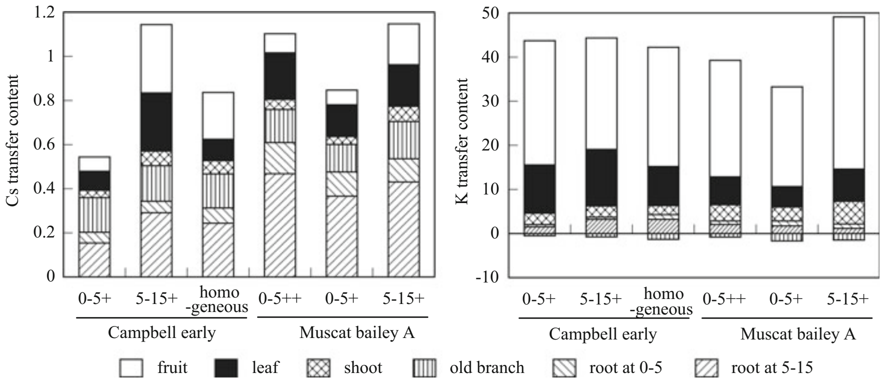


**Fig. 11.3** $^{137}$Cs and $^{40}$K transfer content of grapevine (from Takata et al. 2013b). Transfer content = radioisotopes content *after* harvest-radioisotopes content *before* budbreak. Radioisotopes content = weight per each organ (gDW) × Bq/kgDW at each time

changes in $^{137}$Cs in organs showed the same trend as in the $^{137}$Cs concentration previously discussed. This indicates that there was no difference in tree growth due to the different treatments. There was a 60 % or more increase in $^{40}$K in fruits for each treatment. Evidently, the changes in $^{40}$K and $^{137}$Cs were notably different. In this test, the change in $^{40}$K in the old branches was negative (Fig. 11.3). This is thought to be related to the fact that K in the old branches was quickly used to build new organs after sprouting. On the other hand, at the time of the test, $^{137}$Cs was not present inside the trees, and was not used in the early growth. Because of this, in fruits that have a large K requirement, an extreme difference between $^{137}$Cs and $^{40}$K occurred. The difference in the rates of $^{137}$Cs and $^{40}$K in fruits may be affected by the absorption from the soil and by differences in translocation to the aboveground parts. However, this is unclear based on the categories of this test.

Compared to other tree species, it is believed that the radiocesium absorbed by shallow-rooted species is high when the $^{137}$Cs concentration in the surface soil layer is high. This seems to be relevant in detecting radiocesium in blueberries in Fukushima and Ibaraki prefectures. However, trees in the outdoor planting area already have $^{137}$Cs internally, so the behavior of radiocesium cannot be explained simply based on translocation from the soil. Thus, in order to determine the behavior of radiocesium in perennial fruit trees, it is necessary to examine the radiocesium translocation in the old organs, and not just in the soil.

### *11.2.2 Translocation from Aboveground Old Organs*

In the previous section, we discussed translocation of radiocesium from the soil. However, it is necessary to examine whether the contamination source of radiocesium in fruits may already be present inside the trees. Based on the test that used trees where only the soil surface was covered prior to the accident, the amount of radiocesium that was translocated from the underground to aboveground parts after the accident was so small that it was barely detectable. It is clear that the majority of radiocesium was directly absorbed as it adhered to the tree at the time of the fallout. Furthermore, when contaminated peach trees were planted and cultivated in uncontaminated soil, radiocesium translocated from old organs to new organs, including fruits. The distribution inside the trees showed a high concentration in the primary scaffold limbs and the main trunk. Investigating how the radiocesium present in the old branches of trees is translocated inside the trees at the time of cultivation is just as important (or more so) as investigating translocation from the soil. To study this aspect, tests have been conducted by painting leaves with radiocesium (Zehnder et al. 1995; Carini et al. 1999); however, there have been no reports on the translocation of radiocesium from branches to new organs. Moreover, the distribution of radiocesium in the early growth of new organs cannot be clarified by painting leaves with radiocesium. Thus, to determine the translocation to other parts of the trees when the contamination source is assumed to be only the old branches, the branches of grapes from planting areas that experienced the fallout were grafted to uncontaminated trees, and the distribution of $^{137}$Cs within the uncontaminated trees was observed at the time of harvest. Hence, the translocation from old organs was investigated.

One-year old branches were sampled from ‘Kyoho’ grapes planted in an orchard in Fukushima, and were adjusted to a length of 25 cm and 3 buds. Each branch had been grafted to 1-year-old branch parts of ‘Kyoho’ grapes (4-year-old, 10.0 L potted trees, rootstock cultivar is ‘101–14’) cultivated in a closed greenhouse before the accident. Four trees were selected from those with successful grafts and with confirmed fruiting, and were used as samples in the test (Fig. 11.4). Trees were

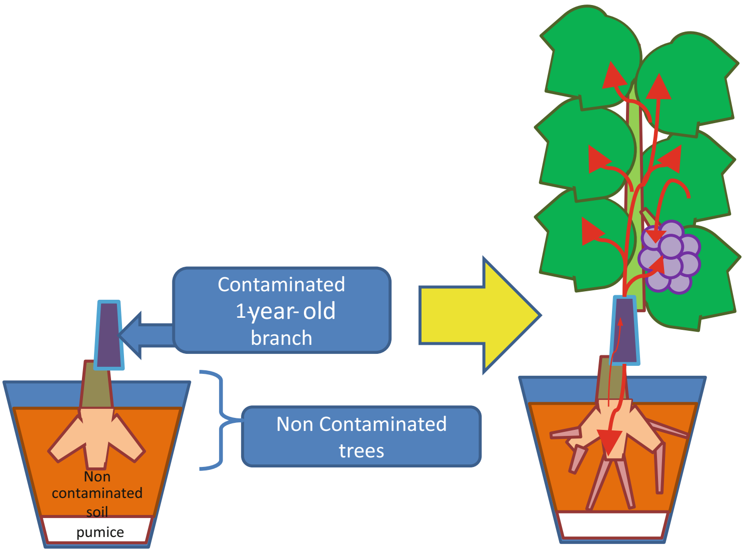


**Fig. 11.4** Shifts of $^{137}$Cs from scion to other organs in grapes

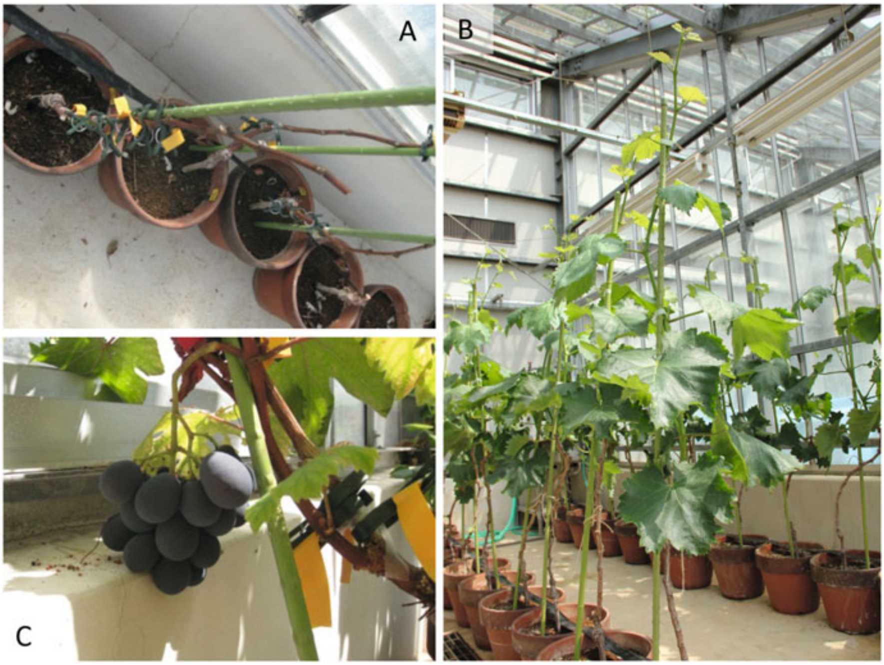


**Fig. 11.5** Photographs of Shifts of $^{137}Cs$ from scion to other organs in grapes. (**a**) at grafting, (**b**) flowering before 1-week, (**c**) mature fruit (limit the number of flowers, so fruit was smaller than usual)

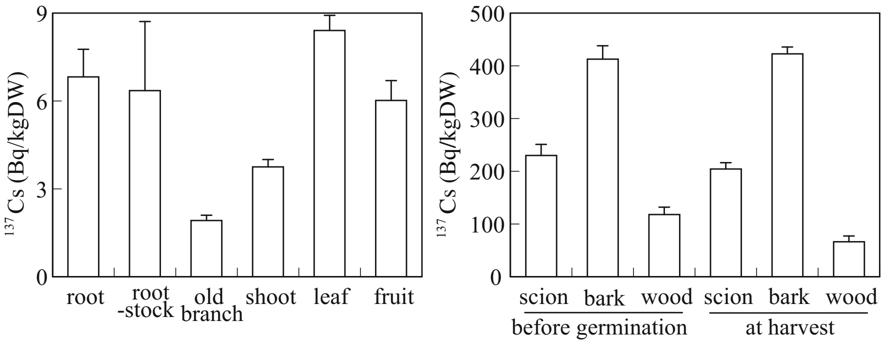


**Fig. 11.6** $^{137}Cs$ concentration of'Kyoho'grapes (from Takata et al. 2013a). *left*: show other than scion at harvest, *right*: scion. Scion homogenized the bark and wood

dissected at harvest time, and $^{137}Cs$ was measured in each part (Fig. 11.5). The scion was divided into bark and wood, and these were measured. The scion and uncontaminated tree prior to the test were similarly tested for the concentration of $^{137}Cs$ concentration and content.

At harvest time, among the concentration of $^{137}$Cs in each part of a tree, the highest value was found in the scion when the scion was the source of contamination (Fig. 11.6). However, $^{137}$Cs was detected from other parts as well. The concentration of $^{137}$Cs in new organs positioned above the contaminated scion was the highest in leaves, followed by fruits and then shoots. This was in agreement with the results obtained from grapes cultivated under vinyl covers in the southern region of Fukushima Prefecture (Takata et al. 2012c). It is believed that the concentration of $^{137}$Cs tends to be high in leaves. The results obtained for old branches, rootstocks, and roots positioned below the scion showed that the values were similar in roots and rootstocks, and old branches had low values. The hypertrophy of old branches was not observed in this test; therefore, it is thought to play a role in the pathway for translocating $^{137}$Cs underground, instead of storing $^{137}$Cs, and thus, low $^{137}$Cs concentrations were observed in the old branches. In rootstocks and roots, it is possible that accompanying the appearance of pioneer roots and their hypertrophy, that $^{137}$Cs stored in new branches was translocated, leading to the similar concentration observed in the fruits. We transplanted contaminated peach trees to uncontaminated soil and investigated the translocation from the old organs (Takata et al. 2012e, 2014b). The concentration of $^{137}$Cs in pioneer roots was higher than that in the leaves. Grape roots used in this test were a combination of both the old roots that existed prior to sprouting and the pioneer roots that appeared after sprouting. Due to the browning of the roots, identification was impossible, so all roots were grouped together. However, since concentrations were also high in the pioneer roots in grapes, it is thought that this led to high concentrations in the whole roots.

When the scion was divided into bark and wood, the concentration of $^{137}$Cs in the bark did not change much from pre-sprouting to harvest time, but the concentration in the wood decreased to 56.1 % (details are provided in the next section). However, according to a study on the $^{137}$Cs concentration in peach bark and wood over time, the $^{137}$Cs concentration in the wood temporarily decreased after sprouting, and continued to decrease until harvest (Takata et al. 2013c). Grapes also use stored nutrients to develop new organs immediately after sprouting. Since $^{137}$Cs quickly translocated to other organs, similar to other stored nutrients, we believe that the concentration in the wood was low at harvest in this test. In the

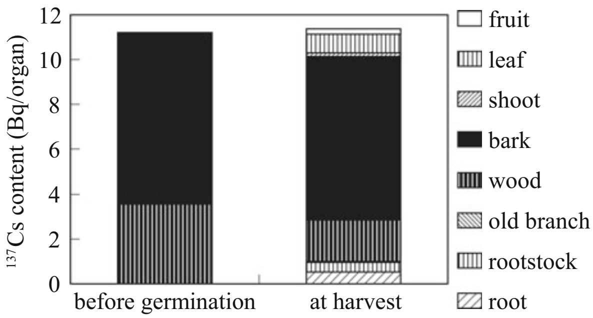


**Fig. 11.7** $^{137}$Cs content of 'Kyoho' grapes (from Takata et al. 2013c). Content = weight per each organ (gDW) × Bq/kgDW. Bark and wood originated in scion

wood, 19.5 % of $^{137}Cs$ was redistributed to the other organs. Similar to the concentration results, it was mostly redistributed to leaves, rootstocks, and roots (Fig. 11.7).

### 11.2.3 Are Transfer Factors in Fruit Trees that Use Soil Concentration as a Guideline Important?

Fruit trees are agricultural products, so radionuclide concentrations in the edible parts are important, and investigating the translocation to the fruits of grapes is fundamentally important. However, transfer factors studied in the existing tests examined translocation from the soil to fruits, so they cannot be directly compared to the proportion of $^{137}Cs$ in old branches translocating to fruits, as was examined in our current tests. Thus, we attempted to compare translocation from the soil to fruits with the translocation inside the trees to fruits. Transfer factors from the soil varied greatly in grapes depending on the conditions. According to previous reports, the transfer factor was assumed to be 0.00079, a value widely accepted in Japan (MAFF 2011). Let us assume that the $^{137}Cs$ concentration in the soil was uniformly 10,000 Bq in the planting area. Then, the concentration in fruits was 7.9 Bq/kg FW. If we express this value per dry weight of the fruits in order to compare with our test, we obtain 44.1 Bq/kg DW. Since the $^{137}Cs$ concentration in the fruits in this test was 6.0 Bq/kg DW, due to the absorption rate from the soil, the $^{137}Cs$ concentration in the soil must be 1359.5 Bq/kg DW in order to reproduce this value. Furthermore, if we assume that it was planted in the soil with a capacity similar to our test (6.0 kg dry soil), the total $^{137}Cs$ content in the soil would be approximately 8157.0 Bq equivalent. However, the scion concentration in this test was 230.0 Bq/kgDW, which is only about 1/6 of the calculated required concentration in the soil (1359.5 Bq/kg DW). Furthermore, in contrast to the 11.2 Bq equivalent $^{137}Cs$ content in the scion, the required $^{137}Cs$ content in the soil would be 8157.0 Bq equivalent, 728 times the total amount needed in branches. Therefore, compared to the radiocesium in the soil, the radiocesium present in the branches has a much higher contribution to the translocation of radiocesium to the fruits, and therefore, this needs to be carefully monitored in the future.

If the translocation of radiocesium from the bark to the internal parts of trees is reduced, it is possible that the proportion of radiocesium derived from soil detected in fruits and leaves will gradually increase. However, because only a few years have passed since the accident, it is important to focus on the presence of radiocesium inside the trees. It is unclear how many years it takes before the contribution from the soil becomes more dominant, or even whether the condition changes at all. If the changes in fruit concentrations reach a state of equilibrium, it may be used as an index. In any case, a long-term survey is necessary.

### 11.2.4 Temporal Changes in the Concentration, Especially Translocation from the Bark

In peach trees 4 months after the accident, radiocesium was present at a higher concentration in the outermost layer of the bark than in the soil (Takata et al. 2012a, d); thus, radiocesium absorbed from the aboveground parts of trees was reported to be higher than radiocesium absorbed from the soil through the roots (Takata et al. 2012b). Furthermore, in the previous section, we mentioned that the radiocesium concentration in the bark did not change much, and that the radiocesium concentration in the wood decreased. From these results, understanding the changes in radiocesium in the old branches is as important as finding the transfer factors from the soil in order to sustain future fruit tree production. Therefore, here we present changes observed in radiocesium concentrations in peach bark and wood over time.

Two-year-old branches (3-year-old branches in 2012) from three trees were sampled from 6-year-old 'Campbell Early' peach trees (*Prunus persica* L. Batsch) in a planting area in Tokyo (andosol), every 2–3 months from July 2011 to November 2012. A part of the sampled bark was divided into the outer and inner bark with the cortical layer as the boundary. For each 10 cm length of the branch, radiocesium and $^{40}$K contents were determined.

Radiocesium concentrations in the wood did not change in 2011 (Fig. 11.8, right), but decreased from February to May 2012, around the time of blooming. The $^{40}$K concentration increased from summer to fall in both years. It is believed that the following factors are related to this trend: (1) with soil as a rich source, $^{40}$K is translocated to the aboveground parts through the roots and is then accumulated in the wood, which plays the role of a storage organ; and (2) to enhance this accumulation, fertilizer containing K was applied in August as a topdressing after the harvest. Around the time of blooming in 2012, the $^{40}$K concentration decreased

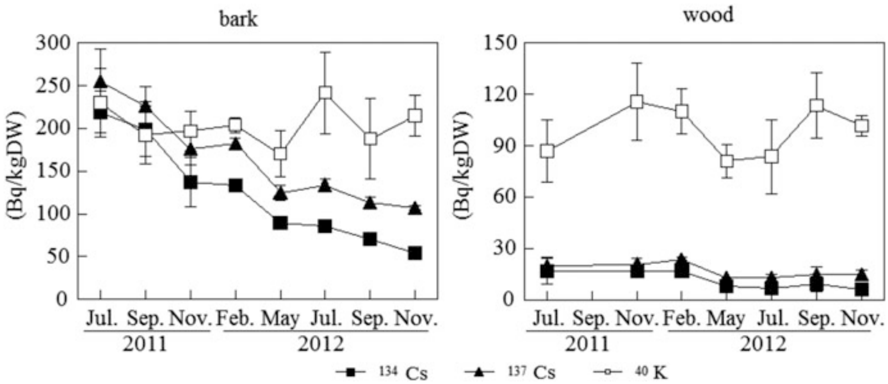


**Fig. 11.8** Seasonal change in radiocaesium and $^{40}$K concentration of peach lateral shoot (from Takata et al. 2013c). *left*: bark, *right*: wood, n = 3

similar to the radiocesium concentration. Although the concentration of $^{40}K$ in the bark showed seasonal variation, it changed by roughly 200 Bq/kg DW (Fig. 11.8, left). On the other hand, the radiocesium concentration decreased with time since July 2011 when the survey started. A gradual decrease was noted in $^{137}Cs$, which has a long half-life. Contributions from factors other than physical attenuation are likely to be significant. These factors include spontaneous peeling of bark and the translocation of radiocesium in the bark to other organs. We discuss the possibilities of these two factors below.

We can estimate bark peeling as follows: the radiocesium concentration in the bark does not change much during the fruit-growing period and the winter. However, it decreases during autumn when there is active nutritional development. This coincides with the period when parts of the outer bark peel easily as old branches swell. It is possible that the concentration of Cs decreased in association with this phenomenon. To clarify this point, the bark was divided into the outer and inner bark, and $^{137}Cs$ was measured. The radiocesium concentration in the outer bark decreased from July to November, then November to May, in both years (Fig. 11.9, left). Three factors possibly affecting this trend are: (1) translocation of radiocesium to the inner bark, (2) peeling of parts of the outer bark, and (3) the dilution effect of radiocesium to the outer bark due to the hypertrophy of the cortical layer.

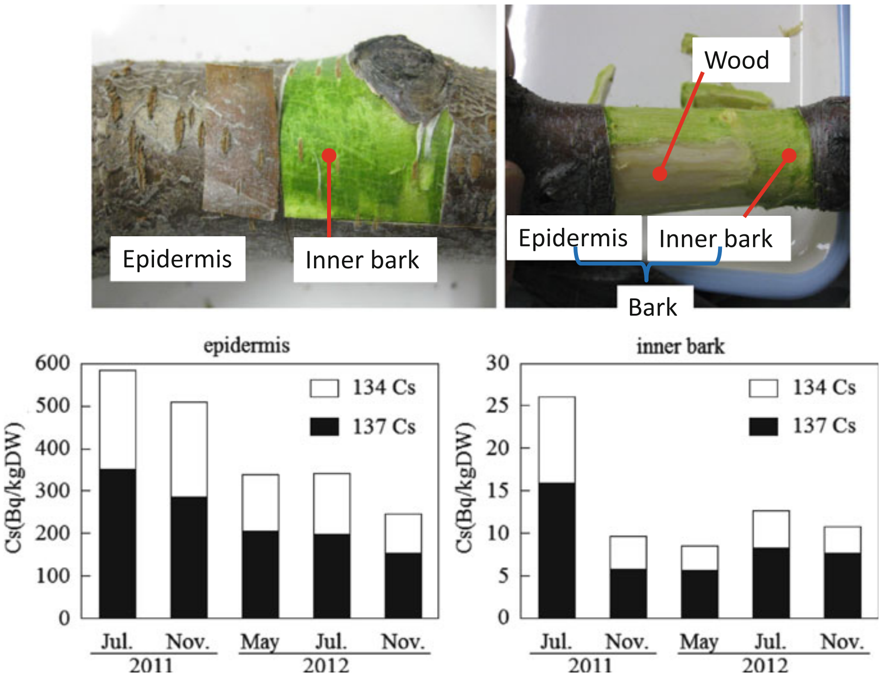


**Fig. 11.9** Seasonal change in radiocaesium concentration of peach bark (from Takata et al. 2013c) *left*: epidermis, *right*: inner bark. *: indicate significant difference compare with last date by *t*-test (P = 0.05)

We can assume that if radiocesium in the outer bark is translocated to the inner bark, the concentration within the inner bark and wood would increase; however, radiocesium concentrations in the inner bark and wood did not increase; hence, this possibility is unlikely. Therefore, we can assume that it is due to peeling of parts of the outer bark or dilution due to the development of the cortical layer. However, to quantitatively understand the translocation of radiocesium from the outer bark, it must be examined after determining the level of outer bark peeling and cortical layer development. Thus, it cannot be determined solely based on our results. In addition, the change in the concentration of radiocesium in the whole bark is similar to the change of $^{137}$Cs concentration in the outer bark; therefore, it was considered to be easily influenced by the changes in the outer bark at higher concentrations.

The radiocesium concentration in the inner bark decreased significantly from July to November 2011, but showed no change in 2012 (Fig. 11.9, right). In 2011, there was a possibility that the radiocesium in the inner bark translocated to the inner organs (wood), or the outer organs (the outer bark). However, since November 2011, the concentration in the inner bark did not change much; therefore, it is possible that there was little translocation from or towards the inner bark. It is possible that some changes occurred in the permeability within the bark, such as the form of radiocesium, following the accident.

If the decreased concentration of the outer bark was due to the peeling of the bark, peeling organic matter containing a large amount of radiocesium may have re-adhered to new organs, such as leaves and fruits. There are many unknowns about the translocation of radiocesium derived from organic matter, such as bark, to fruits after it re-adheres to leaves and young fruits. However, it is difficult to wash the pericarp surface layer of fruit trees, such as peaches, prior to shipment. Thus, for such fruit trees, manual removal treatments, such as cleaning the bark positioned closest to the fruits and shaving the outer layer of bark, will lower the risk of directly contaminating the surface of fruits through secondary adherence.

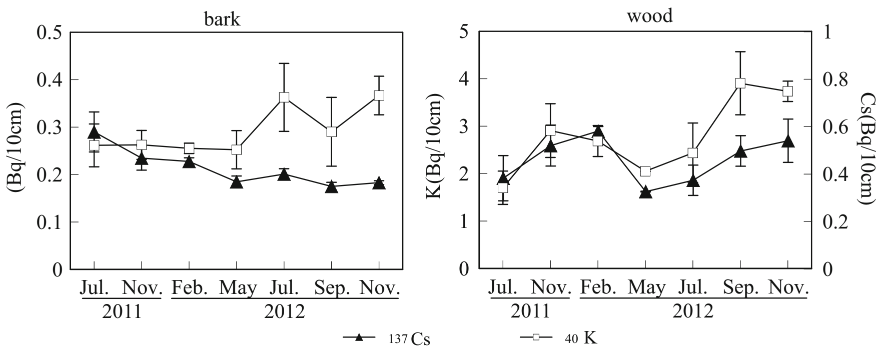


**Fig. 11.10** Seasonal change in $^{137}$Cs and $^{40}$K content of peach lateral shoot (from Takata et al. 2013c) *left*: bark, *right*: wood, (n = 3). Content = weight per 10 cm lateral shoot (kgDW) × Bq/kgDW

The nuclide content per 10 cm of branch was obtained by multiplying the organ concentration by organ weight (Fig. 11.10). The $^{137}$Cs content in the bark showed a gradual decreasing trend, similar to the change in $^{137}$Cs concentration. The $^{40}$K content was also similar to the $^{40}$K concentration, but was higher in 2012 than 2011, and showed large variability. This was thought to be due to hypertrophy of the bark and difference in the level of hypertrophy depending on the part. The $^{137}$Cs content in the wood was lower than the $^{40}$K content, but the manner of change in 2011 was similar to that of $^{40}$K. In May 2012, the $^{137}$Cs and $^{40}$K contents in the wood decreased for a period, and then increased again in the autumn. We believe that the increase in the weight associated with the hypertrophy of the wood played a major role in the increase of the nuclide content of the wood in the autumn in both years. However, the level of increase was different each year, and $^{137}$Cs showed a lower value compared to $^{40}$K in 2012. This is likely because the portion of radiocesium that decreased in the inner bark in the fall and winter of 2011 was translocated to the wood, while such translocation did not occur in 2012. Thus, the level of increase compared to $^{40}$K was different each year. Therefore, in 2012, when there was no translocation of radiocesium from the inner bark, the increased radiocesium in the wood was likely to have derived from the soil. Thus, it is possible that there is a difference in the translocation of $^{137}$Cs and $^{40}$K to the aboveground parts from the current orchard soil. In particular, it is said that the radiocesium was high in the surface soil layer (5 cm) (Shiozawa et al. 2011), but the roots of peaches are often at 5 cm or deeper, so it is assumed that $^{137}$Cs, compared to $^{40}$K, was not absorbed as much from the soil.

Based on these results, the radiocesium concentration in the peach bark decreased 2 years after the accident, with a decreasing trend even for $^{137}$Cs, which has a long half-life. The main reason for this is the decreasing effect of peeling outer bark where radiocesium had accumulated. In the previous section, we noted that the concentration in the wood significantly decreased, but the concentration in the bark did not change much. In addition, considering that the concentration in the inner bark barely changed 8 months after the accident, as shown in this section, it is possible that the translocation of radiocesium to the inner parts of trees from the outer bark becomes more difficult as time passes since the accident.

## 11.3 Prediction of Mature Fruit Radiocesium Concentration

In some regions in Japan, fruit shipment was self-regulated even if the concentration was below the regulatory requirement in the years following the accident. Recently, a system that measures the radiocesium concentration in agricultural products was established. For example, rice produced in Fukushima prefecture is shipped after a full inspection is conducted. However, for fruits with a short shelf life, shipping after a full inspection could greatly increase the disposal rate.

Therefore, it is expected that a system will be established in which the radiocesium concentration of the harvested fruits is predicted prior to harvest. In this chapter, we have been discussing the translocation of radionuclides inside trees with a focus on radiocesium. It is still difficult to fully understand the changes in concentrations in the actual fruits only based on the existing results.

When predicting the radiocesium concentration in the fruits, although there is an index such as transfer factors, numerical estimates vary greatly in the literature, even for the same fruit. The transfer factors of fruits may vary depending not only on the soil characteristics but also on the condition of trees, such as their age and degree of pruning. However, the factors that affect the coefficients are still unknown. Furthermore, as discussed in the previous section, the effects of direct infiltration of radiocesium from the fallout on the aboveground parts on the concentration of radiocesium in the fruits are more significant than the effects of absorption from the soil through the roots. The existence of radiocesium that directly infiltrates trees like this makes it difficult to predict the concentration in the harvested fruits based on the radiocesium concentration in the soil. Incidentally, the concentration of radiocesium in peach fruits in the accident year was shown to have decreased as the fruits matured (Sato 2012). If it is true that the concentration in the fruits decreases as the fruits mature, it will be possible to predict the radiocesium concentration in the fruits prior to their harvest.

### *11.3.1 Fruit and Leaf Radiocesium Concentration*

In this section, we study the changes in radiocesium concentration in fruits in the year after the accident during the fruit growth period. We sampled ‘Akatsuki’ peaches (*Prunus persica* L. Batsch.) planted in a commercial growing field on Ryozen, Date City, Fukushima Prefecture. Over time, we sampled fruits and leaves from 15 days after full bloom to harvest time in 2012. From each tree, 10–50 fruits were sampled, while 50 leaves in mid-position on shoots were randomly sampled from the trees. The concentrations of $^{134}$Cs and $^{137}$Cs per dry weight of fruits were both at their highest 15 days after full bloom, they decreased from 30 to 50 days after full bloom, and then remained nearly constant until the mature stage (Fig. 11.11). Changes in $^{134}$Cs and $^{137}$Cs were similar during the fruit growth period, and $^{134}$Cs changed to about 70 % of $^{137}$Cs. The $^{40}$K concentration in the fruit was at its highest 15 days after full bloom, similar to the radiocesium concentration. It decreased after that, but the ratio by which it decreased was different. In other words, although the concentrations of $^{137}$Cs and $^{40}$K were nearly identical 15 days after full bloom, these values greatly diverged from each other 30 + days after full bloom. The radiocesium concentration in the leaves 15 days after full bloom was higher than that in other periods. On the other hand, the $^{40}$K concentration in the leaves increased from 15 to 60 days after full bloom and gradually decreased thereafter. In the existing reports, there are planting areas where the total K concentration in peach leaves increased from 30 to 60 days

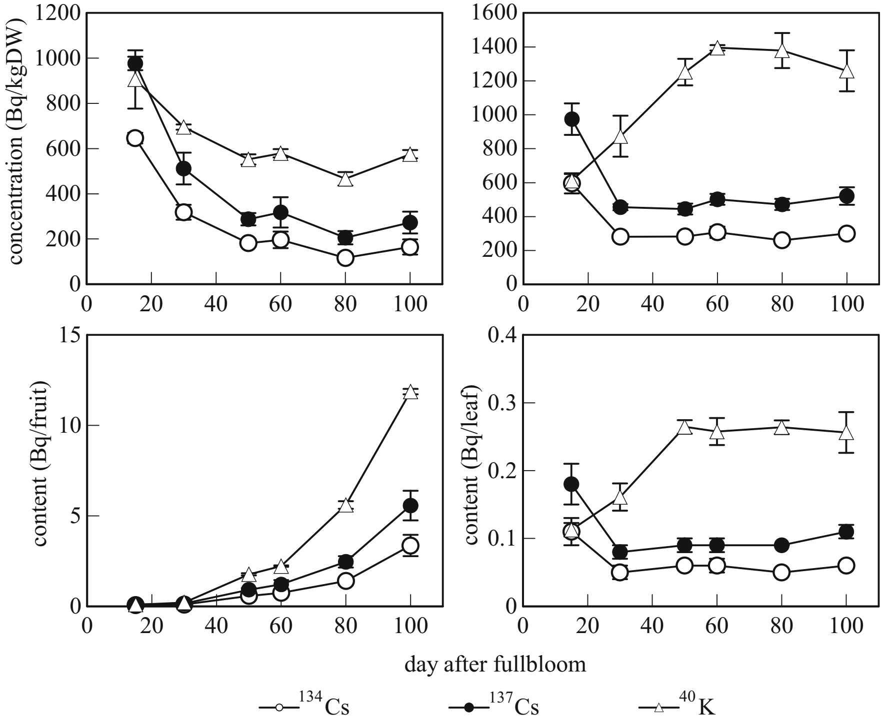


**Fig. 11.11** Changes in radiocaesium and $^{40}K$ concentration (*upper*) and content (*lower*) of peach fruit (*left*) and leaf (*right*) in periods of fruit development (from Takata et al. 2014a, b) *upper*: Bq/kgDW, lower: Bq/one fruit or leaf. n = 3

after full bloom (Takano 2010). It has also been reported that the concentration decreased gradually from 60 to 120 days after full bloom. The $^{40}K$ in the leaves in our report behaved similarly. Based on these findings, it became clear that there were times when the translocation of radiocesium and $^{40}K$ to fruits and leaves differed. The radiocesium concentration in the fruits cannot be estimated solely from a simple ratio calculation (Cs/K ratio) based on the K concentration. In addition, we conducted similar surveys in the same planting area in 2013 and 2014. The changes in the radiocesium concentration during the same period showed similar results (unpublished data). On the other hand, the changes in the K concentration showed significant variation depending on the year, and the $^{137}Cs$ concentration in the harvested fruits showed a 1/3 to 1/4-fold decrease after about 1 year.

### 11.3.2 Comparison of the Mature Fruit and Thinning Fruit

Compared to radiocesium, $^{40}K$ sometimes showed a different modality in the leaves; hence using these values to predict the concentration in harvested fruits is difficult. On the other hand, since the year of the accident, the radiocesium concentration in the peach fruits decreased with maturity. Therefore, from each orchard, we sampled 3 'Akatsuki' trees (from 5- to 24-years old) from each of the 24 peach orchards in Fukushima Prefecture at 60 days after full bloom (which is the thinning time) and at maturity. Then we examined the possibility of predicting the radiocesium concentration in the mature fruits using thinned fruits. In Japanese peach production, the amount of fruits is adjusted through steps such as disbudding, deblossoming, and primary and secondary thinning. Sampling fruits during these periods may be less labor-intensive than separately sampling fruits. Therefore, for the sampling period, we chose 60 days after the full bloom as the hypertrophy of fruits would be in progress and the Bq per fruit starts to increase (Fig. 11.12). Additionally, consideration was given in this test to the moisture condition of peach

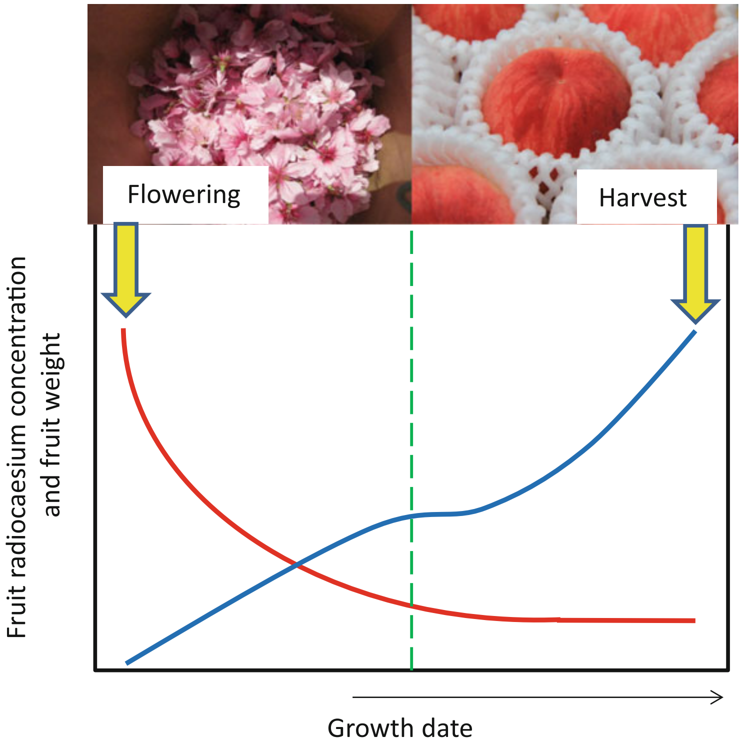


**Fig. 11.12** Target timing of prediction. *Red curve*: peach fruit radiocaesium concentration, *blue curve*: peach fruit weight, *green line*: target timing of prediction (using thinning fruits)

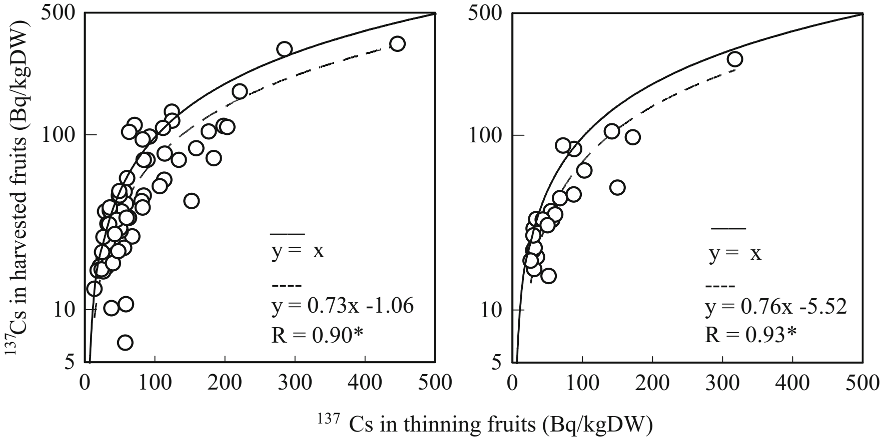


**Fig. 11.13** Relationship between thinning fruit and harvested fruits in $^{137}$Cs (from Takata et al. 2014a, b) *left*: each tree, (n = 70), *right*: each orchard, (n = 24). *Dashed line* means correlation line. *Solid line* means Y = X line

fruits changing with the weather, conditions of the planting area, and days passed since sampling. The radiocesium concentration was expressed on a dry weight basis (Bq/kg DW). Figure 11.13 shows the relationship of $^{137}$Cs between the harvested fruits and fruits sampled at the time of thinning 60 days after full bloom for all 72 trees. When $^{137}$Cs concentrations of thinned and matured fruits were compared, a significant and strong correlation was noted. Based on that, it is possible to estimate the concentration in the harvested fruits by measuring the radiocesium concentrations in the thinned fruits 60 days after full bloom. However, to predict the safety of the harvested fruits by actually using the thinned fruits, it is more important to know how many trees exist for which the concentration in the harvested fruits is higher than in the thinned fruits, than it is to calculate the predicted radiocesium concentration of the harvested fruits by substituting values into the obtained correlation equation. Therefore, we added a solid line showing the Y = X relationship. Values plotted above and to the left of this solid line indicate that the $^{137}$Cs concentration is higher in the harvested fruits than in the thinned fruits. Thus, 9 out of 70 trees were “outliers” that had higher values in 60th-day thinned fruits than in the matured fruits. To maintain safety, it is important to eliminate such outliers. As a countermeasure, using a method to accelerate the measurement period of the thinned fruits may be an option. As mentioned earlier, the radiocesium concentration is higher in fruits 30 days after full bloom than 60 days after full bloom. Thus, it may be that the accuracy of the safety prediction for harvested plants may be increased. However, in this case, the $^{137}$Cs concentration was higher than that in our samples from 60 days after full bloom, although the radiocesium content per fruit was low. Therefore, it is important to note that the number of sampled fruits at the time of measurement was quite high, and that the change in concentrations in the fruits should be considered because it is a period when the variations in temperature and planting area affect the conditions of fruit growth. On one hand, the concentration of the harvested fruits cannot be the same or above that of the concentration 30 days after full bloom, yet there is a possibility of overestimating the concentration of the harvested fruits. Thus, for trees that surpassed the regulatory required value at 30 days after full bloom, we must consider the necessity of retesting at 60 days or later. The second possible countermeasure is a method using safety coefficients that produces higher safety estimates by adding a coefficient to values such as calibration curves. For example, when setting $Y = X + 10$ without changing the slope of the curve, 68 out of 70 trees were at or below the level of thinned fruits + 10.0 Bq/kg DW, so the number of outliers was reduced. Although we must carefully examine the value added as a safety coefficient, it is very unlikely that the fruits from the trees that had sufficiently low radiocesium concentrations in the thinned fruits would suddenly present extremely high values at the time of harvest; thus, it is worth considering. Furthermore, by measuring the radiocesium concentration of the thinned fruits ahead of time, compared to measuring everything during a short harvest period, less concentrated labor periods can be achieved. Additionally, if one attempts to use the obtained values for the following year by observing the change in one tree over time, it is unlikely to increase compared to the previous year; therefore, it might be possible to exclude trees with low concentrations from the measurement target in the following year.

Next, we investigated the correlation for the same set of data for each of 24 planting areas. Out of 24 planting areas, 23 had lower $^{137}Cs$ concentrations in the mature fruits than the thinned fruits. Tanoi et al. (2013) showed that individual variations exist in rice in a paddy field, so it is quite possible that the radiocesium concentrations would vary in each tree in an orchard. Therefore, it is premature to determine the concentration of the whole planting area based on several trees. However, at least planting areas with high radiocesium concentrations can be chosen, which can possible reduce the effort required to measure individual trees later on. Of course, it is possible to determine the safety of trees by tests conducted during this period, excluding the trees in planting areas with values close to the shipment limits for radiocesium.

## 11.4 Conclusions

Since radiocesium is distributed on the surface layer of the soil in orchards, it is important to focus on the translocation of radiocesium from the soil to trees when they have shallow roots. Moreover, understanding the behavior of radiocesium in old organs is equally significant. If the concentrations in the bark and wood are obtained separately, a better understanding of the proportion of radiocesium translocated to the fruits is possible, because the translocation of radiocesium from the bark to the internal part of trees becomes more difficult as time passes after an accident.

We confirmed that there was a difference in the behaviors of radiocesium concentration and $^{40}K$ concentration in the fruits and leaves of peaches. Furthermore, differences can arise between the behaviors of radiocesium and K inside the trees; therefore, it is risky to consider the relationship of radiocesium and K in perennial crops as similar to single annual crops that have only soil as a radiocesium source.

Comparison of the concentration of $^{137}Cs$ in the fruits sampled 60 days after full bloom with that of harvested fruits revealed a strong correlation. However, the concentrations in the harvested fruits were not always lower than the fruits sampled 60 days after full bloom. Since trends in the planting area and the internal parts of trees can be understood to a certain degree by measuring the thinned fruits at 60 days, this indicates that the safety could be determined through tests during that time, excluding planting areas and internal parts of trees with numerical values extremely close to the shipment limit.

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