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Use of different surface covering materials to enhance removal of radiocaesium in plants and upper soil from orchards in Fukushima prefecture

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The effectiveness of a decontamination methodology whereby herbaceous plants were grown through different materials covering the soil surface followed by subsequent removal of the material, associated plant tissues and attached soil on ^{137}Cs removal from soil was evaluated. Revegetation netting sown with Kentucky bluegrass and white clover had a high effectiveness in ^{137}Cs removal when rolling up the plants, roots, and rhizosphere soil approximately 6 months after sowing. The removal rate was lower when there was higher ^{137}Cs vertical migration down the soil profile. The maximum removal effectiveness of 93.1% was observed by rolling up fertilized Kentucky bluegrass with a well-developed root mat without netting, indicating that applying nutrients to encourage the development of roots or root mats in the 3 cm topsoil rhizosphere is an efficient technology to increase the decontamination effect of plant removal in orchards. Netting and weeding were able to remove up to 80% of ^{137}Cs in the soil without the use of heavy machinery. There was a significant relationship between the removal ratio and the removed soil weight per area. Using the relationship on the site below the canopy, removal of 14.3 kg m^{-2} DW soil would achieve a removal ratio of 80%. The effectiveness of the technique will decrease with time as radiocaesium migrates down the soil profile but this would be expected to occur slowly in many soils.

1. Introduction

On March 11, 2011, the Great Eastern Japanese earthquake caused a huge tsunami, resulting in a partial core meltdown in units 1, 2 and 3 at the Fukushima Daiichi Nuclear Power Plant (FDNPP), followed by a series of explosions. A large quantity of radioactivity was released into the environment from March 12 to 14, 2011 after the Fukushima Daiichi accident (FDA) (International Atomic Energy Agency, 2015). Radioactive deposition was deposited primarily by rainfall and snowfall on March 15, 2011 (Chino et al., 2011; Imanaka, 2012). The radioactive fallout contaminated fruit production orchards in Fukushima Prefecture which is one of the major production areas of deciduous fruits in Japan (Ministry of agriculture, forestry and fisheries, 2016). Most deciduous fruit trees, except for Japanese apricot [*Prunus mume* (Sieb.) Sieb et Zucc.)], had not yet developed leaves because the FDA took place during the dormant phenological stage of deciduous fruit trees (Sato et al., 2015). The scaffold trunk and branches of peach, cherry, apple, Japanese pear, and grape canopies intercepted some of the radioisotopes (Sato, 2012), which were also deposited directly onto the topsoil and also via throughflow and stemflow (Schimmack et al., 1993, Kato et al., 2012, Loffredoa et al., 2014). After the Chernobyl accident, which occurred on 26 April 1986, almost all the species of fruit trees had already developed leaf, and radiocaesium was thought to have migrated into tree tissues mainly via the leaves

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(Monte et al., 1990, Antonopoulos-Domis et al., 1991). Most deciduous fruit trees would be anticipated to be less impacted by the deposition of radiocaesium after the FDA than that occurring after the Chernobyl accident. However, early measurements of growing fruits showed that a number of different types of fruit had been contaminated (Sato et al., 2015).

The transfer of radiocaesium to fruit was, and remains, a major concern in Japan. The main purpose of subsequent remediation for fruit production focused on preventing radiocaesium migration or translocation to fruit. A mechanism of radiocaesium transfer from bark via translocation to fruit, which may be associated with lenticels or other lesions in the bark, was confirmed after the FDA (Takata, 2013). Bark washing with a high pressure washer was conducted in most orchards in Fukushima Prefecture from leaf-fall in autumn 2011 to the season prior to budding in 2012. However, about 90% of the radiocaesium in the soil remained in the upper 0–3 cm in orchards (Sato, 2014) where there were many roots of undergrowth plants growing between the fruit trees in most orchards in Fukushima Prefecture. Fruit tree roots are not present in the upper 0–3 cm layer so radiocaesium uptake via the roots of fruit trees was probably negligible during 2011 (Sato et al., 2015), as reported after the Chernobyl accident (Antonopoulos-Domis et al., 1991). The ^{137}Cs activity concentrations termed [^{137}Cs] in the major types of deciduous fruit decreased in subsequent years (Tagami and Uchida, 2014; Sato, unpublished data), indicating that there was a low transfer of radiocaesium via the roots of fruit trees (as also noted by Antonopoulos-Domis et al., 1991).

Due to consumer concern about radiocaesium contamination there was a reduction in both direct sales and orchard sales in subsequent years after the FDA. Furthermore, farmers working in orchards had higher external doses than those working in rice paddies and other low-lying crops due to external exposure from radiocaesium associated with the soil and tree surfaces. There was also concern that if radiocaesium migrates further down the soil profile it may eventually enter the rooting zone of the trees, enhancing radiocaesium uptake from the soil. The latter may not be a significant issue since in the majority of soils radiocaesium remains in the upper soil layers, as evidenced from data for ^{137}Cs deposited after the above-ground nuclear weapons fallout in Japan (Mahara, 1993).

Removal of soil is a well-known remediation option, especially in urban areas (EURANOS, 2009). Removal of soil in orchards has been carried out in Fukushima city since the spring of 2012. However, there are several difficulties in applying this option for orchards namely:

i Many orchards in Fukushima Prefecture are located in upland areas, where it is difficult to use heavy machinery because of the steep slope and dense planting.
ii Extensive remediation or removal of soil is difficult to carry out without damaging trees and their root systems.
iii A large amount of waste is generated from the removal of trees and associated contaminated soil.

No specific remediation options which are suitable for orchards have been tested or developed after the Chernobyl accident. Fukushima Prefecture initially recommended sod culture, which is a soil management method to enrich the nutritional status of orchard soil by cultivating herbaceous plants (Sato et al., 1978). The use of a mixed sward of Kentucky bluegrass and white clover was proposed as it would especially enhance the supply of nitrogen and potassium (an analogue of caesium) in the soil layer of the rhizosphere under fruit trees and increase the productivity of fruit trees. After sod culture, the plant swards in orchards grew to more than 30 cm height so the swards were mowed 4 to 5 times during the growing season to prevent problems with insect pests and to ensure easy access for routine orchard management. Since more than 90% of radiocaesium remained within the 0–3 cm topsoil during the first year after the FDA, remediation options were also considered that would (i) decontaminate the soil by removing ^{137}Cs and (ii) decrease the amount of associated waste, which was anticipated to be high, due to the low soil density in topsoil by the removal of the sward with associated roots. Weeding by hand is labour intensive so the aim of this work was (i) to determine the effectiveness, on the removal of ^{137}Cs in soil of removing plant material combined with a layering material, which would enable the sward to be easily removed by rolling it up with associated upper root and soil (ii) to confirm the relationship between the effectiveness of the plant material removal and the depth profile of ^{137}Cs in soil.

2. Materials and methods

2.1. Examinations conducted on sites below a tree canopy

The study was conducted at the Fruit Tree Research Center, Fukushima Agricultural Technology Center, (FTRC), located approximately 65 km from the FDNPP. The observation areas were brown forest soils. The soil type was loamy clay in all of investigated areas. A series of different experiments were conducted over this period the main features of which are given in Table 1. For all studies described below, the soil surface was mowed to remove most of the undergrowth plant material from the study sites before treatment. Where applied, the seed mixture used was *Poa pratensis* L. (Kentucky bluegrass (KB)) at 40 g m^{-2} and *Trifolium repens* L. (white clover (WC)) at 30 g m^{-2} was sown over the surface of the material. No fertilization was applied to the study sites. For soil sampling, a stainless core sampler (83 mm inside diameter), was used which was developed by the Research Center for Electron Photon Science (RCEPS) of Tohoku University for measuring [^{137}Cs].

Study 1 in 2012 compared the effectiveness of the natural vegetation and a mixture of KB and WC in enhancing soil decontamination of radiocaesium.

Study 2 in 2013 evaluated the effectiveness of four different laying materials on decontamination of radiocaesium in soil. Four different covering materials were applied as listed in Table 1. Each removal examination was conducted by a pair of processes, which is a removal of soil surface and core samplings of remaining. At first, before rolling up, soil surface was carved along the edge of the sheet or netting using a stainless knife. The layering material of each treatment was rolled up by hand with the associated plants, roots, and rhizosphere soil. Next, four or five soil cores of the upper 3-cm soil layer remaining beneath the stripped soil were collected.

For comparison, we also studied the effect of allowing renewed growth of the naturally occurring vegetation to occur associated with either root ball netting or revegetation netting.

Study 3 in 2014 evaluated the effectiveness of removal of different types of plant without the application of layering material in grape and apple orchards. Soil cores were also collected as described above.

2.2. Decontamination of open sites using revegetation matting

Study 4 was conducted in open sites in 2014 and 2015 in a grape vineyard established prior to the FDA. The study combined revegetation netting and herbaceous sowing of KB + WC in both spring sowing (SS) and autumn sowing (AS). The coverings were rolled up by hand and soil cores (n = 5 per sample point) were taken as described above. One 60 cm × 60 cm sample from each removed layer was prepared to measure [^{137}Cs] and dry weight.

Table 1
Details of the different treatments and controls applied in different types of orchard.

Study	Year	Canopy	Study site	Laying date	Sowing date	Layer material	Plant type	Removal date
1	2012	Peach	Below canopy	21/Apr	10/May	Wood pulp	KB + WC	9-Nov, 13-Nov, 20-Nov
		Peach	Below canopy	21/Apr	NA	Wood pulp	NA	
2 - a	2013	Peach	Below canopy	09/May	09/May	Wood pulp	KB + WC	02/Dec
2 - a		Peach	Below canopy	09/May	09/May	Nonwoven fabric sheeting	KB + WC	02/Dec
2 - a		Peach	Below canopy	09/May	09/May	Revegetation netting[b]	KB + WC	02/Dec
2 - b		Peach	Below canopy	09/May	NA	Revegetation netting[b]	Natural forbs/grasses	02/Dec
2- b		Peach	Below canopy	09/May	NA	Root ball netting[a]	Natural forbs/grasses	Decomposed
3	2014	Grape	Below canopy	NA	NA	NA	KB rootmat	08/May
		Grape	Below canopy	NA	NA	NA	WC	08/May
		Grape	Below canopy	NA	NA	NA	Shepherd's-purse	08/May
		Apple	Below canopy	NA	NA	NA	Bittercress	12/May
4	2014	Grape	Open site	26 Mar 14	26 Mar 14	Revegetation netting[b]	KB + WC	2 Dec 14
	2015	Grape	Open site	25 Sep 14	25 Sep 14	Revegetation netting[b]	KB + WC	2 Dec 15

Note: KB and WC mean Kentucky bluegrass and white clover. Natural forbs and grasses are shepherd's-purse, deadnettle, bittercress, and others. No fertilization was applied in each survey location during examination. NA not applicable.
[a] Approximately 2 mm mesh.
[b] Approximately 18 mm mesh.

2.3. Vertical distributions of the root of undergrowth

This study was conducted to confirm the root depth profile of undergrowth. The study was conducted in a 'Kogyoku' apple orchard (KO), a 'Yuzora' peach orchard (YO) and the site of the soil removal examination with revegetation netting (see Table 1 studies 4) in a vineyard (VY) in the FTRC. Topsoil samples of 15 cm depth were collected at 5 points in KO, 3 points in YO and at a point inside and outside the revegetation nettings in VY to describe the root profile in the areas where the undergrowth roots were located. A core sample containing roots was sub-divided into three portions (0–3 cm, 3–9 cm, 9–15 cm). Combined samples were washed more than 7 times with hot water to remove the turbid colour from the supernatant water, and then washed with ultrasonic washing machine for 5 min. The weight of each sample was measured after wiping off the moisture on the surface of sample with a paper towel.

2.4. Vertical distributions of ^{137}Cs in soil

This study measured the depth profile of ^{137}Cs in soil at each site in this series of studies. The soil type of all orchards was loamy clay classified as brown forest soils (United States Department of Agriculture, 2014). Topsoil samples of 0–30 cm depth were collected at each site shown in Tables 1 and 4. The sampling points in the site below canopy were not at the same orchard as that used for the study 1–3 nearby and would be similar. Each core sample was sub-divided into several portions with 3 cm–9 cm width to examine the depth profile of ^{137}Cs. The samples were mixed well, without removing stones, and placed in plastic counting vessels (U-8 vessel; 5 cm diameter and 5 cm height) and counted on the detector. Sub-samples were oven-dried at 105 °C to constant weight and the [^{137}Cs] in soil was converted to a dry weight (DW) basis using the water content data.

For study 1–3, the vertical distribution of radiocesium within the top 0–30 cm soil layer was expressed as a distribution rate, *DR*, according to depth, as calculated by the following equations:

$$DR = 100 f_s wiCiT_c^{-1}, \quad (1)$$

$$w_i = h_i . h_{min}{}^{-1}, \quad (2)$$

$$T_c = \sum f_s wiCi, \quad (3)$$

where $_i$ represents the sample interval number, f_s is the soil density coefficient, w_i is a weighting coefficient based on the thickness of the soil interval, h_i is the thickness of each interval, h_{min} is the thickness of the smallest interval and C_i is the [^{137}Cs] for each soil interval. f_s in 0–3 was expressed as the ratio of the soil density between 0 and 3 cm and layers below 3 cm. The f_s of KO and 'Akatsuki' peach were 0.47 and 0.98, and the f_s in layers of 3–30 cm was assumed to be 1.0. For study 4, the vertical distribution of ^{137}Cs within the top 0–30 cm soil layer was expressed as a proportion of the total inventory.

2.5. Radiocaesium measurements

The [^{137}Cs] in all 0–3 cm soil samples was measured with a sodium iodide (NaI) scintillation spectrometer (CAN-OSP-NAI, Hitachi Aloka Medical) at FTRC. The [^{137}Cs] in the 0–30 cm soil core and root samples were analyzed with Ge semiconductor detector systems at RCEPS in 2012 and at the Foundation for Promotion of Material Science and Technology of Japan in 2014. The counting time for each sample varied between 1 and 24 h, depending on the [^{137}Cs]. Decay correction was made to the sampling date.

2.6. Regression analysis between removal rate and removed soil weight per area

To evaluate the effect on soil decontamination, the removal ratio of ^{137}Cs (*RR*, %) was calculated by the following equation:

$$RR = 100a/(a + A), \quad (4)$$

where a is the ^{137}Cs deposition density (kBq m^{-2}) in the removal layer and A is the ^{137}Cs deposition density in the 3 cm soil layer remaining beneath the stripped soil. A or a was calculated by the following:

$$A \text{ or } a = wCS^{-1}, \quad (5)$$

where w (kg) is the removal dry weight, C (kBq kg^{-1} DW) is the [^{137}Cs] in the removed soil with sheet or the core soil and S (m^2) is the removal sheet area or the sum of the cross area where four (Study 1 and 2) or five (Study 3 and 4) 3 cm soil layers were collected beneath the stripped soil with a stainless core sampler.

The proportional formula between *RR* and the removed soil weight by area (kg m^{-2}) was obtained using the least-squares method.

The *RR* was compared between treatments statistically based on 2-sample *t*-test in 2012 and study 4 or Tukey's test in 2013, respectively.

3. Results and discussions

3.1. Effectiveness of type of laying material and the presence of undergrowth plant on soil decontamination

The procedures used in studies 1, 2 and 3 in 2012–2014 are shown in Fig. 1 and the data obtained and *RR* values are shown in Table 2. Study 1 in 2012 considered the effectiveness on soil decontamination of sowing KB + WC compared with natural vegetation, after the application of wood pulp on both the experimental areas. A significant increase of *RR* (at 5% by 2-sample *t*-test after the arcsine transformation of data) was found in the areas sown with KB + WC (39.3 ± 21.2%, mean and standard deviation, SD) compared with the control (0.4 ± 0.3%) (Table 2). For example, the *RR* maximum among the replicates was 60.6% when removing 9.0 kg m^{-2} of soil. Contaminated soil was held by the roots of KB and WC passing through the wood pulp sheeting, but this did not occur on the control (Fig. 1D).

Study 2 in 2013 evaluated the effectiveness of four different laying materials on decontamination of radiocaesium in soil. There was a significantly higher *RR* on the revegetation netting 5 (23.8± 3.1%) compared with wood pulp sheeting 3 (5.1 ± 2.4%) ($p < 0.05$ by Tukey's test) both sown with KB and WC (Table 2). The *RR* reached a maximum of 25.9% in revegetation netting 5 with sowing, which was lower than that obtained with the sown wood pulp sheeting in 2012, when removing 6.8 kg m^{-2} of soil. The *RR* on the sown wood pulp sheeting 3 in 2013 was the lowest at 5.1% because no herbaceous plants had grown through the wood pulp sheeting. The maximum and minimum values for *RR* represent the ability and risk of each treatment, respectively. The failure to grow was partially because there were abundant sunshine and dry conditions in May so the seeds sown and retained on the wood pulp sheeting could not absorb moisture. Furthermore, the mesh of wood pulp sheeting was too fine for young forb and grass plants which germinated below the wood pulp sheeting to pass through. In contrast, revegetation netting had the widest mesh amongst the laying materials used in the study. The use of root ball netting, which is easily decomposed in the soil, was an impracticable procedure because the netting decomposed about one month after covering the soil surface.

Overall, the results indicated that the effectiveness of such a decontamination methodology arises from a combination of the type of laying material and the herbaceous plants, which affects the growth vigor of the vegetation.

The study of undergrowth removal without laying material in 2014 was conducted on the site where there was an enrichment of the undergrowth vegetation. The *RR* of KB removal was a maximum of 93.1% with a removed soil weight of 12.9 kg m^{-2} (Table 2). KB is well known to develop a good root mat (Sugiura et al., 1988); in our study it was approximately 3 cm in thick which could be easily rolled up as a carpet (Fig. 2). The second highest *RR* was 57.7% for WC with a removed soil weight of 6.3 kg m^{-2} (Table 2). WC didn't develop a root mat, but spread a large number of stolons (runners) from which fibrous roots were generated (Devkota et al., 1997). The stolons of white clover trapped a comparatively large amount of soil. The *RR* of shepherd's-purse, 43.7%, and bittercress, 39.1 ± 4.8%, were lower than those of KB and WC. Since shepherd's-purse and bittercress had neither root mat nor stolons, they could not be easily rolled up. The results indicated that the effectiveness of ^{137}Cs removal is a function of the density of the roots.

The *RR* of the study 4 in open site after spring and autumn sowing using the revegetation netting was 42.4± 8.1% and 39.6 ± 17.5%, in 2014 and 2015 respectively (Table 3). No significant difference between the sowing seasons was shown in the *RR*. The maximum *RR* was 60.8%, which was the same value as that in study 1 of 2012. However, the removed soil weight of 20.2 kg m^{-2} was 2.2 times higher than that in 2012.

Sanderson and Cresswell have measured the horizontal deposition in FTRC using a backpack survey system (Cresswell et al., 2013) developed by the Scottish Universities Environmental Research Center (SUERC) (Sanderson et al., 2013). The ^{137}Cs deposition density in the open area measured in November 2012 was 150 kBq m^{-2} to 175 kBq m^{-2}, which was lower than those of 225 kBq m^{-2} to 325 kBq m^{-2} in the site planted with grapes in the

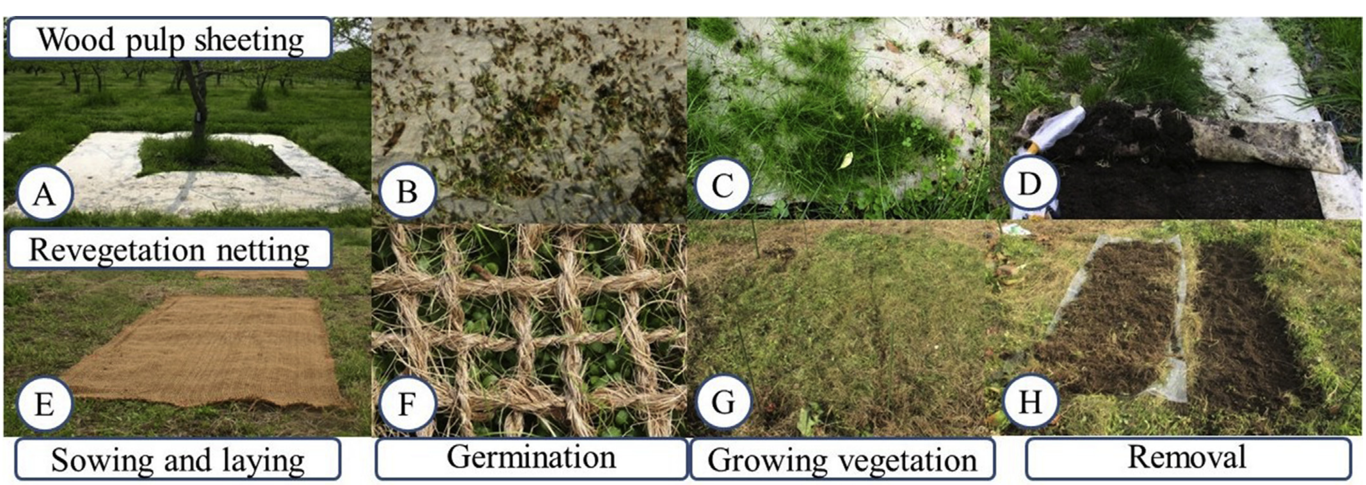

Fig. 1. The processes of the examination in 2012 and 2014. Examinations conducted in 2012 used wood pulp sheeting. Mixed seeds were sown on May 10, 2012 (A). Significant germination of KB had occurred after 11 days, with less WC germinated (B). KB growth dominated on Jul 2, 2012 (C). Sheeting was rolled up on Nov 13, 2012 (D). During 2013 different laying materials were compared, and revegetation netting (E) selected for the subsequent investigations. Mixed seeds were sown on Sep 26, 2014(E). After 11 days, significant germination of both KB and WC had occurred (F). The KB and WC were nourished for a year to enrich the root (G). The revegetation netting was rolled up with the plants, roots, and rhizosphere soil to strip the topsoil on Dec 2, 2015 (H).

Table 2
Data on removal characteristics of each study and associated [^{137}Cs] and calculated *RR* values of removed netting with vegetation or weed (site below the canopy).

Survey year	No	Treatment	Replicates	Removed area (m^2)	Weight (kg DW)	[^{137}Cs] (kBq kg^{-1} DW)	Removed weight by area (kg m^{-2})				^{137}Cs deposition density (kBq m^{-2})		*RR (%)*			
		Covering materials and weed		Mean	Mean	Mean	Maximum	Minimum	Mean	SD	Mean	SD	Maximum	Minimum	Mean	SD
2012	1	Wood pulp sheeting + sowing (KB + WC)	3	0.331	2.34	6.57	9.0	4.4	6.9	2.3	46.4	18.5	60.6	18.1	39.3	21.2
		3 cm soil layer beneath the stripped soil	3	0.022	0.59	10.2	32.6	29.5	30.5	1.8	78.9	38.6	–	–	–	–
	2	Wood pulp sheeting (control)	3	0.349	0.33	1.10	1.1	0.8	0.9	0.1	1.0	0.5	0.8	0.2	0.4	0.3
		3 cm soil layer beneath the stripped soil	3	0.022	0.66	2.64	32.4	24.0	27.3	4.5	276	78.6	–	–	–	–
2013	3	Wood pulp sheeting + sowing (KB + WC)	3	0.362	0.53	8.25	1.7	1.0	1.5	0.4	13.1	10.0	7.8	3.2	5.1	2.4
		3 cm soil layer beneath the stripped soil	3	0.022	0.50	9.76	24.5	21.7	23.0	1.4	220	100	–	–	–	–
	4	Revegetation netting	3	0.412	1.60	4.05	4.6	3.4	3.9	0.7	24.9	4.6	21.5	6.8	14.5	7.4
		3 cm soil layer beneath the stripped soil	3	0.022	0.56	5.21	29.5	22.9	25.8	3.3	172	108	–	–	–	–
	5	Revegetation netting + sowing (KB + WC)	3	0.440	2.50	5.60	6.8	4.5	5.7	1.1	39.8	12.5	25.9	20.2	23.8	3.1
		3 cm soil layer beneath the stripped soil	3	0.022	0.67	4.04	33.6	28.4	30.7	2.6	125	21.7	–	–	–	–
	6	Nonwoven fabric sheeting + sowing (KB + WC)	3	0.383	1.44	12.2	4.8	2.5	3.8	1.2	46.4	15.6	20.3	8.7	16.9	7.1
		3 cm soil layer beneath the stripped soil	3	0.022	0.52	10.2	26.1	20.7	24.2	3.0	239	54.3	–	–	–	–
2014	7	Removal of Kentucky bluegrass rootmat	1	0.600	7.74	22.1	–	–	12.9	–	407	–	–	–	93.1	–
		3 cm soil layer beneath the stripped soil	1	0.027	0.80	3.66	–	–	29.5	–	129	–	–	–	–	–
	8	Removal of White clover root layer	1	0.600	3.78	21.8	–	–	6.3	–	198	–	–	–	57.7	–
		3 cm soil layer beneath the stripped soil	1	0.027	0.66	4.12	–	–	24.4	–	123	–	–	–	–	–
	9	Removal of shepherd's-purse root layer	1	0.600	3.03	22.7	–	–	5.0	–	151	–	–	–	43.7	–
		3 cm soil layer beneath the stripped soil	1	0.027	0.68	5.84	–	–	25.3	–	181	–	–	–	–	–
	10	Removal of bittercress root layer	3	0.250	1.84	9.35	9.2	6.3	7.3	1.6	68.2	12.2	44.6	35.4	39.1	4.8
		3 cm soil layer beneath the stripped soil	3	0.027	0.72	4.01	29.5	24.6	26.4	2.7	106	3.2			–	–

Note: SD represents standard deviation. KB and WC mean Kentucky bluegrass and white clover. *RR* represents the removal ratio of ^{137}Cs in soil.

Fig. 2. Root mat of Kentucky bluegrass enables soils to be rolled up as a carpet (A), which was measured approximately 3 cm thickness in this examination(B).

Table 3
Characteristics of the removed material using revegetation netting and seeding with KB and WC.

Year	Treatment	Removed area (m^2)	Weight (kg DW)	[^{137}Cs] (kBq kg^{-1} DW)	Removed weight by area (kg m^{-2})				^{137}Cs deposition density (kBq m^{-2})		*RR (%)*			
		Mean	Mean	Mean	Maximum	Minimum	Mean	SD	Mean	SD	Maximum	Minimum	Mean	SD
2014	Revegetation netting + sowing (KB + WC)	0.360	6.73	3.06	21.9	15.8	18.7	3.1	57.1	10.2	50.8	34.6	42.4	8.1
	3-cm soil layer beneath the stripped soil	0.027	0.77	2.82	32.7	25.8	28.4	3.7	78.1	14.9	–	–	–	–
2015	Revegetation netting + sowing (KB + WC)	0.360	5.06	2.86	20.2	11.2	14.1	6.6	40.6	20.3	60.8	18.0	39.6	17.5
	3-cm soil layer beneath the stripped soil	0.027	0.64	2.59	28.0	20.4	23.7	3.2	60.7	20.3	–	–	–	–

Note: SD represents standard deviation. KB and WC mean Kentucky bluegrass and white clover. *RR* represents the removal ratio of ^{137}Cs in soil.

same vineyard, (where study 3 on undergrowth removal without laying materials was conducted in 2014), and the survey sites below the canopy (Sanderson et al., 2013). Such data indicated that the ^{137}Cs downward-migration in the open site was faster than in the site planted with grapes. The vertical migration of ^{137}Cs down the soil profile may be due to the infiltration and percolation of water from precipitation (Kaihotsu, 1979, 1984; Shiozawa, 2013). Since rainfall was intercepted by the canopy of trees followed by stemflow down to the main trunk, the infiltration water supplied via throughfall was probably lower below the canopy. Some of the undergrowth of revegetation sowing forbs and grasses remained in the soil escaping from the mesh in study 4 in 2014 in contrast to that using wood pulp sheeting study 1 in 2012.

The study using revegetation netting indicated that increasing the mesh density of the revegetation netting would increase *RR*. Conversely, since the wood pulp sheeting was easy to roll up, the practicality of wood pulp sheeting would increase by making appropriate holes to enhance the permeability of seed or small plants. Overall, these results indicated that sod culture using Kentucky bluegrass and white clover was effective in removing ^{137}Cs from soil by encouraging the development of root mat and stolons.

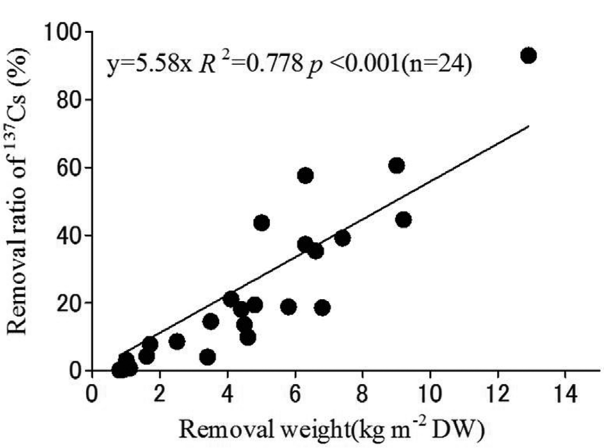

Fig. 3. Relations between removal ratio of ^{137}Cs (*RR*) and the removed soil weight per area on the site below the canopy.

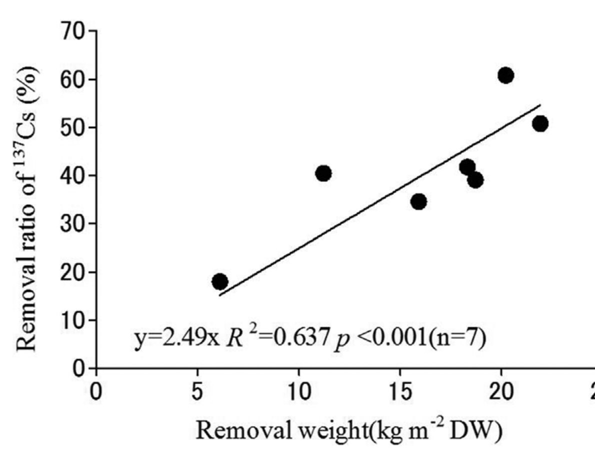

Fig. 4. Relations between removal ratio of ^{137}Cs (*RR*) and the removed soil weight per area on the open site.

Table 4
DRs of [^{137}Cs] or ^{137}Cs inventory in the 3 cm topsoil in the first year of soil removal.

Study	Study site	Sampling site	Sampling date	Replicates (Location)	DRs of [^{137}Cs] or ^{137}Cs inventry in the 3 cm topsoil				
					[^{137}Cs] (kBq kg^{-1} DW)		Amount of ^{137}Cs (kBq)		DR/Inventory
					Mean	SD	Mean	SD	(%)
1, 2, 3	Below canopy	'Yuzora'peach	30 Jan 12	2	8.5	2.4	–	–	83.3
		Apple	24 May 12	3	14.5	10.0	–	–	85.6
		Peach	25 Dec 12	1	7.5	–	–	–	85.9
		Mean							84.9
4	Open site	Vineyard	2 Sep 14	2	3.32	0.37	0.39	0.10	39.4
Ratio of below canopy to open site									2.15

Table 5
Depth distribution of root weight of undergrowth collected on September 2, 2014.

Depth(cm)	Weight (kg m^{-2} DW)							Inventory (%)
	Apple	Peach	Vineyard		Mean		SD	
			Inside of netting	Outside of netting				
0–3	0.40	0.21	0.26	0.31	0.30	±	0.08	73.8
3–9	0.09	0.05	0.10	0.06	0.07	±	0.02	18.5
9–15	0.04	0.06	0.02	0.01	0.03	±	0.02	7.7
Total	0.53	0.32	0.38	0.38	0.40			100.0

Note: SD represents standard deviation.

3.2. Comparison of the effectiveness of ^{137}Cs decontaminations due to soil removal on sites below the canopy and on open sites

There was a significant relationship between *RR* and the removed soil weight per area in both studies on sites below a canopy and on open sites, of $y = 5.58x$ $R^2 = 0.778$ $p < 0.001$ and $y = 2.49x$ $R^2 = 0.637$ $p < 0.001$ respectively (Fig. 3 and Fig. 4). The DRs of [^{137}Cs] in the 3 cm topsoil were an average of 84.9% under a canopy in 2012, the first year of the soil removal study (Table 4). The inventory of ^{137}Cs in the 3 cm top soil in the open site was lower at 39.4% in 2014 (Table 4). The ratio of proportional coefficient between the study sites of 2.24 was similar to the ratio of DRs of sites below the canopy to the inventory of open site in each 3 cm top soil, i.e., 2.15 (Table 4). As would be expected, the effectiveness of ^{137}Cs removal is a function of the ^{137}Cs depth profile. Using the relationship on the site below the canopy, removal of 14.3 kg m^{-2} DW soil would achieve an $RR = 80\%$.

^{137}Cs downward-migration in soil is affected by the infiltration and percolation of water from precipitation (Shiozawa, 2013). Since rainfall is intercepted by canopy of trees, after which throughfall and water flowing over bark, termed stemflow, occurs, it is obvious that the infiltration and percolation water were higher in the open space without the canopy. The difference of concentration profile between sites below the canopy and the open site in each 3 cm top soil infers that the vertical migration of ^{137}Cs down the soil in the open space was advanced by the infiltration and percolation of water from precipitation.

3.3. Vertical distributions of root of undergrowth

Averaged values in three orchards of root weight of undergrowth were 0.30 kg m^{-2} DW in the 0–3 cm layer, 0.07 kg m^{-2} DW in 3–9 cm layer and 0.03 kg m^{-2} DW in 9–15 cm layer. Inventory of root weight in 3 cm topsoil layer became up to 73.8% of amount of roots in 0–15 cm depth (Table 5). These results indicated that decontamination was due to development of roots or root mats in the rhizosphere of undergrowth in the 3 cm topsoil. Dominance of the undergrowth root was one of the reasons why soil density (g cm^{-3}) in the 0–3 cm layer was lower than that in the 3–30 cm layer. More than 90% of the radiocaesium in the soil remained in the upper 0–3 cm in orchards applied with sod culture in the accident year of 2011 (Sato, 2014). It was clarified that the earlier removals of the undergrowth root in the upper 0–3 cm, the lower amount of waste to attain the appropriable radiocaesium decontamination.

Since the revegetation netting and the wood pulp sheeting cost approximately 1000 JPY per m^2 and 650 JPY per m^2 respectively, those materials were expensive to be applied in the large scale of area. Efficient equipment for stripping netting or root mat should be developed to apply these technologies in wider scale. However, the revegetation netting is likely useful in the small site of orchard. Removal of KB and WC without the application of layering material would not be expensive, but the effectiveness depends on advancing of root growth. Sod culture with the mixture of KB and WC is likely expectable to take preventive measures against radiocaesium deposition on the soil. Since topsoil in orchard was enriched with organic and inorganic nutrients, it is better that waste is embedded in each orchard until radiocaesium in soil decrease to appropriate level.

4. Conclusion

The effectiveness of a decontamination methodology whereby herbaceous plants were grown through different materials covering the soil surface followed by subsequent removal of the material, associated plant tissues and attached soil on ^{137}Cs removal from soil was evaluated. Significant correlations were observed between removal rate of ^{137}Cs and mass of soil removed. Netting and weeding are able to remove up to 80% of ^{137}Cs in the soil without using heavy machinery. The effectiveness of ^{137}Cs removal is a function of the ^{137}Cs depth profile and the density of the roots developed by the undergrowth.

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