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NOTE

Local variation of soil contamination with radioactive cesium at a farm in Fukushima

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Abstract

Radioactive cesium concentration in soil was measured at 27 sections with 5 points per section, and surface dose of ground was measured at 10 sections with 13 points per section at a farm in Fukushima to assess local variation of soil contamination with radioactive cesium. As for the cesium in soil, averages of the coefficient of variance (CV) and the maximum/minimum ratio in each section were 49% and 4.9, respectively. As for the surface dose, average of its CV in each section was 20% and the maximum/minimum ratio reached a maximum of 3.0. These findings suggest that exact evaluation of soil contamination with cesium is difficult. Small changes or differences in soil contamination may not be detected in studies of the environmental radioactivity.

Key Words: Cesium, Fukushima, Soil

The accident of Fukushima Daiichi Nuclear Power Station in March 2011 has caused environmental pollution with various radioactive materials in extensive regions of eastern Japan. The amounts of radioactive materials released to the atmosphere by this accident were estimated to be 11 EBq for ^{133}Xe, 160 PBq for ^{131}I, 18 PBq for ^{134}Cs, 15 PBq for ^{137}Cs, 3.2 PBq for ^{140}Ba, 0.14 PBq for ^{90}Sr, *etc.*[3]. Because of the long half-life and the enormous amount released, ^{134}Cs and ^{137}Cs will be the only radionuclides that contribute to the future exposure of human and animals virtually.

Radioactive cesium concentration in soil is basic information for the assessment of environmental contamination and the production of safe and secure agricultural products. We have been conducting a long-term survey on the radioactive contamination of environment in Fukushima since the spring of 2013, but the data of soil contamination fluctuated considerably within the samples collected at the same location

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(unpublished data). Saito *et al.* have conducted a large-scale survey and reported that the deposition density of radioactive cesium greatly varied with sampling locations[4]. These findings suggest that the distribution of radioactive cesium on the ground is uneven within relatively small area, however, it is unclear how much degree the variation of the contamination level is in a farmland.

In this study, therefore, radioactive cesium concentration in soil and surface dose of ground were measured in multiplicate at a farm located in the evacuation zone of the Fukushima disaster to assess local variation of soil contamination with radioactive cesium. In addition, distribution of radioactivity on the ground was visualized by a gamma camera.

This study was conducted at a farm (pasture and surrounding forest) in Namie town, Fukushima prefecture. This farm is 12 km away from the Fukushima Daiichi Nuclear Power Station, and designated as the “difficult-to-return zone” where the annual integral dose is 50 mSv or more. The farm was divided into 74 sections of 46 meters square using a free software, Kashmir-3D (DAN Sugimoto, http://www.kashmir3d.com) and GPS (eTrex30xJ, Garmin, Kansas, USA).

Soil samples were collected from appropriately selected 27 sections (pasture: 17, forest: 10) in September 2014. The sampling was conducted at 5 points per section (center, east, west, south and north points with 5 m distance) using a soil core sampler with liner tube (DIK-110C, Daiki Rika Kogyo Co., Ltd., Saitama, Japan). The liner tube was cut at 5 cm from the top of the core to collect the soil of 0–5 cm layer, because radioactive cesium is mostly retained in the upper 5 cm layer of soil[2,5]. The soil sample was blended well in a plastic bag, filled into the U9 polypropylene container and measured for ^{134}Cs and ^{137}Cs by a NaI scintillation spectrometer (AT1320A, Atomtex, Minsk, Belarus). The concentration of radioactive cesium in soil (Bq/kg) was converted into the deposition density on the ground (Bq/m^2). Ambient dose rate at 1 m high was measured by

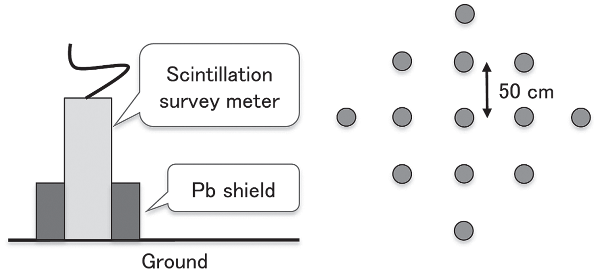

Fig. 1. Measuring method for the surface dose of ground (left) and the layout of 13 points surveyed (right).

an ionization chamber (ICS-323C, Hitachi Aloka Medical, Tokyo, Japan) at the center of the same sections.

Surface dose rate of ground was measured in 10 sections (pasture: 5, forest: 5) using a NaI scintillation survey meter (TSC-172, Hitachi Aloka Medical, Tokyo, Japan) equipped with a Pb shield of 2 cm thick. This shield cuts about 90% of the lateral incident gamma ray from ^{137}Cs. This survey meter was placed on the ground, and the surface dose rate was measured at 13 points within an area of 1 m radius in each section (Fig. 1).

Radioactivity distribution on the ground of this farm was photographed by a gamma camera equipped with 256 CdTe detectors (HGD-E2000, Hitachi Aloka Medical, Tokyo, Japan). The radiation image is smoothed and superimposed onto the optical photo.

Inter-sectional differences of the soil contamination and the surface dose of ground were examined by ANOVA. Coefficient of variance (CV), an index of relative variation, was compared by F test between the ambient dose and the soil contamination. A p-value less than 0.05 was considered statistically significant.

Total average of the soil contamination was 9.0 MBq/m^2. The average of 5 sampling points in each section ranged from 3.5 to 15.7 MBq/m^2 but there was no significant difference among sections (Table 1). The contamination level varied widely with sampling points within a section (Fig. 2). The average of its CV and the maximum/minimum ratio for five points in each section was 49% and

Table 1. Soil contamination, ambient dose and surface dose in each section

	Minimum	Average ± SD	Maximum
Contamination of soil (n = 5 × 27 sections)			
Average† (MBq/m^2)	3.5	9.0 ± 3.6*	15.7
CV† (%)	18.1	49.4 ± 21.6	94.1
Max/min ratio†	1.6	4.9 ± 4.1	19.0
Ambient dose (27 sections)			
1.0 m high (μSv/h)	12.6	21.2 ± 3.1*	25.4
Surface dose (n = 13 × 10 sections)			
Average† (μSv/h)	5.6	7.0 ± 1.1	8.6
CV† (%)	7.2	20.2 ± 6.4	30.7
Max/min ratio†	1.3	2.1 ± 0.5	3.0

† values were calculated within each section. *relative variation of the ambient dose was significantly smaller than that of the soil contamination ($p < 0.01$).

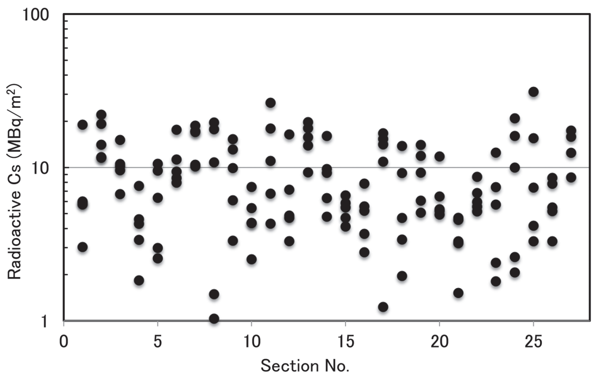

Fig. 2. Variation of the contamination level of soil in each section.

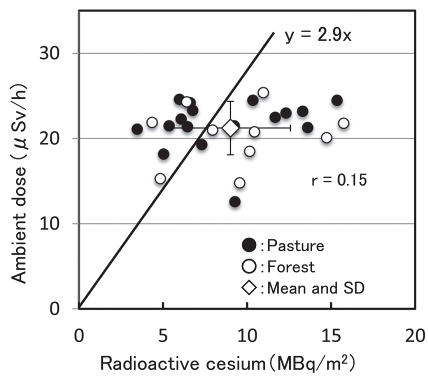

Fig. 3. Relationship between the ambient dose rate and the contamination level of soil. Solid line: relationship based on the conversion factor reported by IAEA (2000)

4.9, respectively (Table 1).

The average of the ambient dose (1 m high) measured at the center of each section was 21.2 μSv/h. The ambient dose also varied with sections but its variation was significantly smaller than that of the contamination of soil (Table 1). On the other hand, no significant correlation was observed between the ambient dose rate and the contamination level of soil ($r = 0.15$, Fig. 3).

The surface dose of ground was unequal even within small area of 1 m radius. The average of its CV in each section was 20% and the maximum/minimum ratio reached a maximum of 3.0 (Fig. 4, Table 1). The average of the surface dose of ground in each section was in a range from 5.6 to 8.6 μSv/h but there was no significant difference among sections.

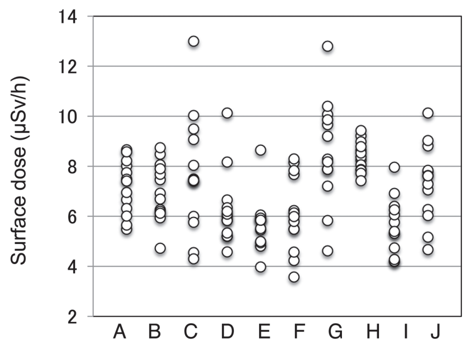

Fig. 4. Variation of the surface dose rate of ground in each section.

Fig. 5 shows the gamma-ray photographs taken at this farm. These are composite of optical black and white photo and gamma-ray intensity: the area expressed in red indicates that the

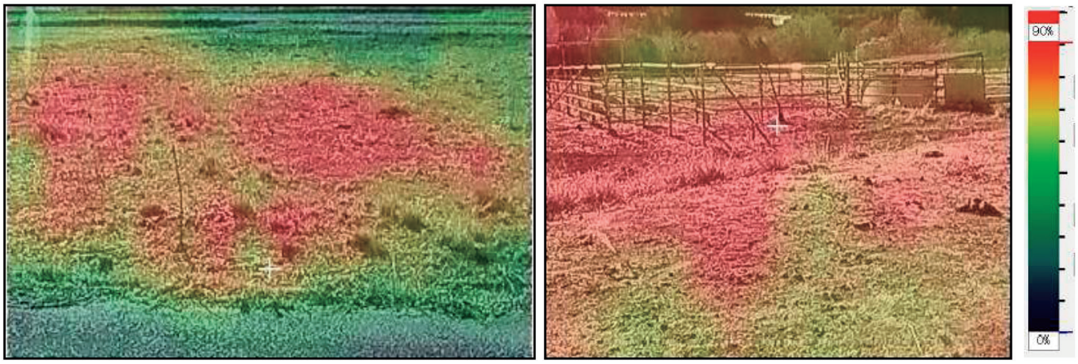

Fig. 5. Gamma ray photographs at this farm. The color expresses relative intensity of gamma ray.

radioactivity is relatively high. It was evident that radioactive cesium was distributed unevenly on the farmland.

This study demonstrated that the contamination level of soil greatly varies within small area. Uneven distribution of radioactive cesium diminishes the reliability of the assessment of soil contamination. The average CV of soil contamination was 49% in this study. This indicates that the 95% confidence interval of the population average is "sample average $\pm$ 61%" even though 5 samples were measured at one location. In other words, we need more than 25 samples to make the 95% confidence interval less than "sample average $\pm$ 20%". Therefore, exact evaluation of soil contamination is difficult, and small changes or differences in soil contamination may not be detected statistically in studies of the environmental radioactivity.

Saito *et al.* have reported that the average of CV for 5 soil samples per location (2,168 locations) was 36%, which is smaller than that of this study[4]. This difference results from the difference of sampling area. We collected 5 samples from an area of 7×7 m, but Saito *et al.* collected the samples from an area of 3×3 m. It is reasonable that the CV increases as the sampling area becomes large, because broad-based variation is added to the local variation.

Surface dose rate of ground measured by a survey meter with Pb shield reflects the amount of radioactive cesium just under the detector. Although vertical distribution of cesium in soil affects the measured value, this effect will not be so high because radioactive cesium in soil decreases exponentially with depth and is retained mostly in the upper 5 cm layer of soil[2,5]. The present result demonstrated that radioactive cesium contamination of soil varies even within extremely small area of 1 m radius. The smaller CV (20%) than that of the soil contamination (49%) is consistent with the explanation described above.

Ambient dose rate reflects the contamination level of soil. In this survey, however, there was no correlation between the ambient dose rate and the contamination level of soil (Fig. 3). Saito *et al.* have also reported that the correlation of the ambient dose rate and the contamination density of ^{137}Cs was not so good[4]. Because gamma-ray is scarcely absorbed by the air, radiation dosimeters indicate the average intensity of radiation emitted from wide area around the detector. Therefore, ambient dose rate may not be necessarily correlated with the local contamination level of soil.

Conversion factor from the contamination level of soil to the ambient dose rate is 5.4 μSv/h/(MBq/m^2) for ^{134}Cs and 2.1 μSv/h/(MBq/m^2) for ^{137}Cs[1]. The conversion factor at the sampling time was 2.9 μSv/h/(MBq/m^2) because the ratio of ^{134}Cs : ^{137}Cs was 1 : 3 in our soil samples. The overall average of our observed values approximately corresponded to the theoretical relationship between the ambient dose rate and the contamination level of soil based on this conversion factor (Fig. 3). This suggests that the average level of soil contamination can be roughly estimated by measuring the ambient dose rate at several points in the target area. The value estimated by the ambient dose rate might be more reliable than the value measured actually with soil samples, because variation of the ambient dose rate was smaller than that of the contamination level of soil.

Acknowledgments

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