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Vertical distribution of radiocesium affects soil-to-crop transfer coefficient in various tillage systems after the Fukushima Daiichi Nuclear Power Plant accident

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ABSTRACT

After the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident in March 2011, radiocesium (^{134}Cs and ^{137}Cs) released into the atmosphere contaminated soil across a large part of northeastern Japan. In croplands, moldboard plow and rotary tillage systems redistribute the radiocesium to deeper layers, lowering the level of contamination. However, the long-term effects of tillage on radiocesium contamination of crops and the form and distribution of radiocesium in the soil after continuous tillage remain unclear. We investigated the distribution of radiocesium in soil and changes in plant uptake in organic soybean fields in Ibaraki (~170 km from FDNPP) to clarify the tillage effect on radiocesium uptake while controlling contamination level. From 2011 to 2015, soybeans and winter cover crops (fallow weeds, rye, and hairy vetch) were cultivated using three tillage systems (moldboard plow/rotary harrow, MP; rotary cultivation, RC; and no tillage, NT). Radiocesium contamination in soil, and plant uptakes were considerably lower in 2012 compared with the first year of the accident in 2011. Four and 5 years after the accident, the NT treatment showed the highest absorption of radiocesium by soybeans and highest radiocesium deposit density in cover crops. Cover crop radiocesium contamination was significantly correlated with aboveground biomass. Soil surface (0–2.5 cm) radiocesium contamination in NT was significantly higher than at other depths and in other tillage treatments. A similar trend was observed in exchangeable radiocesium in the soil profile, although the values were only 23.9–48.0% (2014) and 32.6–71.9% (2015) of radiocesium in the soil. A positive correlation was also observed between exchangeable radiocesium at the soil surface and soybean radiocesium contamination, but this relationship was not observed for cover crop radiocesium contamination. The transfer factor (TF) of soybean grain and residue was highest in the NT treatment. The TF based on exchangeable cesium (eTF) was particularly high. Cover crops showed different TF and eTF values, but rye always had the lowest values. Soybean radiocesium contamination was higher in NT than in MP and RC. TF of soybean was significantly correlated with the depth of the vertical distribution of both radiocesium and exchangeable cesium. This research revealed that the TF value was significantly influenced by plant biomass accumulation and the soil radiocesium distribution.

1. Introduction

The total amounts of ^{137}Cs and ^{131}I released in Fukushima Prefecture due to the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident triggered by a magnitude 9.0 earthquake and the resulting tsunami on 11 March 2011 were estimated to be approximately 1.5×10^{17} Bq and 1.3×10^{16} Bq, respectively (Chino et al., 2011). Agricultural soils were highly contaminated by the radionuclides deposited after the FDNPP accident, and the distributions of these nucleotides in soil have been investigated (Harada and Nonaka, 2012; Kato et al., 2012; Shiozawa et al., 2011).

In agricultural land, however, tillage inversion redistributes the surface soil to the deep soil layer and creates a non-uniform distribution pattern. Therefore, the radiocesium depth distribution in cultivated soils depends on the tools used for mechanical soil manipulation (such as a moldboard plow [MP] or rotary cultivator [RC]). Harada and Nonaka (2012) measured the radiocesium distribution in a paddy field; higher concentrations of radiocesium generally existed in shallow soils, but tillage inversion displaced the radioactive materials at the soil surface to deeper soil layers. Hoshino et al. (2015) also reported that no-tillage (NT) left a large concentration of radiocesium (^{134}Cs + ^{137}Cs) in the 0–2.5 cm soil layer (1324.8 Bq kg^{-1}), whereas MP and RC

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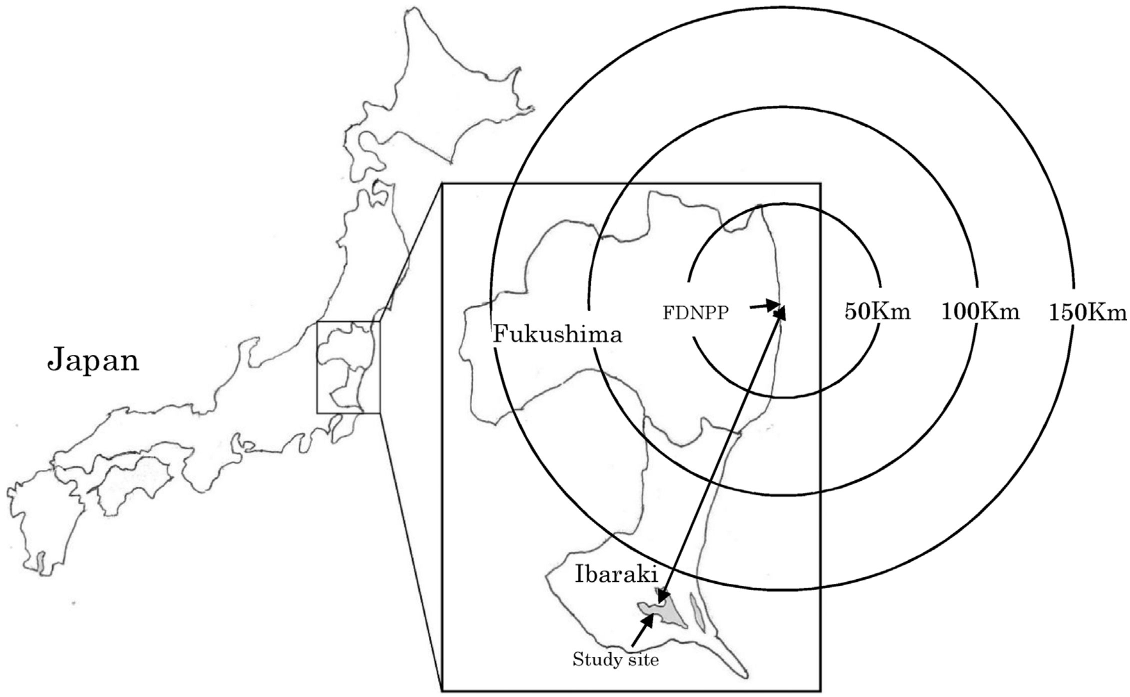

Fig. 1. Location of the test field in Ami, Ibaraki Prefecture. The test field is 170 km southeast of the Fukushima Daiichi Nuclear Power Plant.

reduced the radiocesium contamination at the soil surface (to 509.7 and 782.7 Bq kg^{-1}, respectively).

These radiocesium distribution changes were strongly associated with soil vertical translocation due to tillage inversion. Ito et al. (2015) studied the effects of tillage on nematode distributions from 2009 to 2011 and reported that over 85% of the total radiocesium deposited in 2011 was in the 0–2.5 cm soil layer. After tillage, MP enhanced mixing of the surface soil into deeper layers, with 21% of the surface soil mixed within the 2.5–7.5 cm layer, 19% within the 7.5–15 cm layer, and 52% within the 15–30 cm layer. RC incorporated 43% of the surface soil within the 2.5–7.5 cm layer and 35% within the 7.5–15 cm layer. As expected, no changes in the soil distribution were noted in the NT treatment. Few studies, however, have examined radiocesium distribution changes after the FDNPP accident, particularly under conditions of repeated tillage inversion in agricultural ecosystems.

The chemistry of ^{137}Cs in soil is well understood (Davis, 1963; Schulz et al., 1960; Yamaguchi et al., 2012a; Yamaguchi et al., 2012b). After an initial deposition of radioactive material on the soil surface, immediate and strong adsorption of ionized cesium (Cs) onto clay particles occurs (Staunton and Roubaud, 1997; Tamura, 1964). Soil with high concentrations of exchangeable Cs tended to enhance Cs uptake in rice (Tsumura et al., 1984). Thus, soil Cs availability is a significant factor determining Cs uptake.

Although Cs is a cation that binds strongly with soil, increased exchangeable Cs in the soil may enhance uptake by crops, as reported by Tsumura et al. (1984) in rice. On the other hand, Cs and potassium (K) are both group I metals and are thus easily taken up by plants (Absalom et al., 1999; Yamaguchi et al., 2012a; Yamaguchi et al., 2012b). Therefore, it is important to understand the effects of soil K availability in combination with exchangeable Cs in the soil. Because K competes with ^{137}Cs in the transfer process from soil solution to plant body (Shaw and Bell, 1991; Smolders et al., 1997), K fertilizer application and other farming practices can reduce radiocesium contamination in crops (Kato et al., 2015; Lembrechts, 1993). For example, Wakabayashi et al. (2016) reported that short-term flooding reduced the radiocesium uptake by rice by increasing the exchangeable K in a paddy field. Tillage and cover crop residue also promote K availability in the soil. In a study of long-term tillage management, Deubel et al. (2011) reported that NT increased the K concentration in the uppermost soil layer, although plant K uptake was not increased. Radiocesium and K dynamics in agroecosystems differ depending on the soil management scheme. However, there is little information available regarding the relationship between soil inversion by tillage and the distribution of exchangeable radiocesium in the soil. In addition, the effects of different tillage systems on exchangeable Cs and K distribution and radiocesium contamination in soybean plant tissue have not been investigated since the FDNPP accident occurred.

The transfer factor coefficient (TF) from soil to crop in Japan after the FDNPP accident has been examined for paddy rice (Endo et al., 2013), forage crops, and soybean (Takeda et al. 2014). The TF values were 1.5×10^{-2} to 7.2×10^{-3} for soybean, suggesting relatively high TF values compared with those of other vegetable and field crops. Soil management practices also affect TF values. For example, Rigol et al. (2008) reported the TF values after the Chernobyl accident in various soils subjected to several agricultural treatments (disking, ploughing, fertilizing, and liming). Hoshino et al. (2015) noted that NT plots showed significantly higher TF values compare with MP and RC plots. However, the reason why the NT condition showed higher TF values remains unclear.

The aim of this study was to investigate the vertical redistribution of radiocesium after soil tillage inversion as related to exchangeable radiocesium distribution. We also examined the relationship between the depth of the contaminated layer buried with little mixing soil radiocesium distribution and the uptake by soybean and cover crops.

2. Materials and methods

2.1. Study site

This experiment was conducted from 2014 to 2015 at a field study site (36°1′57.7″N, 140°12′43.6″E) located 170 km from the FDNPP in the Kanto region of Japan (Fig. 1). The site is in the humid subtropics; the mean monthly temperature and monthly precipitation ranged from 3.6 to 26.6 °C and from 21.0 to 314.0 mm (1389 mm year^{-1}) during the study period (Fig. 2). According to the national survey regarding radiocesium in 1999, ^{134}Cs was not detected in the soil in Ibaraki