RADIOCESIUM CONCENTRATION IN STEMS, LEAVES, AND PANICLES OF RICE GROWN IN A SANDY SOIL REPLACEMENT PADDY FIELD TREATED WITH DIFFERENT RATES OF CATTLE MANURE COMPOST IN KAWAMATA, FUKUSHIMA

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Removing soil surface is an effective method to reduce radioactive cesium (137Cs) in the contaminated agricultural land but this can result in the loss of soil fertility. Our experimental paddy field in Kawamata-town, Fukushima had the surface soil removed and replaced by sandy soil. The cattle manure compost was used to improve soil fertility. The objectives of this study were to determine the effects of cattle manure compost application at rates of 0 (control), 10, 20 and 40 t ha⁻¹ on rice yields and on 137Cs transfer to stems, leaves and panicles of rice in 2015. Results showed that rice yields were increased with rates of cattle manure compost. Application of cattle manure compost caused the increase of exchangeable potassium (K) in the soil, resulting in reduction of 137Cs in rice parts. The 137Cs concentration was higher in stems than in leaves and was not detected in panicles.

The 137Cs concentration in the aboveground parts of rice was decreased to the lowest (TF = 0.009) in soil that received 20 t ha⁻¹ of cattle manure compost, which was 2.4 times lower than that in the control. The transfer factor of 137Cs (TF) in aboveground parts of rice was negatively correlated with exchangeable K in the soil. The ratio of 137Cs/K was higher in stems than in leaves and that was related to the concentration of exchangeable Ca, and Mg in the soil. The results indicated that exchangeable K, Ca and Mg derived from cattle manure compost affected the uptake and distribution of 137Cs in rice plants.

Key Words: 137Cs, rice, soil fertility, sandy soil replacement, cattle manure compost

1. INTRODUCTION

On 11 March 2011, a major earthquake followed by a huge tsunami hit wide areas of northeast Japan. Due to this event, the Fukushima Daiichi Nuclear Power Plant (FD1NPP) was damaged, causing large amounts of radionuclides including 137Cs (half-life, 30.2 years, emission of β and γ rays during the decay)
to be released to the atmosphere subsequently deposited on the ground \(^1\). The \(^{137}\)Cs can enter the human body through contaminated foods \(^2\). Food crops produced in \(^{137}\)Cs contaminated land are the main pathway for \(^{137}\)Cs ingestion in human \(^3\).

After the FD1NPP accident, the Ministry of Agriculture, Forestry, and Fisheries (MAFF) proposed three methods for recovering the contaminated agricultural lands \(^4\); (1) removal of top soil, (2) mixing the soil with water and separating fine particles, and (3) reverse tillage. Removal of top soil seems to be an effective method, as the major portion of \(^{137}\)Cs is fixed in the top soil layer \(^5,6,7\). In our study area, Kawamata-town, Yamanichi et al. \(^8\) reported that \(^{137}\)Cs was fixed in the top 1 cm of the soil. Based on the above articles, removing the top 0-15 cm layer is estimated to remove more than 80% of the \(^{137}\)Cs from the land \(^9\). However, it is impossible to remove 100% of \(^{137}\)Cs from the soil, since some small amount may have been absorbed in the deeper layers. According to Ohse et al. \(^10\) after removal of the 0-10 cm soil layer, approximately 25% of the original cesium remained in the deeper layers. Therefore, reduction of \(^{137}\)Cs uptake by crops through soil management is necessary.

For agricultural lands, removing surface soil is an effective method to reduce \(^{137}\)Cs content in the soil, but this may result in a loss of soil fertility. Improving the soil after the removal is thus necessary. Application of organic matter such as rice straw and cattle manure compost are possible options because of their low cost and high potential for soil improvement. According to Nishiwaki et al. \(^11\) using rice straw and cattle manure compost to recover soil productivity after removal of surface soil, successfully increased rice production. However, the authors found that application of manure compost caused radiocesium increases in the soil, because the manure compost was also contaminated by radiocesium \(^12\). Cattle manure compost is low cost fertilizer with high plant nutrients, particularly potassium (K) \(^12,13\). It is well known that potassium effectively reduces \(^{137}\)Cs uptake by plants \(^14\).

To obtain more information concerning the effects of cattle manure compost application on \(^{137}\)Cs in soil and rice, we conducted a field experiment in Kawama-town, Fukushima prefecture. The experimental paddy field had been decontaminated by removing the soil surface followed by replacement with sandy soil. Cattle manure compost was subsequently applied before rice planting. The objectives of this study were to determine the effects of various rates of cattle manure compost application on rice yields and on \(^{137}\)Cs distribution in stems, leaves, and panicles of rice plants.

## 2. MATERIALS AND METHODS

### (1) Experimental field and treatments

The experimental field was located in Kawamata-town, approximately 50 km northwest of the FD1NPP. The field is bordered by a water way on the north side and a water drainage canal on the south side. The field has an area of 0.48 hectare (ha) and is divided into four plots, each measuring 15 x 80 m. Before the experiments, surface soil had been removed and then replaced with sandy soil.

In each plot, cattle manure compost was applied at 0 (control), 10, 20 and 40 t ha\(^{-1}\), and tillage was done before planting rice (\textit{Oryza sativa} L., cv. Akitakomachi). Twenty-three days old rice seedlings were transplanted with a spacing of 18 x 25 cm on 27 May and harvested in October 2015.

### (2) The chemical fertilizer and irrigation

The chemical fertilizers, KCl (K = 40 kg ha\(^{-1}\)) and N-P-K (N = 65, P = 87, K = 65 kg ha\(^{-1}\)) were added for all plots. The field was irrigated with an irrigation system. After the transplant of rice, the field had been water logged until harvest.

### (3) Cattle manure compost and \(^{137}\)Cs

The cattle manure compost was made from the milk-cow manure mixed with rice husk and fermented over 6 months. The \(^{137}\)Cs concentration of compost was less than 400 Bq kg\(^{-1}\). Chemical components of compost are shown in Table 1.

### (4) Soil and rice sampling

We collected soil and rice samples at harvest on 5 October 2015. In each plot, we collected soil samples at three points with two layers (0-5 and 5-10 cm) using soil core. Rice samples were collected from three points in each plot, and at each sampling point we cut the aboveground parts of rice plants in a 1 m\(^2\) sector. Rice samples were separated into three parts: stem, leaf, and panicle. All samples were oven dried at 75 or three days. The dried rice was ground into powder before the chemical analyses and \(^{137}\)Cs measurement.

| Analyzed factors | Dried weight bases |
|------------------|--------------------|
| Total-N (%)      | 1.2                |
| Total-C (%)      | 39.7               |
| P\(_2\)O\(_5\) (%)| 0.86               |
| CaO (%)          | 1.3                |
| MgO (%)          | 0.6                |
| K\(_2\)O (%)     | 3.13               |
| Ash (%)          | 24.6               |

Data was provided by Fukushima Prefecture.
(5) Rice yield component measurement
At the harvest, 12 hills (in average) at each sampling point were collected. Grain yield was measured by brown rice weight. The ripened grains were selected by sieving through 1.8 mm mesh. Thousand-grams weights were measured for brown rice at 14.5% moisture content.

(6) Soil analysis
Fresh soil samples were used for inorganic nitrogen analyses. The remaining soils were air dried at room temperature for one week before being sieved through a 2 mm mesh. The dried soils were used for physical and chemical analyses and 

Inorganic nitrogen (NO₃⁻ and NH₄⁺) in fresh soil was extracted with 2 M KCl at a ratio of 1:10 (soil: solution) and their concentrations were measured with a continuous flow analyzer (BL-TEC Autoanalyzer, QuAAtro-HR). Exchangeable K, Mg, Ca, and Na in dried soil were extracted with 1 M CH₃COONa at a ratio of 1:20 (soil: solution) and their concentrations were measured with an atomic absorption spectrophotometer (Z-5300 Polarized Zeeman Atomic Absorption Spectrophotometer). Cation exchange capacity (CEC) measurement was based on the semi-micro Schollenberger method. Total carbon (TC) and nitrogen (TN) were measured with a CN coder (MT-700 Mark II, Yanaco, Kyoto, Japan). Soil pH and EC were measured at a ratio of 1:5 (soil: water) with pH/ion meter (Horiba F-23, Japan) and conductivity meter (Horiba DS-14, Japan), respectively. Soil texture classification was determined by the pipet method.

(7) Rice analysis
Rice samples were digested by the Kjeldahl method. After digestion, K concentration was measured with an atomic absorption spectrophotometer (Shimadzu AA-6800F, Japan).

(8) Radioactivity measurement
Concentrations of 

soil and rice were measured with a Ge semiconductor (GMX 15200P, Seiko EG&G, Tokyo Japan). Soil samples for the radioactivity measurement were prepared by adding 70 g of dried soil into plastic containers (U8 containers 47 mm in diameter and 60 mm in height); the samples measured 35 mm deep and 1.1 g cm⁻³ in density. Rice samples (approximately 14 to 42 g DW) of each part were added to the containers. Each U8 container was sealed in a polyethylene bag before being placed into a Ge semiconductor. The times of measurement were 30 minutes for soil and 24 hours for rice samples.

(9) Data calculations
The data were used to calculate as the following quantities:

a) Harvest index (HI)¹⁸,¹⁹:

\[
\text{Grain weight (DW)} / \text{Total rice weight (DW)}
\]

b) The 

transfer factor (TF)¹⁴ from soil to rice part:

\[
\frac{\sum_{i=1}^{n} m_i \times c_i}{\sum_{i=1}^{n} m_i} \times \frac{[^{137}\text{Cs}}{[^{137}\text{Cs in soil}}
\]

where \( n \) denotes the concentration of 

in soil (Bq kg⁻¹); this was an average of the values for 0-5 cm and 5-10 cm layers.

c) The TF of aboveground parts of rice plant:

\[
\frac{\sum_{i=1}^{n} m_i \times c_i}{\sum_{i=1}^{n} m_i} \times \frac{[^{137}\text{Cs in rice part}}{[^{137}\text{Cs in soil}}
\]

where

- \( n \) is the number of rice parts: stems, leaves, and panicles
- \( m \) is mass weight of each part (g m⁻², DW)
- \( c \) is concentration of 

in each part (Bq kg⁻¹)

d) The \( \text{Cs/K ratio in each rice part:} \)

\[
\frac{[^{137}\text{Cs (Bq kg}^{-1}) \times 2.35 \times 10^{-13} (\text{cmol, Bq}^{-1})}{\text{K (cmol, kg}^{-1})}
\]

(10) Statistical analysis
The effect of compost application on soil nutrients was tested by Tukey multiple comparisons test using the R Statistical Software package (R i386 3.2.0). One-way analysis of variance of rice yields and rice components was done using Microsoft Excel.

3. RESULTS AND DISCUSSION

(1) Effect of cattle manure compost application on soil properties
Soil properties in the experimental plots at harvest are shown in Table 2. Soil pH, EC, and bulk density did not change due to compost application. In contrast, clay content was significantly increased by the compost application (\( P<0.05 \)). Total carbon (TC) and total nitrogen (TN) were significantly increased by applying 20 t ha⁻¹ of compost (\( P<0.05 \)).

Ammonium (NH₄⁺) in soils did not differ among plots and accounted for 0.02 to 0.06 % of TN, while nitrate (NO₃⁻) was not detected in the majority of soils. Soil cation exchange capacity (CEC) did not significantly differ among plots and layers (\( P>0.05 \)) (Table 3). Exchangeable K, Mg, and Ca were significantly increased by applying 20 t ha⁻¹ of compost (\( P<0.05 \)). However, Na did not differ between plots (\( P>0.05 \)).

Somewhat unexpectedly, soil nutrients in the 40 t ha⁻¹ plot seemed to decrease as compared to those of the 20 t ha⁻¹ plot. Among three sampling points in the 40 t ha⁻¹ plot, the south side of the plot showed a
Effect of compost application on 137Cs concentration in soils

In all plots, 137Cs remained in the soil after removing the soil surface (Fig. 1). The concentration of 137Cs varied widely within each plot, with a coefficient of variation of 14 to 50%, and did not differ between the top and sub layers.

The concentration of 137Cs in soils tended to increase with increasing composting rates and was positively correlated with soil exchangeable K \((r^2 = 0.79)\) (Fig. 2). The 137Cs concentration in the 20 t ha\(^{-1}\) plot was higher than in other plots, and a similar trend was observed with soil nutrients. This was probably due to 137Cs remaining in the soil after removal of the soil surface and combination with the compost being contaminated by 137Cs (<400 Bq kg\(^{-1}\)).

Effect of compost application on soil properties at harvest.

| Treatment t ha\(^{-1}\) | Bulk density Mg m\(^{-3}\) | Clay % | pH | EC \(\mu\)S cm\(^{-1}\) | \(NH_4^+\) mg-N kg\(^{-1}\) | NO\(_3^-\) mg-N kg\(^{-1}\) | T-C g kg\(^{-1}\) | T-N g kg\(^{-1}\) | SOM % |
|-------------------------|--------------------------|--------|----|-----------------|-----------------|----------------|-------------|-------------|-------|
| top soil (0-5 cm)        |                          |        |    |                 |                 |                |             |             |       |
| 0                       | 1.3 a                    | 5 b    | 5.3 a | 29.5 a          | 0.56 a          | ND             | 10.8 b      | 0.98 b     | 1.86 b |
| 10                      | 1.3 a                    | 11 a   | 5.4 a | 31.2 a          | 0.63 a          | 0.26           | 17.0 ab     | 1.38 ab    | 2.92 ab |
| 20                      | 1.2 a                    | 10 a   | 5.4 a | 26.6 a          | 0.68 a          | 0.57           | 22.7 a      | 1.74 a     | 3.90 a |
| 40                      | 1.3 a                    | 9 a    | 5.7 a | 29.4 a          | 0.39 a          | ND             | 19.7 a      | 1.49 ab    | 3.39 a |
| sub soil (5-10 cm)      |                          |        |    |                 |                 |                |             |             |       |
| 0                       | 1.4 a                    | 4 b    | 5.6 a | 33.9 a          | 0.41 a          | ND             | 10.6 b      | 0.93 b     | 1.81 b |
| 10                      | 1.3 a                    | 10 a   | 5.5 a | 36.6 a          | 0.42 a          | ND             | 14.1 ab     | 1.19 ab    | 2.43 ab |
| 20                      | 1.2 a                    | 9 a    | 5.6 a | 34.8 a          | 0.36 a          | ND             | 21.7 a      | 1.61 a     | 3.72 a |
| 40                      | 1.3 a                    | 9 a    | 5.7 a | 22.4 a          | 0.25 a          | ND             | 17.5 a      | 1.32 ab    | 3.01 a |

SOM = Soil organic matter, ND = Not detected.

Effect of compost application rates on CEC, exchangeable K, Mg, Ca and Na in soil at harvest.

| Treatment t ha\(^{-1}\) | CEC cmol\(_e\) kg\(^{-1}\) | K cmol\(_e\) kg\(^{-1}\) | Mg cmol\(_e\) kg\(^{-1}\) | Ca cmol\(_e\) kg\(^{-1}\) | Na cmol\(_e\) kg\(^{-1}\) |
|-------------------------|----------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| top soil (0-5 cm)        |                            |                         |                         |                         |                         |
| 0                       | 16.24 a                    | 0.15 b                  | 0.82 b                  | 6.35 b                  | 0.28 a                  |
| 10                      | 15.78 a                    | 0.39 ab                 | 0.95 a                  | 7.48 ab                 | 0.32 a                  |
| 20                      | 19.02 a                    | 0.47 a                  | 0.94 ab                 | 7.86 a                  | 0.28 a                  |
| 40                      | 14.60 a                    | 0.40 ab                 | 0.88 ab                 | 6.81 ab                 | 0.28 a                  |
| sub soil (5-10 cm)      |                            |                         |                         |                         |                         |
| 0                       | 14.24 a                    | 0.18 b                  | 0.80 b                  | 6.47 b                  | 0.34 a                  |
| 10                      | 23.33 a                    | 0.42 ab                 | 0.97 ab                 | 7.46 ab                 | 0.32 a                  |
| 20                      | 15.39 a                    | 0.55 a                  | 1.09 a                  | 8.31 a                  | 0.31 a                  |
| 40                      | 21.49 a                    | 0.43 ab                 | 0.88 ab                 | 6.65 ab                 | 0.27 a                  |

Note: For Table 2 and Table 3, Values in a column followed by the different letters are significantly different at \((P<0.05)\) based on Tukey's multiple-comparison test.

(3) Effect of compost application rates on rice yields

Rice yield related traits are shown in Table 4. Total mass of rice increased by 2, 22, and 34 %, and unhulled grains weight increased by 1.6, 19, and 31 % by applied 10, 20 and 40 t ha\(^{-1}\) of compost, respectively. Harvest index (HI) and grain to straw ratios were not significantly different between plots but tended to decrease in the 40 t ha\(^{-1}\) plot \((P>0.05)\).

Rice grain yields and components are listed in Table 5. Panicle number, spikelet per panicle, and percentage of ripened grains were not significantly different between plots \((P>0.05)\). However, the 1000-grains weight of rice in the 40 t ha\(^{-1}\) was significantly higher than those in other plots \((P<0.05)\).

(4) Effect of compost application rates on 137Cs in rice plant parts

The concentration and transfer factor (TF) of 137Cs in rice parts are listed in Table 6. The concentration of 137Cs in all rice parts was much lower than the Japanese standard (100 Bq kg\(^{-1}\)).
The transfer factor (TF) of $^{137}$Cs from soil to aboveground parts was decreased by cattle manure compost application. The TF value was lowest in the plot with 20 t ha$^{-1}$ of compost (TF = 0.009), this was 2.4 times lower than that of the control plot. We found that TF values in aboveground parts of rice plants were negatively correlated with exchangeable K in the soil ($r^2 = 0.64$) (Fig. 3).

The TF value of $^{137}$Cs of stems was higher than that of leaves, indicating that $^{137}$Cs accumulation in stems was greater than that in leaves. In the present study, $^{137}$Cs was not detected in rice panicles. This result differed from those of other researchers. Endo et al.\textsuperscript{23}, who studied a heavily contaminated paddy field in Minami-Soma town in 2011, found that TF of $^{137}$Cs of rice panicles ranged from 0.019 to 0.026. Uchida et al.\textsuperscript{24} reported that TF of $^{137}$Cs of brown rice in Japan before the FD1NPP accident was in the range of 0.001 - 0.03.

Application of potassium (K) effectively reduces $^{137}$Cs uptake by rice roots and its accumulation in rice grains\textsuperscript{25, 26, 27}. Saito et al.\textsuperscript{25} reported that radiocesium

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**Table 4** Rice yield related traits.

| Treatment t ha$^{-1}$ | Total dry mass g m$^{-2}$ | Unhulled grain % | Straws g m$^{-2}$ | HI | Grain/Straw ratio |
|-----------------------|--------------------------|-------------------|-------------------|----|------------------|
| 0                     | 1116 ± 156 a             | 568 ± 86 a        | 547 ± 71 a        | 0.509 ± 0.007 a | 1.04 ± 0.029 a   |
| 10                    | 1139 ± 89 a              | 577 ± 34 a        | 561 ± 60 a        | 0.508 ± 0.021 a | 1.04 ± 0.084 a   |
| 20                    | 1359 ± 343 a             | 681 ± 139 a       | 678 ± 205 a       | 0.505 ± 0.026 a | 1.03 ± 0.107 a   |
| 40                    | 1499 ± 355 a             | 745 ± 185 a       | 753 ± 185 a       | 0.497 ± 0.038 a | 0.99 ± 0.154 a   |

Mean ± SD; $n = 3$, Values in a column followed by the same letter are not significantly different ($P > 0.05$) based on one-way analysis of variance.

**Table 5** Grain yield and component.

| Treatment t ha$^{-1}$ | No. of panicles m$^{-2}$ | No. of spikelets panicle$^{-1}$ | Ripened grains % | 1000-gains weight g | Grain yield g m$^{-2}$ |
|-----------------------|--------------------------|--------------------------------|-------------------|---------------------|-----------------------|
| 0                     | 371 ± 57 a               | 61 ± 4 a                       | 86.7 ± 2.3 a      | 23.1 ± 0.3 bc       | 453 ± 64 a            |
| 10                    | 366 ± 24 a               | 64 ± 3 a                       | 85.0 ± 2.7 a      | 22.9 ± 0.2 c        | 458 ± 39 a            |
| 20                    | 417 ± 42 a               | 64 ± 8 a                       | 85.7 ± 1.4 a      | 23.4 ± 0.2 ab       | 593 ± 36 a            |
| 40                    | 438 ± 13 a               | 67 ± 4 a                       | 86.9 ± 1.0 a      | 23.7 ± 0.2 a        | 601 ± 149 a           |

Mean ± SD; $n = 3$, Values in a column followed by the same letter are not significantly different ($P > 0.05$) based on one-way analysis of variance.

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concentration of brown rice decreased by the increasing of exchangeable K in soil. Kato et al.\textsuperscript{26} recommended that exchangeable K in soil should be higher than 0.50 cmol kg\(^{-1}\).

Saito et al.\textsuperscript{27} found that application of potassium fertilizer on the early growth stage effectively reduced \(^{137}\)Cs concentration in rice grain. According to Nobori et al.\textsuperscript{28}, rice grown in K-deficient culture solution showed 6.7 times more \(^{137}\)Cs translocation from leaves to the panicle than those in the K-sufficient solution. Appropriate soil K content during the growth stage of rice reduced \(^{137}\)Cs transportation and accumulation in rice panicle\textsuperscript{29}.

Our results could be explained that exchangeable K derived from the cattle manure compost effectively reduced \(^{137}\)Cs uptake and accumulation in leaf and panicle of the rice plants.

(5) Distributions of \(^{137}\)Cs, K, and N in rice plant parts

Concentrations of \(^{137}\)Cs, K, and N in each rice plant part are shown in Fig. 4. Distributions of \(^{137}\)Cs and K in the rice plant parts were similar and differed from those for N. Both \(^{137}\)Cs and K in stems was higher than in leaves and panicles, suggesting that \(^{137}\)Cs transport in the rice plants was associated with K transporters. The mechanism regulating \(^{137}\)Cs distribution in plant organs is closely related to the K transport\textsuperscript{29, 30, 31}.

However, the translocation and accumulation of \(^{137}\)Cs and K in plant parts were not exactly the same in our experiment. This can be explained by their different physical characteristic such as the ionic radiuses (1.69 nm for Cs and 1.33 nm for K)\textsuperscript{32}. Different of \(^{137}\)Cs and K accumulation in rice parts has been previously reported\textsuperscript{20, 28}. Rice parts with higher \(^{137}\)Cs/K indicate greater \(^{137}\)Cs accumulation or greater K transportation. In the present study, the \(^{137}\)Cs/K ratio was higher in stems than in leaves in 10 and 20 t ha\(^{-1}\) plots (Fig. 5). Our results agreed with those of Kondo et al.\textsuperscript{20}, who reported that the \(^{137}\)Cs/K ratio in roots was higher than in aboveground parts of rice.

Similarly, Tsukada et al.\textsuperscript{33} reported that the stable-Cs/K ratio decreased in the younger leaf blade positions of rice plant, indicated that Cs was lower translocated to younger leaves than K.

In contrast, the \(^{137}\)Cs/K ratios of rice plants in the 0 and 40 t ha\(^{-1}\) plots were higher in leaves than that in stems; these plots were low in Mg and Ca compared to the 10 and 20 t ha\(^{-1}\) plots. This result suggests that soil with low Mg and Ca might affect K uptake, resulting in a permision of \(^{137}\)Cs translocation between rice organs. The K transport mechanism in plant cells is regulated by cations including K, Ca, Mg, Na in soil solution\textsuperscript{34, 35, 36, 37, 38}. In the present study, the \(^{137}\)Cs/K ratio of leaves was negatively correlated with exchangeable K, Mg, and Ca in the soil (Fig. 6), suggesting that K, Mg and Ca affected \(^{137}\)Cs translocation inside the rice plants. However, those correlations were not apparented in stems (Fig. 7).

The differences in \(^{137}\)Cs/K ratio in rice plant parts indicated that their was discrimination in the rate of \(^{137}\)Cs versus K transportation\textsuperscript{3} and that was affected by both external nutrient conditions and rice plant physiology\textsuperscript{39, 40, 41, 42, 43}.

In addition, regardless of soil nutrient condition, it is important to study rice plant physiological mechanism controlling \(^{137}\)Cs distribution and accumulation in different rice parts.

4. CONCLUSIONS

Application of cattle manure compost induced the increase of rice yields. Concentrations of \(^{137}\)Cs in rice plant parts were decreased by application of cattle manure compost. The lowest \(^{137}\)Cs was found in rice grown in the 20 t ha\(^{-1}\) plot (2.4 times lower than control soil) probably because of the increase of soil K (exchangeable K). The \(^{137}\)Cs in rice plant parts was decreased: stems > leaves and was not detected in the panicles of rice plants in all plots.

Distribution of \(^{137}\)Cs in rice plant parts was similar to that of K. Different of \(^{137}\)Cs /K ratio in rice plant parts indicated the different accumulation rate of \(^{137}\)Cs and K. The \(^{137}\)Cs/K ratio in stems was higher than that in leaves in the soil with higher Mg and Ca, indicating that Mg and Ca in soil regulated \(^{137}\)Cs translocation between rice plant parts.

For future research, an important goal will be to understand the mechanism of \(^{137}\)Cs transportation and accumulation between rice parts. The effects of Mg and Ca on \(^{137}\)Cs distribution in rice plants should be more researched.
Table 6 Concentration of $^{137}$Cs in rice plant parts and transfer factor (TF).

| Treatments t ha$^{-1}$ | Stems Bq kg$^{-1}$ | Leaves Bq kg$^{-1}$ | Panicles Bq kg$^{-1}$ | TF of stems | TF of leaves | TF of aboveground parts |
|------------------------|--------------------|---------------------|-----------------------|-------------|-------------|-------------------------|
| 0                      | 21                 | 14                  | ND                    | 0.050       | 0.034       | 0.022                   |
| 10                     | 35                 | 6                   | ND                    | 0.051       | 0.009       | 0.020                   |
| 20                     | 24                 | 5                   | ND                    | 0.024       | 0.005       | 0.009                   |
| 40                     | 18                 | 9                   | ND                    | 0.026       | 0.013       | 0.011                   |

The $^{137}$Cs concentration in each rice part was measured with $n = 1$; ND = Not detected.

Fig. 4 Concentrations of total- K, total- N and $^{137}$Cs in rice plant parts ($n = 1$).

Fig. 5 The $^{137}$Cs/K ratios of stems, leaves, and panicles of rice ($n = 1$). ND = Not detected.
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