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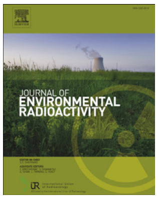

Measurement and estimation of radiocesium discharge rate from paddy field during land preparation and mid-summer drainage

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ABSTRACT

In this research, we evaluated the range of ^{137}Cs discharge rates from paddy fields during land preparation and mid-summer drainage. First, we investigated ^{137}Cs discharge loads during land preparation and mid-summer drainage and their ratio to the ^{137}Cs inventory of paddy field soil. We found that total discharge rates were 0.003–0.028% during land preparation and 0.001–0.011% during mid-summer drainage. Next, we validated the range of obtained total discharge of ^{137}Cs from the paddy fields using a simplified equation and literature review. As a result, we conclude that the range of total outflow loads of suspended solids for the investigated paddy field was generally representative of paddy fields in Japan. Moreover, the ^{137}Cs discharge ratio had a wide range, but was extremely small relative to ^{137}Cs present in paddy field soil before irrigation.

1. Introduction

Large amounts of radioactive substances were released into the atmosphere by the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident, and have spread over a wide area of land and ocean centered on Fukushima Prefecture (Chino et al., 2011). Many studies on environmental dynamics of radioactive substances deposited on farmland, grassland, forest and ocean were conducted after the Chernobyl nuclear power plant accident (IAEA, 2006). However, investigation of the dynamics of radiocesium (^{137}Cs and ^{134}Cs) associated with highly contaminated paddy fields, a unique land use in the Asian monsoon region, has just begun after the FDNPP accident. Because paddy fields cover 7% of Fukushima Prefecture, it is important to evaluate the annual discharge rate of radiocesium and impact of paddy field cultivation on environmental dynamics of radioactive substances, through water use and soil disturbance information of paddy field cultivation.

Tanaka et al. (2013) and Yoshikawa et al. (2014) indicated that ^{137}Cs flowing into paddy fields from irrigation water contributed only 0.02–0.05% of the ^{137}Cs inventory in paddy field soil caused by atmospheric fallout following the accident. Yoshikawa et al. (2014) calculated the ^{137}Cs discharge load from paddy field using ^{137}Cs concentrations in suspended solid (SS) and hydrological data for discharged water. They estimated the annual discharge rate of ^{137}Cs from paddy fields as 0.2–0.7% of the ^{137}Cs inventory in soil. However, there are few reports of radiocesium discharge load variation during major drainage events associated with water management.

Typically, rice cropping is done only once per year in Japan, and during an irrigation season there are two major events in which large amounts of turbid water are drained from paddy fields: land preparation and mid-summer drainage, which are carried out in mid-April through the beginning of May and at the end of June through mid-July, respectively. Discharge loads of substances such as nitrogen, phosphorus and soil from paddy fields have mainly been observed during land preparation before rice planting rather than mid-summer drainage (Hama et al., 2006; Shimizu and

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Matsui, 2008; Somura et al., 2009; Sudo et al., 2009; Wakai et al., 2005). The land preparation involves paddy field irrigation with large volumes of water and tilling of the plowed layer (0–15 cm) during maintained flooding. The objective of land preparation is to reduce permeability of the soil, restrain soil hardness, mix fertilizer and soil in the plowed layer, and level the land to make it suitable for rice planting. Generally, paddy water is not drained during land preparation tillage but several days after land preparation, to adjust water depth so it is suitable for rice planting by machines. Paddy water is also temporarily drained during mid-summer to dry the field for supplying oxygen to the soil to promote rice growth. It was found that with muddy water discharge during land preparation and mid-summer drainage, most substances such as nitrogen and phosphorus released from the fields were in particulate rather than dissolved form (Kondo, 2012).

Wakahara et al. (2014) demonstrated that total ^{137}Cs discharge ~~over time~~ during land preparation was 0.6–1.0% of the ^{137}Cs inventory in paddy soil. However, their observation was of nonstandard management of paddy fields; i.e., drainage continued during land preparation tillage. Consequently, SS runoff load was substantially greater than paddy fields managed in a common way, in which there is little leakage during tillage (Sato and Taguchi, 2000). Therefore, ^{137}Cs runoff was potentially overestimated. This suggests that the amount of radiocesium runoff depends on the manner of water management.

The magnitude of radiocesium runoff from paddy fields depends not only on the manner of water management but also on differences in inventory of radiocesium and/or soil texture. To acquire general values of radiocesium discharge load from paddy fields, investigation of a large number of fields with a wide range of characteristics is necessary.

In this research, we conducted measurements of ^{137}Cs discharge loads during land preparation and mid-summer drainage and their ratio to the ^{137}Cs inventory of paddy field soil. First, we measured in detail the actual ^{137}Cs discharge load/ratio from six paddy fields managed by the common method of land preparation and mid-summer drainage. Then, we developed an equation for estimating the ^{137}Cs discharge ratio based on the data obtained. Finally, we evaluated the range of total ^{137}Cs discharge from the paddy fields using a simplified equation and literature review.

2. Material and methods

2.1. Study area

Field survey areas were in Ten-ei Village and Minamisoma City, which are 80–90 km east and 20–30 km north of the FDNPP, respectively, in Fukushima Prefecture (Fig. 1). The deposition density of ^{137}Cs in August 2011 was estimated at 100–300 kBq m^{-2} in Ten-ei Village and 60–100 kBq m^{-2} in Minamisoma City (MEXT, 2011). We selected six paddy fields (three in each area, Paddy A-F) as study sites. The exact locations of the surveyed paddy filed are in Table 1 together with survey date and other information. Rice has been continuously cultivated in Ten-ei Village since the FDNPP accident. However, this cultivation restarted in 2013 in the surveyed paddy fields of Minamisoma City after decontamination work by the Ministry of Agriculture, Forestry and Fisheries. Soil of the paddy fields at Ten-ei Village and Minamisoma City are classified as fine gray lowland soil and gravelly gray lowland soil, respectively (National Institute for Agro-Environmental Sciences, 2010).

2.2. Field survey methods

The field survey included (a) sampling of paddy soil, (b) sampling of discharge water, and (c) measurement of discharge water volume during land preparation and mid-summer drainage periods.

Soil samples were obtained from the plowed layer (0–15 cm) in each paddy field before irrigation. Soil was sampled at three points in each field, near the water inlet, water outlet and center (Fig. 2), using soil samplers (5 cm diameter × 30 cm long; HS-30, Fujiwara Scientific Company, Tokyo, Japan).

Two liters of drainage water flowing through the outlets were collected at 1, 2, 3, 4, 5, 10, 30, 60 and 120 min from the start of surface drainage and at the end of drainage, during both the land preparation and mid-summer drainage periods. Since the land preparation drainage continued for more than 120 min in Paddy D_2013 and F, we also collected drainage water sample at the end of drainage. There was no mid-summer drainage in paddies A, E and F because of their small ponding depths.

To monitor water outflow from paddy fields, water level sensors (HM-900; Hi-net Co. Ltd., Tokyo) were installed near the water outlets of each field (Fig. 2). Water depth of the fields was recorded at 1-min intervals during the land preparation and mid-summer drainage periods. Drainage boxes (Haisuikou 150, Shinwa Co. Ltd., Niigata, Japan) were installed at water outlets for calculating paddy field discharge (Fig. 2).

2.3. Sample pretreatment and measurement of ^{137}Cs

Soil samples from depths 0–15 cm were dried for 24–48 h at 80 °C, mixed well using a mill. Parts of samples were put into plastic containers (U-8 container: diameter = 47 mm, height = 60 mm) to measure radiocesium using a Ge detector.

Each water sample was passed through a 0.45-μm pore membrane filter (A045D047A, Advantec Toyo Roshi Kaisha Ltd., Tokyo) to separate dissolved and particulate fractions. After this filtration, the filters were cut into 2-mm pieces and placed in a U-8 container.

We measured and evaluated only particulate ^{137}Cs runoff from the paddy fields. This was because the activity concentration of dissolved ^{137}Cs is much lower than particulate ^{137}Cs, owing to its large distribution coefficient (Konoplev et al., 2016; Nagao et al., 2013; Tsuji et al., 2014). Here, in environmental water with high SS concentration (>100 mg L^{-1}), the ratio of dissolved to particulate ^{137}Cs was estimated at 3% (Ueda et al., 2013). Although the contribution of dissolved ^{137}Cs in drained water with low SS concentration (<100 mg L^{-1}) was greater than that with high SS concentration, it is believed that the contribution of dissolved ^{137}Cs to total ^{137}Cs runoff is small.

The ^{137}Cs concentration of samples was measured by gamma-ray spectrometry using Ge detectors (SEG-EMS GEM20-70 and GEM35-70, Seiko EG&G Co. Ltd., Tokyo). These detectors were calibrated using radioactivity standard gamma volume sources (MX033U8PP, Japan Radioisotope Association). Concentrations measured in each soil sample were decay-corrected to 1 April 2014.

The ^{137}Cs runoff load/ratio from the paddy fields was investigated based on the data obtained. The ^{137}Cs runoff load was calculated by Eq. (1) and the runoff ratio by Eq. (2). For application of Eq. (1), *SS* and *pCs* values every minute were obtained by linearly interpolating the observation results:

$$Y_{total} = \sum_{t=1}^{n} \left(SS(t)\, Q_{flow}(t)\, pCs(t) \right), \tag{1}$$

where Y_{total} is total ^{137}Cs discharge (Bq ha^{-1}), SS is concentration of suspended substances (kg L^{-1}), Q_{flow} is water discharge (L ha^{-1}), pCs is ^{137}Cs concentration in drained SS (Bq kg^{-1}), t is elapsed time from the start of surface drainage (min), and n is elapsed time at the end