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Original Papers

Aging Effect of ^{137}Cs Obtained from ^{137}Cs in the Kanto Loam Layer from the Fukushima Nuclear Power Plant Accident and in the Nishiyama Loam Layer from the Nagasaki A-bomb Explosion

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We measured ^{134}Cs and ^{137}Cs in the surface soil of the Kanto loam in the eastern Tokyo metropolitan area and the Nishiyama loam in Nagasaki, Japan. The observed ^{137}Cs deposition in the Kanto loam from the Fukushima nuclear power plant (NPP) accident ranged from 4.0 to 77 kBq m^{-2}, which corresponds to 0.3 – 5 times of that in the Nishiyama loam. The ^{137}Cs retardation factor in the Kanto loam obtained seven months after the Fukusima NPP accident and in the Nishiyama loam after 36 and 38 years from the detonation of the Pu atomic bomb (A-bomb) ranged from 180 to 260 and 2000 to 10000, respectively. This difference in the retardation factors is attributed to an aging effect that corresponds to seven months and 36 to 38 years after the deposition of ^{137}Cs occurred on the soil minerals.

Keywords Fukushima nuclear power plant accident, cesium-137, Nagasaki A-bomb, aging effect, Kanto loam, Nishiyama loam, migration

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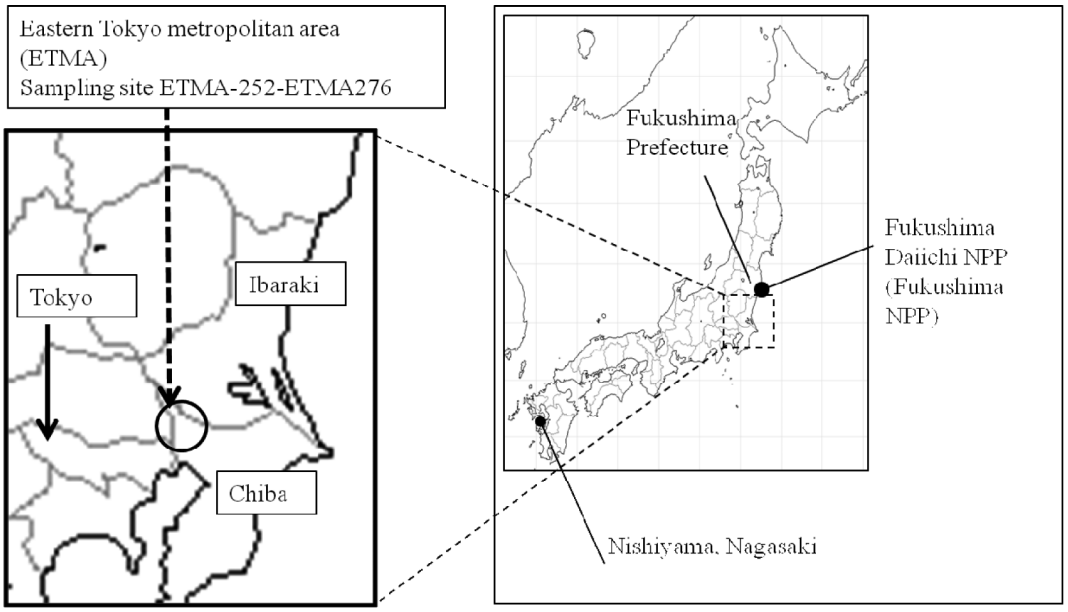
Introduction

The uptake of ^{137}Cs by plant roots is restricted in conjunction with the time after its deposition on surface soil. Fesenko *et al.*[1] reported on the soil-to-plant transfer factor (TF) of ^{137}Cs from the 1986 Chernobyl accident. The TF immediately reduced initially from 1987 to 1989, and further decreased by half approximately every one to two years. The reduction in root uptake is referred to as the aging effect.[1] The aging effect of ^{137}Cs is an important phenomenon when radioactive materials contaminate the surface soil and are uptaken by plants. To evaluate this effect, long-term observations of ^{137}Cs in soil are needed.

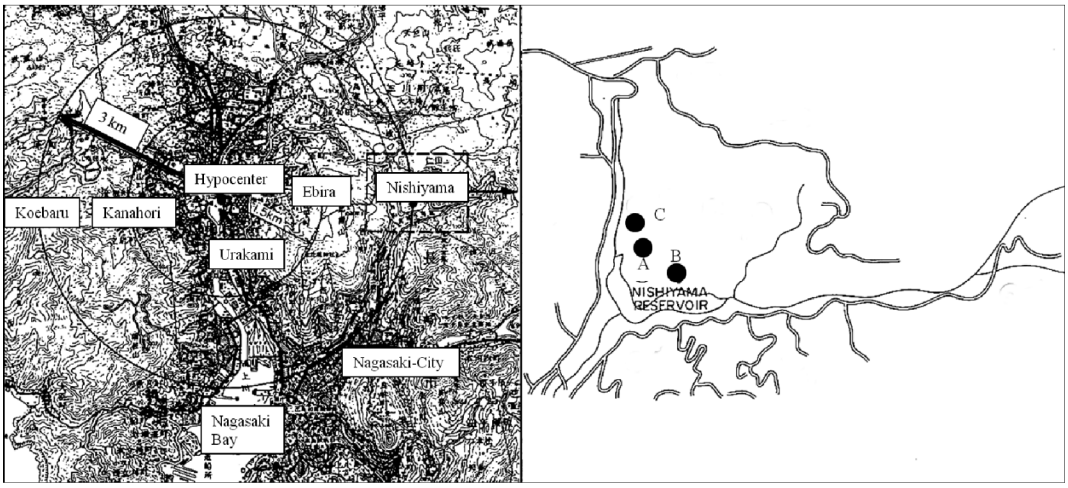
Japan has suffered three devastating nuclear disasters in the past 68 years: (1) the explosion at the Fukushima Daiichi nuclear power plant (NPP) on March 11, 2011, (2) the explosion of a uranium atomic bomb above Hiroshima City on August 6, 1945, and (3) the explosion of a plutonium atomic bomb (A-bomb) above Nagasaki city on August 9, 1945. Radionuclides were released into the atmosphere from the Fukushima Daiichi NPP on March 12, 2011.[2–10] Although the Tokyo metropolitan area, particularly the eastern Tokyo metropolitan area (ETMA; the area south of the Ibaraki Prefecture to the northwest of Chiba Prefecture), is located far from the Fukushima NPP site, high ^{137}Cs deposition was observed in these areas by airborne surveys (Nuclear Regulation Authority; NRA). According to the regional atmospheric dispersion and surface deposition of ^{137}Cs from 5 JST on March 12 to 0 JST on May 1, it is seen that a large amount of ^{137}Cs deposition was observed by airborne monitoring due to wet deposition in the Kanto region, especially in the south region of Ibaraki Prefecture to the northwest part of Chiba Prefecture from March 21 to 23.[11] On the other hand, on August 9, 1945, a plutonium A-bomb exploded 500 m above Urakami in Nagasaki city at 11:02 LT. Half an hour after the detonation, large quantities of fission products and unfissioned plutonium in the form of fallout reached the ground (the so-called black rain). The greatest Pu and ^{137}Cs depositions were found at Nishiyama in an eastern suburb of Nagasaki city, 2.8 km east of the hypocenter,[12-18] strongly suggesting that the local fallout was not deposited as dust or aerosol particles, but as precipitate.[16]

The Tokyo metropolitan area belongs to the Kanto loam region, which mainly consists of clays derived from weathered volcanic ash. The Nishiyama and Tokyo metropolitan areas are located in the Nishiyama and Kanto loam areas, respectively, and the soil of both areas is derived from volcano activity. Mahara and Miyahara[15] and Mahara[14] determined the relative contributions of the local fallout from the Nagasaki A-bomb and the global fallout from nuclear-weapon tests to the total concentration of ^{137}Cs, ^{90}Sr, and ^{239}Pu in the Nishiyama soil 36 and 38 years after the Nagasaki A-bomb. On the other hand, Igarashi *et al.*[19,20] studied the migration of stable Sr, Co, and Cs through the unsaturated Kanto loamy soil by using various field tracer experiments under the direct influence of natural rainfall and evapotranspiration. They evaluated the relationship between the characteristics of groundwater flow and stable nuclides. The

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(a)



(b)

Fig. 1 Sampling sites. (a) Map of ETMA sampling sites. (b) Map of Nagasaki and Nishiyama districts, locations of the soil sampling spots for ^{137}Cs content measurement. Circles: A, the location where a core of 0.3-m diameter and 2.25-m length was collected; B, the location where a core of 0.3-m diameter and 4.5-m length was collected; C, the location where a core of 0.1 m diameter and 0.3 m length was collected.

infiltration rates of stable Cs, Sr, and Co were found to be smaller than those of nonreactive tracers, such as D_2O and Br, and most of the injected Cs remained within 10 cm below the ground surface.

We obtained the content of deposited ^{137}Cs and the 10-cm-depth profile of ^{137}Cs in Kanto loam of the ETMA seven months after the Fukushima accident, and compared it to the vertical profiles of ^{137}Cs in the loam 36 – 38 years later after the detonation of the Pu A-bomb reported by Mahara and Miyahara[15] and Mahara.[14] Thus, we compared the aging effect on ^{137}Cs adsorption in the surface loamy soils of Nishiyama and the Tokyo metropolitan area. We focused on estimating the magnitude of aging effects based on the evaluated retardation factors of ^{137}Cs in the Kanto and Nishiyama loamy soils.

Experimental

Soil samples

Twenty-two undisturbed surface-soil core samples (5 cm $\phi \times 10$ cm) and one undisturbed soil sample (5 cm $\phi \times 5$ cm) were collected in the Kanto loam layer of the ETMA, on October 14 – 18, 2011, as shown in Fig. 1(a). The sampling area covers 18×20 km in the ETMA. The 0 – 5-cm and 5 – 10-cm undisturbed soil samples were collected using a stainless-steel core sampler (Daiki Co., Ltd.). The soil core samples were cut into 0 – 2.5, 2.5 – 5, and 5 – 10 cm long specimens. Each specimen was stored in its own plastic container. In addition, we collected three undisturbed soil cores

(cores A, B and C), which were 0.3 m in diameter, from the Nishiyama district of Nagasaki (map shown in Fig. 1(b)) in 1981 and 1984. Core sample A was a 2.25-m-long core taken in 1981 from point A, core sample B was a 4.5-m-long core collected in 1984 from point B, and core sample C was a 0.3-m-long taken in 1981 from point C. These points were observed to have heavy fallout deposits produced by the atomic bomb in 1945.[15] To prevent cross contamination, the soil cores were carefully excavated by hand from the center of a 0.5-m-diameter soil pedestal. The soil core samples (cores A, B, and C) were carefully quarried with a sharp knife from the 0.5-m-diameter pedestal. Detailed sampling methods are described in Mahara and Miyahara.[15]

We measured the total amount of ^{137}Cs in soil from 0 to 10 cm for the Kanto loam, from 0 to 40 cm for point A in Nishiyama, from 0 to 30 cm for point B in Nisiyama, and from 0 to 30 cm for point C in Nishiyama. The radioactivity of ^{137}Cs in soil sample in Nishiyama was reported by Mahara[14] and Mahara and Miyahara.[15]

Measurement of radioactivity in environmental samples by gamma-ray spectrometry

The radioactivity of the soil samples was measured using a p-type high-purity germanium detector (GMX40P4-76, ORTEC) with a 40% relative efficiency and a multichannel analyzer (MCA 7600-000, Seiko EG&G) with a high-voltage circuit and a pulse-height analyzer. To reduce the background counting rate, the detector was surrounded by four shielding materials: 100 mm of lead, 50 mm of old iron without any ^{60}Co, 5 mm of copper, and 5 mm of acrylic polymer resin. The gamma-ray counting efficiency of the detector was estimated by constructing a relative gamma-ray counting efficiency curve using a certified mixed-radionuclide gamma-ray reference source (MX033U8PP, Japan Radiation Association) containing ^{109}Cd (88 keV), ^{57}Co (122.1 keV), ^{139}Ce (165.9 keV), ^{137}Cs (661.7 keV), ^{88}Y (1836 keV), and ^{60}Co (1173 and 1332 keV). The radiation energies of ^{134}Cs and ^{137}Cs were 796 and 662 keV, respectively.

Analyses of retardation factor of the Cs-137 migration in surface loamy soil

The migration can be approximately estimated from the following one-dimensional advection-dispersion equation:

$$\frac{\partial C}{\partial t} = \left(\frac{D}{R}\right)\frac{\partial^2 C}{\partial Z^2} - \left(\frac{U}{R}\right)\frac{\partial C}{\partial Z} - \lambda C \tag{1}$$

where C is the concentration of ^{137}Cs in the soil water, D is the apparent diffusion coefficient, which is defined as $D = \alpha \cdot U + D^*$ using the longitudinal dispersivity, α, and the molecular diffusion coefficient, D^*, U is the average pore-water velocity of soil water, λ is the decay constant of ^{137}Cs, Z is the soil depth, t is time, and R is the retardation factor, which is the ratio of the movement of soil water to the migration rate of ^{137}Cs in the soil. Assuming that the input concentration of ^{137}Cs in the liquid phase at the ground surface decreases as the radioactivity decays from the source, the initial and boundary conditions for solving Eq. (1) are approximated as follows:

$$\begin{aligned} &C = 0 && Z > 0 \quad t = 0, \\ &C = C_0\exp(-\lambda t) && Z = 0 \quad t > 0, \\ &C = 0 && Z = \infty \quad t > 0, \end{aligned} \tag{2}$$

where C_0 is the initial ^{137}Cs concentration in the surface of the ground. The analytical solution of Eq. (1) with respect to Eq. (2) is given by Marino[21] as

$$C = \frac{C_0}{2}\exp(-\lambda t) \left[\exp\left(\frac{U'Z}{D'}\right)\mathrm{erfc}\left(\frac{Z+U't}{2\sqrt{D't}}\right) + \mathrm{erfc}\left(\frac{Z-U't}{2\sqrt{D't}}\right)\right] \tag{3}$$

where D' and U' are defined as $D' = D/R$, which is the dispersion coefficient of ^{137}Cs, and $U' = U/R$, which is the migration velocity of ^{137}Cs in an unsaturated soil layer. The average soil water movement rate, U, is estimated to be 1.5 m yr^{-1} for Kanto loam and 2.5 m yr^{-1} for Nishiyama loam by considering the natural tritium profile using the displacement flow model of Andersen and Sevel[22] and Shimada[23], and confirmed by a tracer test using Br^- on the Nishiyama site by Mahara and Kudo.[18] A value of 0.10 m^2 yr^{-1} for the Kanto loam and 0.12 m^2 yr^{-1} for the Nishiyama loam was used as the apparent soil water diffusion coefficient D in Eq. (3). The magnitude of the apparent soil-water diffusion coefficient was assumed to be the same as the *in situ* coefficient measured by Shimada[23] from the natural tritium concentration profile in the Kanto loam formation.

The magnitude of the ^{137}Cs retardation factor was determined by fitting to ratio of F/F_0 given by the following equation:

$$\frac{F}{F_0} = \frac{\int_0^Z c(z)\mathrm{d}z}{\int_0^L c(z)\mathrm{d}z} \tag{4}$$

Here, F is a total amount of ^{137}Cs stored in soil to a given depth of x ($0 < x \leq L$), and F_0 the total amount of ^{137}Cs accumulated to a depth of L, *i.e.*, L = 10 cm for the ETMA and 30 cm for Nishiyama. Since most of the injected stable Cs remained within 10 cm of the ground surface of unsaturated Kanto loamy soil near the present study area by using various field tracer experiments in the open-air conditions controlled by natural rainfall and evapotranspiration over 1 y,[20] assuming that 100% of ^{137}Cs exists to 10 cm corresponding to L of the ETMA, we used the radioactivity of ^{137}Cs in the soil from 0 to 5 cm and from 0 to 10 cm. On the other hand, ^{137}Cs in the soil from 0 to 10 cm, from 0 to 20 cm, from 0 to 30 cm were 96, 98, 99% respectively, in the Nishiyama in 1981; thus, it can be concluded that almost all remained within 30 cm of the surface 38 years after the nuclear disaster. Assuming that 100% of ^{137}Cs exists from 0 to 30 cm, corresponding to L of the Nisiyama, we used the radioactivity of ^{137}Cs range from 0 to 30 cm for cores A, B and C.

Results and Discussion

Comparison of ^{137}Cs deposition in the Kanto loam and Nishiyama loam

Table 1 gives the radioactive concentrations of ^{137}Cs and ^{134}Cs in the core sediments from the ETMA. The ^{137}Cs concentration in the core was 3.99 – 76.7 kBq m^{-2}, whereas airborne-survey measurements gave an estimate of 30 – 50 kBq m^{-2}, suggesting that the estimated deposition of ^{137}Cs is only an approximate value. As shown in Table 1, ^{137}Cs in this area is widely distributed. We studied the distribution of ^{137}Cs in this area. Figure 2 shows a contour map of the ^{137}Cs deposition, and a relief map of northern Japan. Figures 2(a) and 2(b) depict the contours of ^{137}Cs deposition according to the land morphology. Figure 2(c) shows the superimposed deposition of ^{137}Cs on the

Table 1 Concentrations of ^{137}Cs and ^{134}Cs in surface soil collected in Kanto loam

Sample No.	^{134}Cs/kBq m^{-2} [a]	^{137}Cs/kBq m^{-2}	$^{134}Cs/^{137}Cs$	Land utilization	Vegetation
ETMA-252	45.6 ± 0.3	45.9 ± 0.3	0.99 ± 0.01	Residential garden (lawn grass)	○
ETMA-253	50.5 ± 0.4	44.6 ± 0.3	1.13 ± 0.01	Bank	◎
ETMA-254	50.4 ± 0.6	58.0 ± 0.5	0.87 ± 0.01	Bank	◎
ETMA-255	9.29 ± 0.09	8.23 ± 0.07	1.13 ± 0.01	Field of grass	◎
ETMA-256	36.5 ± 0.2	37.1 ± 0.1	0.98 ± 0.01	Bank	◎
ETMA-257	11.0 ± 0.1	11.8 ± 0.0	0.93 ± 0.01	Field of grass	△
ETMA-258	9.35 ± 0.16	9.42 ± 0.14	0.99 ± 0.02	Field of grass	△
ETMA-259	56.8 ± 0.3	53.9 ± 0.3	1.05 ± 0.01	Field of grass next to resident	△
ETMA-260	37.6 ± 0.3	41.7 ± 0.2	0.90 ± 0.01	Field of grass	○
ETMA-261	28.1 ± 0.3	25.3 ± 0.3	1.11 ± 0.02	Side of road	◎
ETMA-262	19.7 ± 0.2	21.9 ± 0.2	0.91 ± 0.01	Side of road	○
ETMA-263	57.1 ± 0.6	57.2 ± 0.5	1.00 ± 0.01	Field of grass	△
ETMA-264	6.00 ± 0.07	5.65 ± 0.07	1.06 ± 0.02	Side of road	△
ETMA-266	7.76 ± 0.09	7.86 ± 0.07	0.99 ± 0.01	Field of grass	◎
ETMA-267	30.3 ± 0.1	28.2 ± 0.1	1.07 ± 0.01	Bank	◎
ETMA-268	25.5 ± 0.1	22.7 ± 0.1	1.06 ± 0.01	Bank	◎
ETMA-270	6.51 ± 0.09	7.61 ± 0.08	0.86 ± 0.02	Field of grass	○
ETMA-271	21.8 ± 0.2	23.3 ± 0.1	0.93 ± 0.01	Field of grass	◎
ETMA-272	4.07 ± 0.04	3.99 ± 0.03	1.02 ± 0.01	Side of road	○
ETMA-273	40.3 ± 0.3	37.0 ± 0.2	1.09 ± 0.01	Field of grass	△
ETMA-274	30.7 ± 0.3	29.1 ± 0.3	1.06 ± 0.01	Field of grass	◎
ETMA-275	84.9 ± 0.7	76.7 ± 0.6	1.11 ± 0.01	Field of grass	◎
ETMA-276	32.8 ± 0.4	30.6 ± 0.3	1.08 ± 0.02	Field of grass	◎

a. Concentration of radionuclide at 0:00 LT, 15 March 2011. ◎, Plenty of vegetation; ○, much vegetation; △, minimal vegetation.

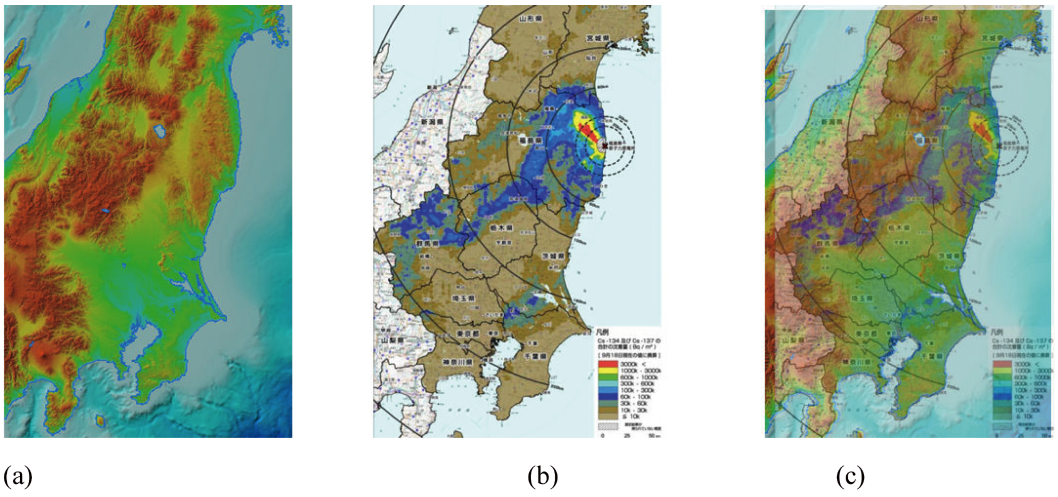


Fig. 2 Concentration of ^{137}Cs in surface soil and topographical map of northern Japan. (a) Topographical map of northern Japan. (b) Deposition of ^{137}Cs from airborne surveys referenced by NRA.[10] (c) Superimposed deposition of ^{137}Cs on the topographical map.

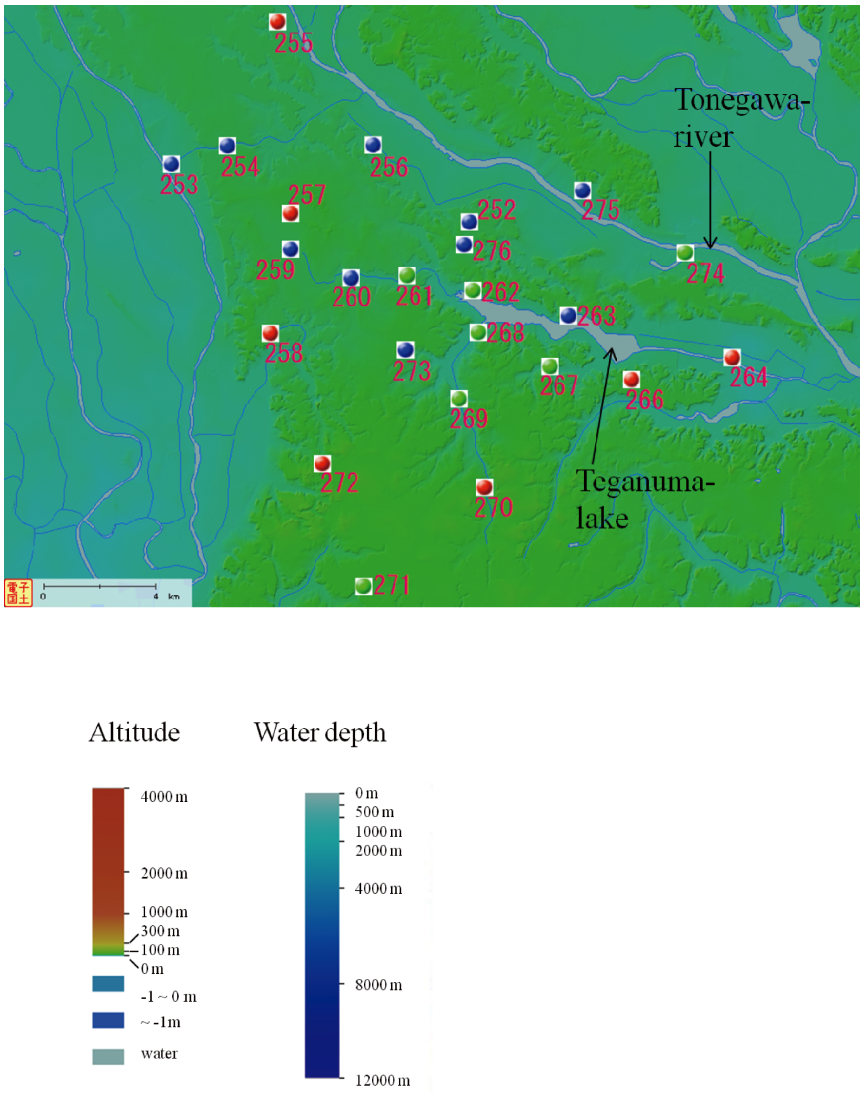


Fig. 3 Distribution of ^{137}Cs concentration in the study area and topographical map: ●, -15; ●: 15 - 30; ●, 30 - 80 kBq m^{-2}.

topographical map. Figure 3 shows the detailed distribution of ^{137}Cs (contour map) in the Kanto loam sampling sites. Although the ^{137}Cs distribution more or less follows the land morphology in this area, the relationship between the ^{137}Cs counter and land morphology might be unclear in the observed area of relatively low-pitched land morphology compared with steeply-pitched mountain areas, such as Gumma Prefecture and Tochigi Prefecture in Fig. 2(c). The deposition of ^{137}Cs in Fig. 2(b) other than the Tokyo metropolitan area is apparently controlled by the washout from the radioactive plume, and depends on the land morphology. Thus, the ^{137}Cs distribution in the ETMA is predominantly controlled by washout from the radioactive plume.

Table 2 lists local and global ^{137}Cs fallout and local ^{137}Cs fallout based on three cores obtained from Nishiyama, Nagasaki, in 1981 and 1984. The total fallout values of ^{137}Cs (local and global fallout) from points A, B, and C calculated in 1985 were 10.7, 14.4, and 11.0 kBq m^{-2}, respectively. The estimated average ^{137}Cs (local and global fallout) deposition at Nishiyama was 12.0 kBq m^{-2} in 1985 by Mahara.[14] According to Mahara,[14] the estimated ratio of the local fallout from the Nagasaki A-bomb to the global fallout from weapon testing was 1.0 in 1981. Therefore, the local fallout of ^{137}Cs from the Nagasaki A-bomb was 6.00 kBq m^{-2}. Finally, we estimated that 15.1 kBq m^{-2} of ^{137}Cs was deposited at Nishiyama, correcting for the radioactive decay in 1945.

Table 2 Concentrations of ^{137}Cs in surface soil core collected in Nishiyama loam

Sampling point	Point A	Point B	Point C
Local and global ^{137}Cs fall out /kBq m^{-2} (Observed value in 1985)	10.7	14.4	11.0
Local ^{137}Cs fallout /kBq m^{-2} (Observed value in 1985)	5.3	7.2	5.5
Local ^{137}Cs fallout/kBq m^{-2} (in 1945)[a]	13.4	18.1	13.9
Averaged value (in 1945)		15.1	
Sampling year	1981	1984	1981
Ref.	14, 15	14	15

a. This value corrected by radioactive decay from observed value in 1985.

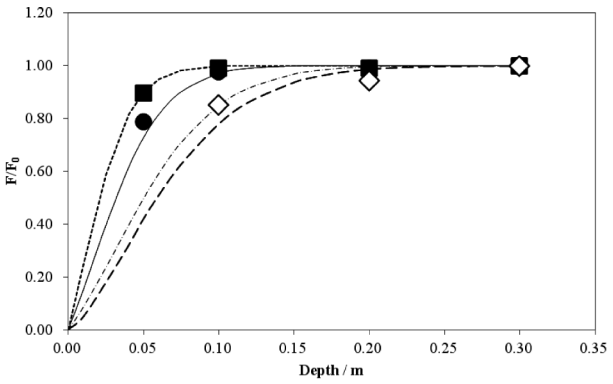
On the other hand, the Pu A-bomb was detonated 503 m above the city of Nagasaki on August 9, 1945. The estimated nuclear explosion energy was 22 ± 2 kt.[24] Since the number of fissions in 1 kt is 1.45×10^{23}, the total number of fissions from the A-bomb is calculated to be $(3.19 \pm 0.29) \times 10^{23}$.[25,26] The fission yield of ^{137}Cs is 6.6% of a 14-MeV fast neutron;[27] therefore, the estimated amount of the produced ^{137}Cs is $(2.1 \pm 0.2) \times 10^{23}$ atoms. One Becquerel (Bq) of ^{137}Cs is equivalent to 1.37×10^{9} atoms; therefore, $(1.53 \pm 0.20) \times 10^{2}$ TBq of ^{137}Cs was released by detonation of the Nagasaki A-bomb in the atmosphere. In contrast, the amount of ^{137}Cs released from the Fukushima NPP to the atmosphere is reported to be 15×10^{3} TBq.[28] Therefore, the amount of ^{137}Cs released was 100-times higher than the amount released from the detonation of the Nagasaki A-bomb. We assumed that ^{137}Cs and Pu were deposited at Nishiyama at the same rate as local fallouts, and that the deposition area was 100 km^2 (within a radius of 1 – 10 km from the detonation hypocenter, Kudo *et al.*[16]). Although the amount of Pu in the Nagasaki A-bomb is classified, Kudo *et al.*[13] estimated that the mass of Pu in the A-bomb ranged between the critical mass of 4.5 and 15 kg. Based on this estimated Pu amount, we assumed that the local deposition rate of ^{137}Cs was 0.25 – 1.0% of the total fission produced ^{137}Cs. Thus, the deposition of ^{137}Cs at Nishiyama was deduced to be between 3.8 and 15 kBq m^{-2}. The deposition rates observed at Nishiyama agreed with the calculated value by the detonation of the Pu-A-bomb. Consequently, the ^{137}Cs deposition in the ETMA was 3.99 – 76.7 kBq m^{-2}, which is 0.26 – 5.1 times as high as the deposition observed at Nishiyama.

Aging effect of the ^{137}Cs trap by soil

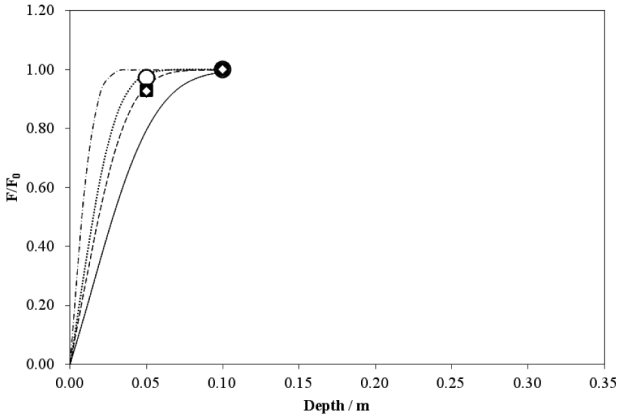
According to our calculations, approximately 2.3 kBq m^{-2} of ^{137}Cs was deposited from the global fallout in the Tokyo metropolitan area between 1957 and 2010 in Tokyo and Ibaraki,[29,30] this accumulation of ^{137}Cs was negligible compared with that from the Fukushima NPP accident. The estimated retardation factor was satisfied with the following conditions: the deposition of ^{137}Cs was more than 40 kBq m^{-2}, and was less affected by any biodisturbance and large grain size. The data of ETMA-252, ETMA-259, and ETMA-263 were selected from Table 1. Although ETMA-252 is on a lawn field, the roots are clearly shorter than 5 cm; therefore, the ETMA-252 data were acceptable to estimate the retardation factor. The ^{137}Cs retardation factors of Nishiyama varied from 2000 to 10000 to fit the *in situ* data in Fig. 4(a), whereas the retardation factors for the Kanto loam varied from 100 to 1000 in Fig. 4(b).

The ^{137}Cs retardation factor of the Kanto loamy soil obtained from ETMA-252, ETMA-259, and ETMA-263 were 257, 180, and 177, respectively, whereas those of Nishiyama loam 36 and 38 years after the Nagasaki nuclear atomic bomb disaster were 10000 for core B, 6000 for core A and 2000 for core C. The ^{137}Cs retardation factor of the soil in Nishiyama was 11 – 56 times higher than that in the Kanto loam. The difference between the retardation factors deduced from the 7-month interaction after the nuclear disaster and those estimated after approximately 40 years depends on the different elapsed times of interaction between ^{137}Cs and soil. The retardation factor will increase with increasing the length of the elapsed time, suggesting that this phenomenon will be caused by an aging effect. Therefore, these data indicate that the aging effects avoid to migrate ^{137}Cs in the soil downward, and assist the strong fixation of ^{137}Cs into soil matrix.

Table 3 lists the ^{137}Cs concentration in surface soil from the Kanto loam and the Nishiyama loam observed at each and 68 years after the 2 disasters. Judging from the left 2.92 – 3.94 kBq m^{-2} of ^{137}Cs in the Nishiyama, Nagasaki in 2011, 67 years after the nuclear disaster derived from Pu A-bomb, at least 0.869 – 16.7 kBq m^{-2} of ^{137}Cs corrected by radioactive decay in the ETMA will be remained after 67 year later without removing the surface soil. As ^{137}Cs of 0.9 – 17 kBq m^{-2} in surface soil of the Kanto loam will be strongly fixed into minerals by aging effects in 2-half lives of ^{137}Cs latter, uptake of ^{137}Cs by plant will be sharply limited in the future.



(a)



(b)

Fig. 4 Migration of ^{137}Cs in the Kanto and the Nishiyama loam soil. (a) Ratio of ^{137}Cs in the Nishiyama loam soil at 0 – 5, 0 – 10, 0 – 20, and 0 – 30 cm for point A and B, and at 0 – 10, 0 – 20, and 0 – 30 cm for point C when 100% of ^{137}Cs is within 30 cm. R: ·····, 10000; ——, 5000; – · –, 2500; - - - -, 2000. Point: ●, A; ■, B; ◇, C. (b) Ratio of ^{137}Cs in the Kanto loam soil at 0 – 5 cm and 0 – 10 cm when 100% of ^{137}Cs is within 10 cm. R: – · –, 1000; ·····, 300; - - - -, 200; ——, 100. ●, ETMA-252; ■, ETMA-263; ◇, ETMA-259.

Table 3 Concentrations of ^{137}Cs in surface soil in Kanto loam and Nishiyama loam

Sampling point	Nishiyama	ETMA
Deposition of ^{137}Cs/kBq m^{-2} (at nuclear disaster)	13.4 – 18.1 (1945 y)	3.99 – 76.7 (2011 y)
68 year after nuclear disaster	2.92 – 3.94 (2011 y)	0.869 – 16.7 (2078 y)
Ref.	14, 15	This work

a. This value corrected by radioactive decay.

Conclusions

We measured ^{137}Cs in the surface soil of the Kanto loam in the ETMA of metropolitan area, and compared the amount of ^{137}Cs from the Fukushima NPP accident in the Kanto loam soils with the local fallout levels of the Nagasaki Pu A-bomb at the Nishiyama loam in Nagasaki. The ^{137}Cs deposition in the 10-cm core soil samples of the Kanto loam ranged from 4.0 to 77 kBq m^{-2} (n = 23). In comparison, the estimated and observed ^{137}Cs deposition levels in the Nishiyama area were from 3.8 to 15 kBq m^{-2}. The ^{137}Cs deposition observed at the Kanto loam was 0.3 – 5 times compared with that observed in the Nishiyama loam.

The ^{137}Cs retardation factors in the loamy soil of the Kanto loam seven months after the accident ranged from 180 to 260, whereas the ^{137}Cs retardation factors in the Nishiyama loam after 36 to 38 years of the nuclear A-Bomb disaster were from 2000 to10000. The difference in the retardation factors between the Nishiyama and Kanto loams is probably caused by the different elapsed times after ^{137}Cs was deposited on the surface soil. Finally, our data indicate that the aging effect limits the migration of ^{137}Cs in the loamy soil.

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