JARQ 55 (1), 5-16 (2021) https://www.jircas.go.jp

Radioactive Cesium Concentration in Silage Corn (*Zea Mays* L.) and Italian Ryegrass (*Lolium Multiflorum* Lam.) Cultivated with Three Different Tillage Methods after the Fukushima Daiichi Nuclear Power Plant Accident

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Abstract

Whole-crop silage corn and Italian ryegrass were cultivated during summer and winter in fields contaminated by radionuclide fallout caused by the Fukushima Daiichi Nuclear Power Plant accident, with three different tillage treatments: shallow tillage treatment (tilled with a rotary tiller to a depth of about 10 cm), conventional tillage treatment (plowed with a normal moldboard plow to a depth of about 20 cm and harrowed with a rotary tiller to a depth of about 15 cm), and deep tillage treatment (plowed with a moldboard plow to a depth of about 35 cm and harrowed with a rotary tiller to a depth of about 15 cm). Vertical distribution of radioactive cesium (Cs) in the soil layers of 0 cm-10 cm, 10 cm-20 cm, and 20 cm-30 cm, and concentrations of radioactive Cs in forage samples were compared among the tillage treatments, as well as the soil chemical properties of those soil layers.

Radioactive Cs in the soil surface layer (0 cm-10 cm) moved into the deeper layers at 10 cm-20 cm and 20 cm-30 cm due to plowing in the conventional and deep tillage treatments. However, significant differences were not observed for both species, either in the radioactive Cs concentration in forage samples or the radioactive Cs transfer factor from soil to plants among the tillage treatments. Moreover, the radioactive Cs concentrations in those plants and their TFs were relatively low for both species. These results suggest that radioactive Cs transfer was reduced by mixing the surface soil, even in the shallow tillage treatment. Furthermore, the exchangeable K_2O content of soil was higher than 0.32 g/kg DW in all soil layers of the experimental fields, and such high content of exchangeable K_2O in the soil was apparently another major reason why radioactive Cs uptake by both species was significantly restricted in all tillage treatments.

Discipline: Crop Science
Additional key words: maize, plowing, transfer factor

Introduction

The accident at the Fukushima Daiichi Nuclear Power Plant (FDNPP) of the Tokyo Electric Power Company in March 2011 caused radionuclide contamination over a wide area of eastern Japan (MEXT

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Received 29 October 2019; accepted 1 April 2020.

2011). Agriculture (including forage and livestock production) was severely affected, especially in the eastern part of the Tohoku region (the prefectures of Fukushima, Miyagi, and Iwate) and northern part of the Kanto region (the prefectures of Tochigi, Gunma, and Ibaraki). When the FDNPP accident occurred, the total acreage of forage crop fields and pastures in those regions was 105,000 ha (MAFF 2012), accounting for 34% of said total acreage on the main island of Japan. Therefore, controlling the transfer of radionuclides from soil to forage crops is essential for reducing the entry of radionuclides from the environment into the human food chain.

To prevent radioactive cesium (Cs) contamination of forage crops, various countermeasures were examined and then immediately implemented (Tsuiki & Maeda 2012a, 2012b, Kobayashi et al. 2013, Harada et al. 2014, Ogura et al. 2014, Yamamoto et al. 2014, Harada 2015, Harada et al. 2015, Shinano 2015, Sunaga et al. 2015, Kobayashi et al. 2016, Komissarov et al. 2017). Those studies and subsequent implementation of countermeasures utilized information and knowledge mainly obtained after the Chernobyl accident in 1986 (Alexakhin 1993, Konoplev et al. 1993, Lembrechts 1993, Lönsjö et al.1989, Nisbet et al. 1993, Segal 1993, Roed et al. 1996, Fesenko et al. 2007). More specifically, the main countermeasures applied for farmlands after the Chernobyl accident can be classified as: (1) physical methods such as removal of contaminated surface soil or plowing to dilute contaminated soil, (2) chemical methods such as applying lime, fertilizer, and some materials fixing radionuclides, and (3) biological methods such as the utilization of alternative crop species or cultivars. Among these countermeasures, physical methods are known to be the most stable decontamination methods and were widely utilized after the Chernobyl accident (Fesenko et al. 2007, Beresford et al. 2016).

Many studies have reported that plowing can effectively decontaminate or reduce the radioactive pollution of crops harvested from contaminated farmlands by moving polluted surface layers to deeper locations (Menzel et al. 1968, Milbourne et al. 1959, Milbourne 1960, Rosén 1996, Camps et al. 2004). Moreover, the deep placement of radionuclides in the soil can reportedly reduce their absorption by plant roots, as compared with shallow placement (Myhre et al. 1964, Evans & Dekker 1965, Lönsjö et al. 1989). And both deep and shallow plowing were used extensively after the Chernobyl accident (Fesenko et al. 2007, Beresford et al. 2016). After the FDNPP accident in Japan, plowing was reportedly an effective method of reducing radioactive Cs absorption by upland field crops such as soybean (Hoshino et al. 2015, Li et al. 2019) and perennial grasses (Harada 2015). However, information about the plowing effects on main forage crops in Japan (whole-crop silage corn and Italian ryegrass) remains limited. Therefore, in this study, we conducted two experiments to investigate the effects of the tillage methods, by differing the cultivation depth on radioactive Cs transfer from soil to the two forage crops. The soil surface layers contaminated by radionuclide fallout after the FDNPP accident were mixed into three different depths (10, 20, and 35 cm), and then the radioactive Cs concentrations in corn and Italian ryegrass were compared among the three treatments, as well as their transfer factors from soil to plants.

Materials and methods

Two experiments for whole-crop silage corn (*Zea mays* L.) (Experiment 1) and Italian ryegrass (*Lolium multiflorum* Lam.) (Experiment 2) were conducted at the Nasu Research Station of the NARO Institute of Livestock and Grassland Science (NILGS) (36°55′ north latitude, 139°56′ east longitude and 304 m ASL) in Tochigi, Japan. The station is located about 112 km south-southwest of the FDNPP. The experimental fields contained Brown Lowland soil (Kurashima et al. 1993). Figure 1 shows the monthly averages of mean, maximum, and minimum air temperatures, as well as monthly cumulative precipitation.

The experimental fields of Experiment 1 (0.17 ha) and Experiment 2 (0.16 ha) are located adjacent to each other on a plain field. From 2005 to 2010, the fields were collectively managed. During the summers of 2005, 2006, 2008, and 2010, corn was cultivated with farmyard manure application (20 t/ha), whereas sudangrass (*Sorghum sudanense* (Piper) Stapf) was cultivated in the summer of 2007 as green manure without farmyard manure application. During the winters of 2005-2009, rye (*Secale cereale* L.) was cultivated with farmyard manure application (20 t/ha). In the year before the FDNPP accident, corn was cultivated from May to September in both experimental fields, and then Italian ryegrass (cultivar ‘Yushun’) was sown only in the field of Experiment 1 on October 27, 2010 with farmyard manure application (20 t/ha). The experimental field of Experiment 2 had lain fallow from September 2010 to May 2011, and then corn was cultivated in the field until September 2011.

1. Experiment 1

Italian ryegrass sown in the previous year was harvested on May 6, 2011, and the degree of its contamination by direct deposition was investigated as follows: a 1 m^2 quadrate was set randomly at six points,

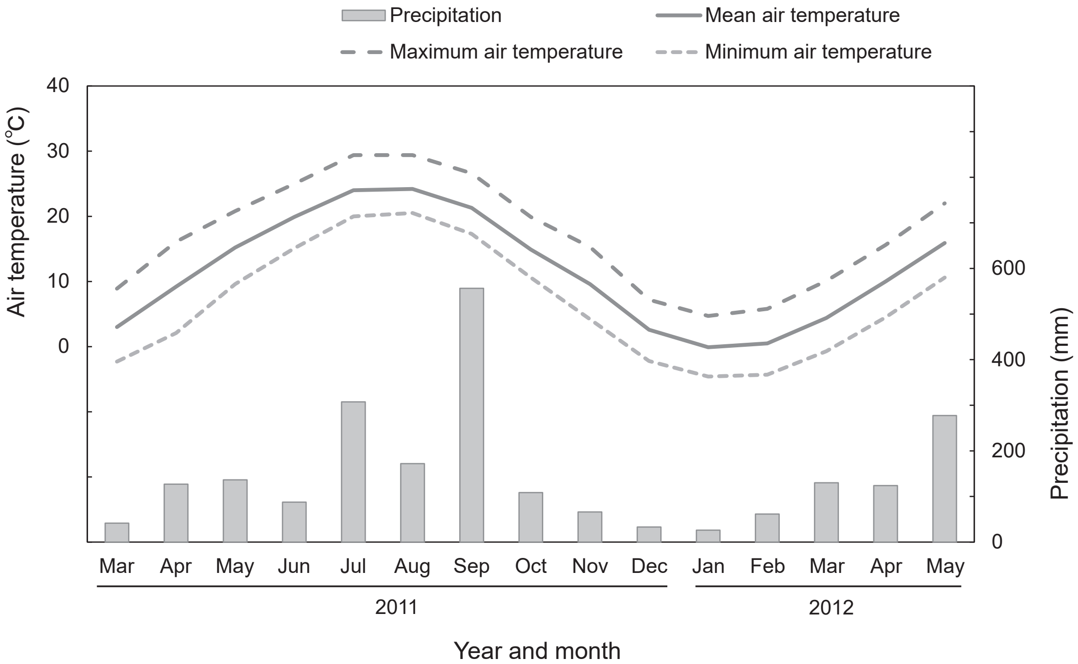

Fig. 1. Monthly average of mean, maximum, and minimum air temperatures, and monthly cumulative precipitation observed at the NARO Institute of Livestock and Grassland Science

and forage samples were cut at 5 cm above ground level. Then within the 1 m^2 quadrate, an area of 0.25 m^2 (50 cm × 50 cm) was selected and cut at the soil surface for collecting the basal plant parts. Those herbage samples were oven-dried at 70°C for 48 hours and used for radioactive Cs measurement.

The corn was planted with three different tillage methods after the harvesting of Italian ryegrass. The three tillage methods were shallow tillage (ST) with a rotary tiller to a depth of about 10 cm, conventional tillage (CT) with a moldboard plow to a depth of about 20 cm and a rotary tiller to a depth of about 15 cm, and deep tillage (DT) with a moldboard plow for deep plowing to a depth of about 35 cm and a rotary tiller to a depth of about 15 cm. A 100 m^2 field plot for the three tillage methods was set in three blocks with a randomized block design. In the experimental field (0.17 ha), each block was set 5 m apart, and in each block, the three plots for the tillage treatments were randomly arranged.

Prior to the plowing treatments, soil samples were collected to examine the vertical distribution of radioactive Cs in the soil. On May 10-11, 2011, at two sites of each block, the soil in the 0.0625 m^2 quadrate (0.25 m × 0.25 m) was carefully excavated by hand to a depth of 30 cm, separating the layers of 0 cm-10 cm, 10 cm-20 cm, and 20 cm-30 cm. At each block, two samples of the same layer were well mixed, and two sub-samples of about 2 kg and 1 kg were taken for measuring radioactive Cs concentration and examining other chemical properties, respectively.

Plowing for the CT and DT treatments was conducted on May 18-19, 2011, and all plots were cultivated with a rotary tiller after an application of chemical fertilizer (N-K_2O-P_2O_5:17-17-17) at a rate of 200 kg/ha for each nutrient component. On May 25, 2011, seeds of corn (cultivar ‘Cecilia’) were sown at a rate of 70,000 seeds/ha. After the field soil was compacted, hydrated atrazine and alachlor emulsion were applied as herbicides. In this cultivation, farmyard manure and lime were not applied in any treatments.

For the purpose of examining the vertical distribution of radioactive Cs in the soil after seeding, soil samples were collected on June 8-9, 2011 at two sites of each plot in the same manner as before planting; soil in the 0.0625 m^2 quadrate (0.25 m × 0.25 m) was excavated to a depth of 30 cm, separating the layers of 0 cm-10 cm, 10 cm-20 cm, and 20 cm-30 cm. At the same time, the bulk density of the soil was measured at each sampling site by excavating the soil to a depth of 30 cm, and then separating each 5-cm layer with a stainless 100-cc core sampler. Each core sample was then weighed and oven-dried at 105°C for 48 hours for determining dry weight. The bulk density of each 10-cm layer was calculated as an average of the two 5-cm layers composing the 10-cm layer.

On September 5, 2011, the corn plants included in a 3 m^2 quadrate (2 rows × 2 m) were harvested from the central areas of each plot. Approximately 20 plants were harvested by cutting at 10 cm above the soil surface. After total fresh weight was measured, five plants were randomly selected. Then the corn plant samples were carefully washed with water to remove soil attached to the basal parts of the plants, due to heavy rains before the harvest (203 mm from the 1st to 3rd of September). After the washing, the samples were chopped into approximately 1-cm pieces using a motor-cutter. The motor-cutter was cleaned with a wetted paper towel after each cutting to avoid contamination between the samples. After the fresh weight of the chopped samples was measured, the samples were dried for four days at 70°C.

Prior to the harvest, the underground parts of the corn were collected on August 24-25, 2011. One corn plant was randomly selected in each plot, and soil in the 0.15 m^2 quadrate (0.75 m × 0.20 m) including the corn plant selected was excavated to a depth of 30 cm, separating the layers of 0 cm-10 cm, 10 cm-20 cm, and 20 cm-30 cm. Each soil sample was washed using a 2-mm sieve, and the underground parts retained on the sieve were dried for four days at 70°C.

Chemical properties were measured for the soil samples collected before planting on May 10-11, 2011 and after planting on June 8-9, 2011. The properties measured for the samples before planting were pH (H_2O), cation exchange capacity (CEC), the contents of exchangeable Ca, Mg, and K, available P, and total nitrogen. As for the samples after planting, the exchangeable K content was measured. The soil pH was measured in water (1:2.5 weight/weight) by using a pH glass electrode. CEC was determined using the replacement method of Schollenberger and Simon (1945). Exchangeable cations were extracted from the soil using an extracting solution (1 N NH_4OAc, pH 7.0), and then measured by atomic absorption spectrometry. Available P was extracted using the method of Truog (1930), and the P content (as P_2O_5) was determined by spectrophotometry. Total nitrogen content was determined by the dry combustion method by using a CN analyzer.

The concentrations of radioactive Cs (cesium-134 (^{134}Cs) and cesium-137 (^{137}Cs)) were determined for the plant and soil samples with a GC3020-7500SL germanium semiconductor detector (Canberra Japan KK, Tokyo, Japan). The counting times were 3,600 seconds for each plant sample of about 0.3 kg packed in a 2-L Marinelli vessel, and 2,000 seconds for each soil sample of about 70 g packed in a 100-mL U-8 vessel. The concentrations of the two isotopes were calculated on a DW basis. The results were corrected for decay of the isotopes, and the radioactive Cs concentration in those samples was expressed as an estimated value at the date of sampling or harvesting. We assumed a half-life of 2.0652 years for ^{134}Cs and 30.17 years for ^{137}Cs.

The transfer factor (TF) was calculated from the following equation:

TF = (^{134}Cs or ^{137}Cs concentration in forage corn (Bq/kg DW)) / (^{134}Cs or ^{137}Cs concentration in soil at the harvesting date (Bq/kg dry soil, 0 cm-30 cm depth))

The average radioactive Cs concentration in the soil layer at a depth of 0 cm-30 cm was calculated as follows: from the value of bulk density and radioactive Cs concentration per dry soil, the concentration of radioactive Cs per volume was calculated for each soil layer. And then from the average values of radioactive Cs concentration per volume of the three layers and their bulk density, the average radioactive Cs concentration per soil dry weight at a depth of 0 cm-30 cm was calculated. Hence, the definition of TF in this study differs somewhat from that widely used in the literature (IAEA 2010).

After measurement of the radioactive Cs concentration, the plant samples were ground using a 2-mm mesh, and the potassium concentration was measured by atomic absorption spectroscopy after wet digestion with nitric acid and perchloric acid.

One-way analysis of variance (ANOVA) was conducted for the data collected on the three tillage treatments, but data on the radioactive Cs concentration in soil was logarithmically converted before one-way ANOVA. The significant level was 5% in this report. The R 3.1.2 statistical software package (R Foundation for Statistical Computing Platform 2014) was used for the analysis.

2. Experiment 2

When the FDNPP accident occurred, the field of Experiment 2 had lain fallow. Corn (cultivar 'Cecilia') was then planted there using the same shallow tillage treatment as in Experiment 1, and harvested in September 2011. After harvesting of the corn, Italian ryegrass was planted with the three different tillage methods in October 2011. A 100 m^2 field plot for shallow tillage (ST), conventional tillage (CT), and deep tillage (DT) was set in three blocks, in the same manner as in Experiment 1. Prior to the plowing treatments, soil samples were collected to examine the vertical distribution of radioactive Cs in the soil at six sites on October 5, 2011, using the same procedure as in Experiment 1.

Plowing for the CT and DT treatments was conducted on October 7, 2011, and all plots were cultivated with a rotary tiller after application of chemical fertilizer (N-K_2O-P_2O_5:17-17-17) at a rate of 150 kg/ha for each nutrient component. On October 12, 2011, seeds of Italian ryegrass (cultivar 'Siwasuaoba') were sown at a rate of 40 kg/ha, and then the field soil was compacted with a roller.

After seeding, the vertical distribution of radioactive Cs in the soil to a depth of 30 cm was examined in all plots on October 18-20, 2011, in the same manner as in Experiment 1, as well as the bulk density of the soil.

On May 2, 2012, Italian ryegrass included in the 1 m^2 quadrate (1 m × 1 m) was harvested at the three sites of each plot by cutting at 5 cm above the soil surface. Fresh weight was measured for all samples, and then three samples from the same plot were mixed and separated into three sub-samples. The first sub-samples were washed with water, dried for two days at 70°C, and then used for determining radioactive Cs concentration. The second sub-samples were dried for two days at 70°C, ground with a 2-mm mesh, and then used for measuring the potassium concentration. The third sub-samples were separated into live Italian ryegrass, weeds, and dead parts, and then dried for two days at 70°C to measure dry matter composition.

At the time of harvest, the underground parts of Italian ryegrass were collected. The two 0.0625 m^2 quadrates (0.25 m × 0.25 m) were excavated to a depth of 30 cm, separating the layers of 0 cm-10 cm, 10 cm-20 cm, and 20 cm-30 cm. Each soil sample was washed using a 2-mm sieve, and the underground parts retained on the sieve were dried for two days at 70°C. Chemical properties of the soil samples, radioactive Cs concentrations in the soil and plant samples, and K concentration in the plant samples were measured using the same methods as in Experiment 1. The TF from soil to plants was calculated with the same equation as used in Experiment 1.

Results

1. Experiment 1

Dry matter yield of the preceding Italian ryegrass was 8.22 t/ha, and dry weight of the basal parts was 1.81 t/ha. The radioactive Cs concentrations in the harvested parts and basal parts of Italian ryegrass were 26.0 kBq/kg DM and 213.2 kBq/kg DM, respectively.

Table 1 lists the radioactive Cs concentration in the soils and several soil chemical properties before the planting of corn. The data on radioactive Cs concentration in Table 1 were calculated from the data on only two of the three blocks, and more than 95% of the total amount of radioactive Cs (^{134}Cs+^{137}Cs) was distributed on average in the soil layer of 0 cm-10 cm in the two blocks. However, cross-contamination occurred in the other block during its sampling, as 19% of the total amount of radioactive Cs in the three soil layers was distributed in the layer of 10 cm-20 cm. There were small differences among the soil layers in terms of the other soil chemical properties. The exchangeable K_2O content was relatively high in all the soil layers (0.24-0.38 g/kg DW).

Table 2 lists the radioactive Cs concentration, bulk density, and exchangeable K_2O content of the soils after the planting of corn with the three tillage treatments. In the surface layer, the radioactive Cs concentration for ST was higher than that for DT. In the layers of 10 cm-20 cm and 20 cm-30 cm, the radioactive Cs concentrations for CT and DT were higher than that for ST. In the ST treatment, 98% of radioactive Cs was concentrated in the surface layer. In the CT treatment, approximately the same amount of radioactive Cs was distributed in both the layers of 0 cm-10 cm and 10 cm-20 cm. In the DT treatment, only 15% of radioactive Cs remained in the surface layer, whereas 55% of radioactive Cs moved into the lowest soil layer. In all the soil layers, the exchangeable K_2O content was at a relatively high level (0.34-0.46 g/kg DW).

The plowing treatment did not affect the plant height at harvesting, dry matter yield, radioactive Cs concentration, and potassium concentration of corn (Table 3). The radioactive Cs concentration was prominently low in all three plowing treatments (22.7 Bq/kg DW on average).

Table 4 lists the TFs for corn. The mean values of TF among the three treatments were 0.0139, 0.0125, and 0.0131 in ^{134}Cs, ^{137}Cs, and ^{134}Cs+^{137}Cs, respectively. Thus, there was no significant difference in TF among the

Table 1. Radioactive cesium (Cs) concentration and chemical properties of soil before the planting of corn

Soil layers	Radioactive Cs concentration[1]			pH(H_2O)	CEC[2]	Exchangeable cations			Available P_2O_5	Total N
	^{134}Cs	^{137}Cs	^{134}Cs+^{137}Cs			CaO	MgO	K_2O		
(cm)	(Bq/kgDW)				($cmol_c$/kgDW)	(g/kgDW)			(mg/kgDW)	(%)
0-10	709.5	850.7	1,560.2	5.79	27.7	1.90	0.26	0.24	145.4	0.39
10-20	6.7	25.8	32.5	5.87	27.8	2.19	0.30	0.32	143.1	0.40
20-30	0.0	13.5	13.5	6.00	32.5	2.16	0.34	0.38	141.5	0.40

[1] Radioactive Cs concentration was calculated as the value on the sampling date (May 11, 2011).
[2] Cation exchange capacity

Table 2. Radioactive cesium (Cs) concentration, bulk density, and exchangeable K_2O content of three soil layers in the three tillage treatments after the planting of corn

Soil layers	Treatments	Radioactive Cs concentration[1]			Bulk density	Exchangeable K_2O content
		^{134}Cs	^{137}Cs	^{134}Cs+^{137}Cs		
(cm)			(Bq/kgDW)		(g/cm^3)	(g/kgDW)
0-10	Shallow tillage	1,457.1 a	1,740.5 a	3,197.6 a	0.811	0.46
	Conventional tillage	751.5 ab	886.9 ab	1,638.5 ab	0.766	0.40
	Deep tillage	244.5 b	302.7 b	547.2 b	0.793	0.41
10-20	Shallow tillage	16.4 b	29.5 b	45.9 b	0.873	0.34
	Conventional tillage	705.1 a	852.3 a	1,557.5 a	0.779	0.45
	Deep tillage	499.9 a	590.8 a	1,090.7 a	0.838	0.42
20-30	Shallow tillage	2.4 b	15.7 b	18.1 b	0.901	0.40
	Conventional tillage	224.9 a	271.6 a	496.5 a	0.913	0.42
	Deep tillage	920.5 a	1,048.3 a	1,968.8 a	0.798	0.40

[1] Radioactive Cs concentration was calculated as the value on the harvesting date (September 5, 2011).
Different lowercase letters indicate significant differences ($P < 0.05$) among the tillage treatments by the Tukey-Kramer test.

Table 3. Plant height, dry matter yield, radioactive cesium (Cs) concentration, and potassium concentration of corn in the three tillage treatments at the harvest on September 5, 2011

Treatments	Plant height	Dry matter yield	Radioactive Cs concentration[1]			K concentration
			^{134}Cs	^{137}Cs	^{134}Cs+^{137}Cs	
	(cm)	(t/ha)		(Bq/kgDW)		(%)
Shallow tillage	334.3	13.5	12.1	12.3	24.5	1.29
Conventional tillage	340.4	13.5	9.1	11.0	20.1	1.36
Deep tillage	311.6	13.3	11.6	11.9	23.5	1.38
Mean	328.8	13.4	11.0	11.7	22.7	1.34
Significance[2]	ns	ns	ns	ns	ns	ns

[1] Radioactive Cs concentration in aboveground parts was calculated as the value on the harvesting date (September 5, 2011).
[2] Result of the ANOVA analysis; the difference was not significant.

Table 4. Transfer factors of radioactive cesium (Cs) from soil to corn in the three tillage treatments

Treatments	Transfer factor		
	^{134}Cs	^{137}Cs	^{134}Cs+^{137}Cs
Shallow tillage	0.0166	0.0139	0.0151
Conventional tillage	0.0102	0.0101	0.0101
Deep tillage	0.0149	0.0135	0.0141
Mean	0.0139	0.0125	0.0131
Significance[1]	ns	ns	ns

[1] Result of one-way ANOVA; the difference was not significant.

treatments.

The vertical distribution of roots was similar among the treatments (Table 5). Given the large deviation among the blocks in all soil layers, there was no significant difference in root dry weight at any soil depth.

2. Experiment 2

Table 6 lists the radioactive Cs concentration in the soils and several soil properties before the planting of Italian ryegrass. Though 97% of radioactive Cs existed in the soil surface (0 cm-10 cm), there were small differences in the other soil chemical properties among the soil layers. The exchangeable K_2O content was relatively high and similar among the soil layers (0.33-0.37 g/kg DW).

Table 7 lists the radioactive Cs concentration, bulk density, and exchangeable K_2O content of the soils after the planting of Italian ryegrass. In the surface layer, the radioactive Cs concentration for ST was higher than that for DT. In the layer of 10 cm-20 cm, the radioactive Cs concentrations for CT and DT were the higher than that for ST, whereas in the layer of 20 cm-30 cm, the order of radioactive Cs concentration was DT > CT > ST. In the ST treatment, 88% of radioactive Cs was concentrated in

Table 5. Vertical distribution of roots of corn in the three tillage treatments

Treatments	Soil layers 0 cm-10 cm Stem	0 cm-10 cm Root		10 cm-20 cm Root		20 cm-30 cm Root		Amount of root dry weight	
	(kgDW/ha)			(kgDW/ha)		(kgDW/ha)		(kgDW/ha)	
Shallow tillage	66.6	1,047.0	(80.8)[1]	195.2	(14.4)	61.7	(4.8)	1,303.9	(100)
Conventional tillage	72.7	1,263.2	(79.0)	243.2	(14.6)	104.9	(6.4)	1,611.2	(100)
Deep tillage	67.8	998.3	(77.3)	148.0	(11.5)	136.2	(11.2)	1,282.5	(100)
Mean	69.0	1,102.8		195.5		100.9		1,399.2	
Significance[2]	ns	ns		ns		ns		ns	

[1] Values in parentheses are the percentages of the root dry weight in each soil layer to the amount of root dry weight.
[2] Result of one-way ANOVA; the difference was not significant.

Table 6. Radioactive cesium (Cs) concentration and chemical properties of soil before the planting of Italian ryegrass

Soil layers	Radioactive Cs concentration[1] ^{134}Cs	^{137}Cs	$^{134}Cs+^{137}Cs$	$pH(H_2O)$	CEC[2]	Exchangeable cations CaO	MgO	K_2O	Available P_2O_5	Total N
(cm)	(Bq/kgDW)				($cmol_c$/kgDW)	(g/kgDW)			(mg/kgDW)	(%)
0-10	1,160.5	1,568.7	2,729.2	5.87	26.1	2.34	0.27	0.35	318.0	0.39
10-20	28.7	42.0	70.7	6.10	26.6	3.00	0.41	0.33	231.7	0.41
20-30	0.0	7.8	7.8	6.23	21.6	2.72	0.43	0.37	157.0	0.30

[1] Radioactive Cs concentration was calculated as the value on the sampling date (October 5, 2011).
[2] Cation exchange capacity

Table 7. Radioactive cesium (Cs) concentration, bulk density, and exchangeable K_2O content of three soil layers in the three tillage treatments after the planting of Italian ryegrass

Soil layers	Treatments	Radioactive Cs concentration[1] ^{134}Cs		^{137}Cs		$^{134}Cs+^{137}Cs$		Bulk density		Exchangeable K_2O content	
(cm)		(Bq/kgDW)						(g/cm^3)		(g/kgDW)	
0-10	Shallow tillage	1,210.4	a	1,514.5	a	2,724.9	a	0.780		0.51	a
	Conventional tillage	381.7	ab	473.9	ab	855.6	ab	0.831		0.42	ab
	Deep tillage	198.2	b	254.6	b	452.8	b	0.801		0.41	b
10-20	Shallow tillage	147.3	b	198.5	b	345.8	b	0.886		0.32	
	Conventional tillage	805.5	a	1,031.5	a	1,836.9	a	0.837		0.39	
	Deep tillage	486.8	a	622.3	a	1,109.1	a	0.857		0.35	
20-30	Shallow tillage	3.2	b	14.2	c	17.4	c	0.916	ab	0.34	
	Conventional tillage	172.4	a	210.0	b	382.4	b	0.966	a	0.35	
	Deep tillage	725.6	a	922.1	a	1,647.6	a	0.861	b	0.35	

[1] Radioactive Cs concentration was calculated as the value on the harvesting date (May 2, 2012).
Different lowercase letters indicate significant differences ($P < 0.05$) among the tillage treatments by the Tukey-Kramer test.

the surface layer. In the CT treatment, the highest concentration was observed in the layer of 10 cm-20 cm. In the DT treatment, only 14% of radioactive Cs remained in the surface layer, whereas 51% of radioactive Cs moved into the layer of 20 cm-30 cm. In the surface layer, the exchangeable K_2O content of ST was higher than that of DT.

Table 8 lists the plant height, dry matter yield, radioactive Cs concentration, and potassium concentration on Italian ryegrass at harvesting. The plant height in the DT treatment was the highest, but total dry matter yield did not differ among the three treatments. The tillage treatment did not affect the radioactive Cs concentration in Italian ryegrass or its potassium concentration.

Table 9 lists the TFs from the soil to Italian ryegrass.

Table 8. Plant height, dry matter yield, radioactive cesium (Cs) concentration and potassium concentration of Italian ryegrass in the three tillage treatments at the harvest on May 02, 2012

Treatments	Plant height		Dry matter yield				Radioactive Cs concentration[1]			K concentration
			Italian ryegrass alive	Weed	Dead parts	Total	^{134}Cs	^{137}Cs	$^{134}Cs+^{137}Cs$	
	(cm)			(t/ha)		(t/ha)		(Bq/kgDW)		(%)
Shallow tillage	88.1	b	2.95	1.14	0.45	4.54	14.8	24.6	39.5	2.46
Conventional tillage	90.1	ab	2.90	1.28	0.50	4.68	11.2	15.3	26.4	2.64
Deep tillage	94.3	a	3.23	0.62	0.51	4.36	15.1	22.9	38.0	2.60

[1] Radioactive Cs concentration in aboveground parts was calculated as the value on the harvesting date (May 2, 2012).
Different lowercase letters indicate significant differences ($P < 0.05$) among the tillage treatments by the Tukey-Kramer test.

Mean values of TF among the three treatments were 0.0232, 0.0271, and 0.0254 in ^{134}Cs, ^{137}Cs, and $^{134}Cs+^{137}Cs$, respectively. There was no significant difference in TF among the treatments.

Table 10 lists the dry weight of the base of stems and the vertical distribution of roots. A significant difference in dry weight of the base of stems was observed among the treatments. Conversely, there was no significant difference in root weight among the three tillage treatments in all three soil layers.

Table 9. Transfer factors of radioactive cesium (Cs) from soil to Italian ryegrass in the three tillage treatments

Treatments	Transfer factor		
	^{134}Cs	^{137}Cs	$^{134}Cs+^{137}Cs$
Shallow tillage	0.0246	0.0316	0.0285
Conventional tillage	0.0190	0.0198	0.0195
Deep tillage	0.0261	0.0298	0.0282
Mean	0.0232	0.0271	0.0254
Significance[1]	ns	ns	ns

[1] Result of one-way ANOVA; the difference was not significant.

Discussion

In Experiment 1, at one block among the three, 19% of total radioactive Cs of the three soil layers was distributed in the layer of 10 cm-20 cm. Many studies conducted after the Chernobyl and FDNPP accidents have reported very slow vertical migration of radioactive Cs, and that most radioactive Cs remained in the upper soil layers under non-plowed conditions (Arapis et al. 1997, Shiozawa et al. 2011, Tsuiki and Maeda 2012a, Yamaguchi et al. 2012, Kobayashi et al. 2013, Matsunaga et al. 2013, Ogura et al. 2014, Komissarov et al. 2017). Therefore, the detection of radioactive Cs in the lower layer before plowing indicated the occurrence of cross-contamination during soil sampling. Although soil sampling was done very carefully by hand in this study, cross-contamination of radioactive Cs could not be completely prevented. Cross-contamination in the soil sampling procedures was also observed in the studies by Milbourn et al. (1959) and Milbourn (1960). However, in this study, the vertical distribution of radioactive Cs in the soil differed significantly among the tillage treatments, and the tendency of vertical distribution was similar to that reported by Hoshino et al. (2015) and Komissarov et al. (2017). Therefore, in this study, radioactive Cs in the soil surface layer (0 cm-10 cm) was effectively moved into deeper layers at 10 cm-20 cm and 20 cm-30 cm due to plowing for the CT and DT treatments.

One noteworthy point in this study is that there was no significant difference in radioactive Cs concentration for both corn and Italian ryegrass among the three tillage treatments, though radioactive Cs in the soil surface layer effectively moved into the deeper layers. In previous studies on deep plowing, Milbourn et al. (1959) reported that when contaminated land was plowed to a depth of 12 in. (30.48 cm), ^{89}Sr absorption by shallow-rooted crops was reduced to less than 30% of that in non-cultivated treatment, though there was less effect with deeper-rooted species. Moreover, Menzel et al. (1968) reported that the relative concentrations of ^{85}Sr in sudangrass (*Sorghum sudanense*) after deep plowing treatment (90-cm deep) were reduced by 36.6% and 50.5% in fodder and seed, respectively, as compared with rotary tilled treatment (20-cm deep). After the FDNPP accident in Japan, Hoshino et al. (2015) compared the radioactive Cs concentration in soybean cultivated by three different systems employing the non-tillage method, moldboard plowing/rotary harrowing, and rotary cultivation. They reported that the radioactive Cs concentration in soybean for the non-tillage treatment was higher than those for the other two treatments, but reported no difference in the radioactive Cs concentration in soybean between the

Table 10. Vertical distribution of roots of Italian ryegrass in the three tillage treatments

Treatments	Soil layers				Amount of root dry weight
	0 cm-10 cm		10 cm-20 cm	20 cm-30 cm	
	Stem	Root	Root	Root	
	(kgDW/ha)		(kgDW/ha)	(kgDW/ha)	(kgDW/ha)
Shallow tillage	1,763.2 a	1,004.3 (84.5)[1]	130.4 (11.0)	53.6 (4.5)	1,188.3 (100)
Conventional tillage	932.1 b	929.0 (82.5)	123.7 (11.0)	73.6 (6.5)	1,126.3 (100)
Deep tillage	1,090.3 ab	809.9 (79.2)	117.9 (11.5)	94.9 (9.3)	1,022.7 (100)

[1] Values in parentheses are the percentages of the root dry weight in each soil layer to the amount of root dry weight.
Different lowercase letters indicate significant differences ($P < 0.05$) among the tillage treatments by the Tukey-Kramer test.

moldboard plow/rotary harrow treatment and the rotary cultivation treatment (Hoshino et al. 2015). Moreover, Li et al. (2019) investigated temporal changes in the vertical distribution of ^{137}Cs in a soybean field, and the effects of tillage systems on radioactive Cs concentrations in soybean and soil-to-crop transfer factors. In their study, the higher the radioactive Cs concentration in the soil surface, the higher the soil-to-crop transfer factor (Li et al. 2019).

As our study did not establish non-tillage treatment, we did not compare the radioactive Cs uptake in the CT or DT treatment with that of a non-tilled condition. After the FDNPP accident, Kobayashi et al. (2013) examined the radioactive Cs uptake of seven plant species including two cultivars of corn under a non-tilled condition at the same location (NILGS), and at almost the same period as Experiment 1 in our study, though the exchangeable K_2O content in the field soil was relatively low at 0.108 g/kg DW. In their study, the radioactive Cs concentrations in two cultivars of corn were 388-398 Bq/kg DW, that is, 17.1-17.5 times higher than the average radioactive Cs concentration in our study. These results suggest that mixing the surface soil effectively reduces radioactive Cs transfer to corn and Italian ryegrass, even in the shallow tillage treatment. Thus, that may be one reason why the effect of tillage methods on radioactive Cs uptake by plants was not significant in both corn and Italian ryegrass in this study. Furthermore, high exchangeable K_2O content in all soil layers is apparently another reason why radioactive Cs uptake by plants was reduced in this study, as discussed later.

In comparing the TFs for corn, the average TF value (^{134}Cs+^{137}Cs) was 0.0131 in this study, and distinctively lower than in previous studies. Skarlou et al. (2003) reported that the TF of ^{134}Cs in two cultivars of corn ranged from 0.038-0.060 and 0.199-0.346 for seeds and vegetative parts, respectively, in a pot experiment using four Greek soils. Schneider et al. (2008) reported that the average TF value ('concentration ratio' in their study) for 14-19 corn hybrids was 0.0205-0.0260 and 0.0044-0.0059 in vegetation mass and grain of mature plants, respectively, in two-year field experiments conducted in the Tula region of Russia. After the FDNPP accident, the study by Kobayashi et al. (2013) mentioned above reported that the TFs for two corn cultivars were 0.256-0.263. Harada et al. (2014) investigated the TF for forage corn in plots to which contaminated farmyard manure (3,900 Bq/kg DW) had been applied at a rate of 44 t/ha, and calculated the TF of ^{137}Cs in corn to be 0.14. In comparison with that finding, the TF for corn in this study was relatively low, though in the range of TF (0.003-0.49) reported in the recent handbook of parameter values by IAEA (2010).

As for Italian ryegrass, the radioactive Cs concentration was 39.5 Bq/kg DW on average for the three tillage treatments, and average TF was 0.0254 in this study. In a previous study, Ølenschlæger and Gissel-Nielsen (1991) reported that the TF ('concentration ratio' in their study) for Italian ryegrass was 1.37-3.41 and 0.200-0.257 in sandy loam and organic soil, respectively. After the FDNPP accident, Harada et al. (2015) investigated ^{137}Cs concentrations of Italian ryegrass grown in 2011-2012 and 2012-2013 in the fields at NILGS, where four rates of farmyard manure had been applied from 2006 to 2010. The ^{137}Cs concentration in the soil was 895-998 Bq/kg DW, and the ^{137}Cs concentration in forage was 7-11 Bq/kg DW. As for data on another annual winter forage crop, Sunaga et al. (2015) reported that the radioactive Cs concentration (^{134}Cs+^{137}Cs) in the foliage of winter rye (*Secale cereale* L.) was 13.4-19.2 Bq/kg DW in fields where the Cs concentration in the soil was 1.35-1.85 kBq/kg DW. In comparison with said data, the radioactive Cs concentration in Italian ryegrass in this study was at the same level as reported by Harada et al. (2015) and Sunaga et al. (2015). However, the TF for Italian ryegrass obtained in this study was much less than that reported by Ølenschlæger and Gissel-Nielsen (1991), but in range of reported TF for grasses (0.0048-0.99) in the handbook of parameter values by IAEA (2010).

Thus, in this study, the radioactive Cs concentrations in plants and the TFs were relatively low in both corn and Italian ryegrass, as compared with previous studies. At the same time, the exchangeable K_2O content in the soil was relatively high in both experimental fields of Experiment 1 and Experiment 2 in this study. Many studies have reported that increased potassium in the soil reduces radioactive Cs concentrations in plants by preventing Cs uptake by the roots (Bange & Overstreet 1960, Shaw & Bell 1991, Alexakhin 1993, Nisbet et al. 1993, Buysse et al. 1996, Smolders et al. 1996, Smolders et al. 1997, Zhu & Smolders 2000, Frissel et al. 2002, Yamamoto et al. 2014; Harada et al. 2015, Harada 2015, Shinano 2015, Eguchi 2017). Frissel et al. (2002) showed that a higher TF was expected for radioactive Cs in cereal grains grown in soil with an exchangeable K content of less than 0.5 $cmol_c$/kgDW (equal to 0.235 g/kg DW as K_2O). After the FDNPP accident, an exchangeable K_2O content higher than 0.3, 0.3, and 0.3-0.4 g/kg DW in soil has been recommended as the critical soil potassium concentration to reduce Cs uptake by soybean, buckwheat, and perennial grasses, respectively (Shinano 2015, Harada 2015). Moreover, Harada et al. (2015) reported that the exchangeable K_2O level needed to reduce the ^{137}Cs concentration in corn would be around 0.3 g/kg DW. In their study, the ^{137}Cs concentration in corn appeared to increase when the exchangeable K_2O content was below 0.15 g/kg DW. Also in their study, the ^{133}Cs concentration in Italian ryegrass appeared to increase when the exchangeable K_2O content was less than 0.10 g/kg DW, though the effects of the exchangeable K_2O content of soil on ^{137}Cs uptake were not clear in Italian ryegrass (Harada et al. 2015). In our study, the exchangeable K_2O content of the soil in all soil layers for all three treatments after planting exceeded 0.34 g/kg DW and 0.32 g/kg DW in Experiment 1 and Experiment 2, respectively. This could be due to the continuous application of farmyard manure since 2005 in making said exchangeable K_2O content higher than the recommended values mentioned above. Thus, due to the high exchangeable K_2O content in the soil, radioactive Cs uptake by the roots was apparently restricted in all soil layers for all three tillage treatments, including the ST treatment in which 97%-98% of radioactive Cs and 81%-85% of root DW were concentrated in the surface layer (0 cm-10 cm).

In conclusion, the effects of tillage methods on the uptake of radioactive Cs by corn and Italian ryegrass were not clear in this study, as the radioactive Cs concentrations in plants and the TFs were relatively low in all three tillage treatments for both species. Moreover, mixing the surface soil was considered effective in reducing radioactive Cs transfer to plants, even in the shallow tillage treatment. In addition, the high exchangeable K_2O content in all three soil layers is apparently another reason why radioactive Cs transfer was restricted in all three tillage treatments in this study. However, further work is needed to confirm that radioactive Cs uptake can be reduced, regardless of plowing treatments when the exchangeable K_2O content in the soil is higher than the recommended level under other soil and climate conditions.

Acknowledgements

This study was supported in part by grants provided by Japan's Ministry of Agriculture, Forestry, and Fisheries. We are grateful to Dr. Yoshito Yamamoto, the former deputy director, and Dr. Kenji Okumura, director of the Division of Forage Crop Research of the NARO Institute of Livestock and Grassland Science (NILGS), for their helpful suggestions and critical reading of this manuscript. We also wish to thank Dr. Yoshihito Sunaga, senior researcher at NARO's Strategic Planning Headquarters, and Dr. Takeshi Shibuya, senior researcher of the NILGS Division of Grassland Farming, for their helpful suggestions, Ms. Junko Kawakami of NILGS for her assistance, and the staff of the Nasu Operations Unit at the NILGS Technical Support Center for their support during cultivation of the crops.

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