Influence of water management and fertilizer application on 137Cs and 133Cs uptake in paddy rice fields

Influence of Water Management and Fertilizer Application on ^{137}Cs and ^{133}Cs Uptake in Paddy Rice Fields

Shokichi Wakabayashi [a,1], Sumio Itoh [a,2], Nobuharu Kihou [b], Hisaya Matsunami [c], Mayumi Hachinohe [d], Shioka Hamamatsu [d], Shigeru Takahashi [a]

[a] NARO Agricultural Research Center
[b] National Institute for Agro-Environmental Sciences
[c] NARO Tohoku Agricultural Research Center, Agricultural Radiation Research Center
[d] National Food Research Institute

Postal addresses:
[a] 3-1-1 Kannondai, Tsukuba, Ibaraki 305-8666, Japan
[b] 3-1-3 Kannondai, Tsukuba, Ibaraki 305-8604, Japan
[c] 50 Harajukuminami, Arai, Fukushima, Fukushima 960-2156, Japan
[d] 2-1-12 Kannondai, Tsukuba, Ibaraki 305-8642, Japan

---

[1] Corresponding author. e-mail: shokichi@affrc.go.jp
[2] Retired.

Highlights:

We examined Cs uptake by rice with varying water management in fields in 2012–2014.

Long flooding treatment enhanced ^{137}Cs and ^{133}Cs uptakes by rice plant.

The successive K fertilization brought cumulative effect on Cs uptake of rice plant.

Uptakes of ^{137}Cs and ^{133}Cs by rice became correlated over the elapsed year.

Abstract

Cesium-137 derived from the Tokyo Electric Power Company's Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident contaminated large areas of agricultural land in Eastern Japan. Previous studies before the accident have indicated that flooding enhances radiocesium uptake in rice fields. We investigated the influence of water management in combination with fertilizers on ^{137}Cs concentrations in rice plants at two fields in southern Ibaraki Prefecture. Stable Cs (^{133}Cs) in the plants was also determined as an analogue for predicting ^{137}Cs behavior after long-term aging of soil ^{137}Cs. The experimental periods comprised 3 y starting from 2012 in one field, and 2 y from 2013 in another field. These fields were divided into three water management sections: a long-flooding section without midsummer drainage, and medial-flooding, and short-flooding sections with one- or two-week midsummer drainage and earlier end of flooding than the long-flooding section. Six or four types of fertilizer subsections (most differing only in potassium application) were nested in each water management section. Generally, the long-flooding treatment led to higher ^{137}Cs and ^{133}Cs concentrations in both straw and brown rice than medial- and short-flooding treatments, although there were some notable exceptions in the first experimental year at each site. Effects of differing potassium fertilizer treatments were cumulative; the effects on ^{137}Cs and ^{133}Cs concentrations in rice plants were not obvious in 2012 and 2013, but in 2014, these concentrations were highest where potassium fertilizer had been absent and lowest where basal dressings of K had been tripled. The relationship between ^{137}Cs and ^{133}Cs in rice plants was not correlative in the first experimental year at each site, but correlation became evident in the subsequent year(s). This study demonstrates a novel finding that omitting midsummer drainage and/or delaying drainage during the grain-filling period enhances uptake of both ^{137}Cs and ^{133}Cs.

Keywords: cesium, potassium fertilizer, flooding, rice, water management

1. Introduction

The accident at the Tokyo Electric Power Company's Fukushima Dai-ichi Nuclear Power Plant (FDNPP), triggered by the Great East Japan Earthquake and subsequent Tsunami in March 2011, widely contaminated the agricultural environment in the southern Tohoku and northern Kanto districts with radionuclides. Cesium-137 (^{137}Cs) has a long half-life of 30 y, and its transfer to agricultural products is a long-lasting problem that demands countermeasures. The optimization of potassium (K) fertilizer application is an effective means to accomplish this (Kato et al., 2015; Saito et al., 2015) because K competes with ^{137}Cs in the transfer process from soil solution to plant body (Shaw and Bell, 1991; Smolders et al., 1997).

Rice (*Oryza sativa*) cropping in flooded soil is the representative agricultural system in Japan. Some previous studies before the FDNPP accident indicate that soil flooding enhances radiocesium uptake by the rice plant. Tensho et al. (1961) demonstrated using pot-culture experiments with artificial addition of radiocesium that the uptake of radiocesium by rice plants is much greater from flooded soil than from unflooded soil. They suggested that ammonium (NH_4^+) as the main form of inorganic nitrogen in flooded soil might enhance availability of radiocesium to plants because NH_4^+ could exchange with radiocesium selectively adsorbed in soil. Pot-culture experiments by D'Souza and Mistry (1980) generated results similar to those of Tensho et al. (1961). Verfaillie et al. (1967) demonstrated in an actual paddy field in Northern Italy in 1964 that preventing flooding decreased ^{137}Cs concentration in rice grain. Although these studies compared the effects of flooding and upland cultivation practices on radiocesium uptake by rice plants, it remains unknown whether variations in the flooding period within a practical range for paddy rice cropping affect ^{137}Cs uptake by rice plants. Smolders and Tsukada (2011) suggested that water management systems that suppress NH_4^+ concentration might be a potential countermeasure against ^{137}Cs transfer to rice crops, and advocated factorial experiments focused on water management and nitrogen (N) fertilization.

We conducted field experiments in paddy crops to investigate the influence of water management (flooding period) on ^{137}Cs concentration in rice plants. Additionally, the effects of different K application treatments were investigated. Stable cesium-133 (^{133}Cs) is regarded as a useful analogue for long-term assessment of ^{137}Cs in agricultural environments, because the fate of radionuclides in the environment follows the behavior of their stable isotopes (Tsukada et al., 2002; Uchida and Tagami, 2007). In this study, ^{133}Cs in rice plants was also determined so the influence of water management and fertilizer treatment on ^{137}Cs uptake long after the fallout event might be predicted.

2. Materials and Methods

2.1. Experimental Fields

The experimental area comprised two paddy fields in southern Ibaraki Prefecture. Site YWR is located in the alluvial plain of the Kokaigawa River in Tsukubamirai City. Site KND is located on the Hitachi tableland in Tsukuba City. According to the soil classification system in Japan (Obara et al., 2011) or the World Reference Base for Soil Resources (International Union of Soil Sciences Working Group WRB, 2014) respectively, YWR soil is Gray Lowland soil or Gleyic Fluvisol, and KND soil is Upland Reformed soil or Thaptandic Regosol (Transportic). These fields had no history of deep tillage after the FDNPP accident, therefore ^{137}Cs was mainly distributed within topsoil.

In previous rice cropping before this experiment in each field, water management had been spatially uniform for more than a decade. A common practice in these areas, called "midsummer drainage," is aimed at enhancing root growth and reducing the number of unproductive tillers of rice plants. It also promotes subsurface drainage through formation of drying cracks in the soil and increases the soil's bearing capacity for machinery operation (Inoue and Tokunaga, 1995). In previous rice cropping at YWR, field flooding was started and topsoil was puddled in early May, a few days before transplanting, as was customary for the water management system. Basal-dressing fertilizer had been applied before flooding. In late June, ponding water was temporarily drained for 2–3 weeks as midsummer drainage. Field flooding ended in early September, a week before harvest. As was customary at KND, field flooding was started and topsoil was puddled in early May. A few days later, basal-dressing fertilizer was applied to the flooded soil. Rice seedlings were transplanted a few days later thereafter. The midsummer drainage was conducted for a week from early July. During drainage period in KND, drainpipe buried in the soil at a depth of 90 cm was opened to promote underdrainage. Field flooding ended at the end of August, two weeks before harvest. (Other details on field management before this experiment, such as fertilizer application, are summarized in Supplementary Tables.)

The experimental periods comprised 3 y from 2012 at the YWR field, and 2 y from 2013 at the KND field. The cultivar "Koshihikari" was transplanted in May and raised until harvest in September. The schedule of paddy field management during the experiment is shown in Table 1. During the season, air temperature ranged from 4.9 to 36.8°C (mean temperature of 23.4°C) and precipitation was recorded as 580, 380 and 760 mm in 2012, 2013 and 2014, respectively at the nearest meteorological observatory (Japan Meteorological Agency, 2015).

2.2. Experimental design

The experimental designs of the two fields are shown in Fig. 1. Each field was divided into three sections for different water management treatments using two plastic corrugated sheets (Nami-ita in Japanese). Each section was identified by the three type of water management as follows: A long-flooding (LF) section, which was flooded from before transplanting to the end of August or early September; a medial-flooding (MF) section, which was drained in midsummer for 7 or 8 d and 7–12 d earlier at the end of flooding than the LF section; and a short-flooding (SF) section, which was drained in midsummer for 14–16 d and 15–20 d earlier at the end of flooding than the LF section. In 2014, however, midsummer drainage for the MF and SF sections was increased to 20 d because of prolonged rainy weather. At KND, only one water outlet existed for surface drainage; therefore, pumps were used to discharge standing water at that site.

Each water management section was divided into six (at YWR) or four (at KND) subsections for different fertilizer treatments. Control subsections (CR) at each site received 3.0 g m^{-2} of N as ammonium sulfate ($(NH_4)_2SO_4$), 2.6 g m^{-2} of P as calcium superphosphate (mainly $Ca(H_2PO_4)_2 \cdot H_2O$), and 5.0 g m^{-2} of K as potassium chloride (KCl) as basal dressing, and 3.0 g m^{-2} of N as $(NH_4)_2SO_4$ and 2.5 g m^{-2} of K as KCl as top-dressing in late July. Three types of subsections at each site were defined according to the KCl application strategy; no K fertilizer application (0K: no K), triple basal dressing without top-dressing (3BK: totally 15 g m^{-2} K), and triple top-dressing without basal dressing (3TK: totally 7.5 g K m^{-2} K). Of the remaining subsections at YWR, one type received 7.5 g m^{-2} of K as potassium silicate (K_2SiO_3), which is a release fertilizer, as basal dressing instead of KCl (KS). The other type differs from the control subsections in having had no top-dressing of KCl (0TK) in 2012 and increased N fertilizer application in 2013 and 2014 (IN: 4 g m^{-2} of N as $(NH_4)_2SO_4$ and the same amount of N as controlled-release coated urea, LPSS100) as basal dressing.

The field position of each treatment-defined subsection was not changed during the experimental years in order to observe the cumulative effect of field management, especially fertilizer application, over the years.

2.3. Sample collection, and radiometric and chemical analysis

In mid-September, the aerial parts of matured rice were harvested at about 2 cm above ground from a 5.0 or 6.5 m^2 area of each subsection. A sample of the underlying topsoil, which was 17 cm thick on average, was also collected from a harvest area of each subsection with a shovel or a root auger (4 cm diameter; DIK-102A, Daiki Rika Kogyo Co., Ltd., Japan). Brown rice samples were obtained after air-drying, husking, and sieving through 1.8 mm sieves. Straw samples were dried at 70 °C, brushed to remove surface tissue stained with soil remnants, and milled. Soil samples were air-dried and sieved through 2.0 mm sieves.

Concentrations of ^{137}Cs in straw, brown rice, and soil samples were determined with germanium (Ge) gamma-ray detectors (GEM55P, GEM20-70, SEIKO EG&G, Co., Ltd., Japan; GC2020, GC2520, GC4020-7500SL-2002SCL, Canberra, USA) using 2.0 L of plant samples or 100 mL of soil samples. Before measurement, each sample was mixed to homogenize the material and was then uniformly packed into a plastic container. The counting efficiency of the Ge gamma-ray detectors was calibrated using gamma-ray reference source (MX033MR and MX033U8PP, Japan Radioisotope Association, Tokyo, Japan). The decay corrections were made to the harvest day in each year.

To measure ^{133}Cs and K concentration in brown rice and straw, 100 mg of milled sample was digested in duplicate with 70% nitric acid on the hot plate at 105°C. The digestion solution was analyzed using inductively coupled plasma mass spectrometry (Agilent 7700x, Agilent Technologies, Japan) and atomic absorption spectrometry (iCE 3300, Thermo Fisher Scientific K.K., Japan) to measure ^{133}Cs and K concentrations, respectively. The standards for calibration were prepared using multi-element calibration standard 3 (containing 10.0 mg L^{-1} of ^{133}Cs; PerkinElmer, Inc., USA) and KCl powder (>99.5%; Wako Pure Chemical Industries, Ltd., Japan). The average standard error between duplicates was 3% and 1% of the analytical value for ^{133}Cs and K analysis, respectively.

To estimate exchangeable K, soil samples were shaken with 1 mol L^{-1} ammonium acetate solution at pH 7.0 for 1 h at a solution/soil ratio of 10 mL g^{-1}. The K concentration of the supernatant solution after centrifugation and filtration was determined by atomic absorption spectrometry. The extraction was duplicated, and the average standard error between duplicates was determined to be 1% of the analytical value.

To investigate the influence of water management and increasing N fertilizer application on soil NH_4^+ concentration, the exchangeable NH_4^+ content of soils in the CR and IN subsections was determined before and during cultivation in 2014 at the YWR field. Soil cores (3 cm diameter and 10 cm depth) were collected five times in triplicate: the days before transplanting (15 May), before midsummer drainage (23 June), after midsummer drainage in the MF and SF sections (16 July), after heading stage (6 August), and after drainage in the LF section (5 September). Each wet core sample was stirred to homogenize, and a part of it was used for 1-h extraction with 2 mol L^{-1} KCl solution (solution/soil ratio of 10 mL g^{-1}) within the sampling day. After centrifugation and filtration, the NH_4^+ concentration of the supernatant solution was determined using an Autoanalyzer (QuAAtro 2-HR, BL-TEC, Japan). The remaining wet samples were used to estimate exchangeable K contents during cultivation. Similar to KCl extractions, 1-h extractions with 1 mol L^{-1} ammonium acetate solution were conducted. The K concentration of the supernatant solutions was determined using atomic absorption spectrometry.

The mass of dried plant material or soil is used in expression of all measured quantities (plant yields, amounts of chemical species).

2.4. Statistical analysis

The Grubbs' test was applied to identify outliers in datasets for each field and year using R software version 3.1.1 (The R Project for Statistical Computing, Vienna, Austria. URL http://www.r-project.org). A value of brown rice ^{137}Cs for subsection 3TK of the SF section at KND in 2013 was regarded as an outlier at $p < 0.001$, and was thereby excluded from analyses.

The data of four subsections (CR, 0K, 3BK, and 3TK) for 2013–2014, which have counterparts in all sections of both fields, were subjected to mixed model analysis of variance (ANOVA) with the SAS Add-In for Microsoft office version 6.1 M1 (SAS Institute Inc., USA). This dataset is structured as a split-plot design with site as the block, water management as the primary factor, fertilizer as the secondary factor, and experimental year as the tertiary factor. In this paper, the statistical term "significant" refers to $p < 0.050$ and "significant tendency" to $0.050 < p < 0.100$. When the effects of water management or fertilizer were significant without any interaction in ANOVA, Tukey's post hoc multiple comparison test was performed to determine significant difference among sections or subsections. When significant interactions between experimental year and water management or fertilizer were revealed by ANOVA, a post-hoc Tukey's test was performed separately for both 2013 and 2014 datasets at an adjusted significance level ($p < 0.050 / 2 = 0.025$).

Correlations between ^{137}Cs and ^{133}Cs concentrations in straw and brown rice were calculated by linear regression using Microsoft Excel 2013.

3. Results

The soil ^{137}Cs concentrations were closely similar in the two fields (Table 2). For each field in each year, the average soil ^{137}Cs concentration for each type of water management or fertilizer treatment ranged within a narrow interval (for example, 153–177 Bq kg^{-1} at YWR and 152–185 Bq kg^{-1} at KND in 2014). The ANOVA results for the 2013–2014 dataset revealed no significant differences in ^{137}Cs among soils that experienced different water management or fertilizer treatment, but there were significant differences for the different experimental years. The values were lower in 2013 than in other years, which could be attributed to a sampling error caused by using a different tool in 2013 (root auger) than in the other years (shovels). When root augers were vertically inserted into the soil during sampling, the penetration resistance appeared to be lower than when a shovel was used, indicating that the sampling with the auger may have been deeper. This could have allowed accidental inclusion of the less-contaminated soil from the plow sole in the topsoil samples.

The exchangeable K content after harvest was higher at YWR than at KND (Table 2). The values for 0K and 3BK were the lowest and the highest, respectively, among the values for different fertilizer treatments, corresponding to their ranking in respect to K application amounts. The average exchangeable K content for 3BK increased annually in each field, in contrast to stable or decreasing values for 0K, so the differences widened over years. Water management sections exhibited small exchangeable K differences at KND. At YWR, the difference was negligible in 2012, but in the subsequent years, the exchangeable K content was highest in the soil that had experienced longer drainage treatment (SF). The ANOVA results for the 2013–2014 dataset revealed significant fixed effects of fertilizer and experimental year and their interaction (data not shown).

The annual mean values of yields of straw and brown rice varied slightly across the different kinds of water management or fertilizer treatments (Table 3). Although these yields for LF at YWR were relatively low in 2014, ANOVA for the 2013–2014 dataset revealed no significant fixed effects for yields of both materials (data not shown). Straw yields were lower in the first experimental year than in the subsequent year(s) in each field.

The K concentration in straw and brown rice varied more between experimental years than between experimental treatments (Table 4). Water management practices and fertilizer treatments did not cause the value to vary by more than 10% from the grand mean in each year at each field. The ANOVA results for the 2013–2014 dataset revealed a significant difference only between experimental years (data not shown).

The ^{137}Cs and ^{133}Cs concentrations found in straw and brown rice are presented in Fig. 2. The ANOVA results for the 2013–2014 dataset are summarized in Table 5.

Concentration of ^{137}Cs in straw was higher for LF than for MF and SF in each case, except for 0K at KND in 2013 (Fig. 2a). The annual mean values for each water management are shown in Fig. 2 together with the annual grand mean (white bars in Fig. 2). Compared to MF, the annual mean values for LF were higher by 28%–52%, while those of SF were almost the same, except in each field's first experimental year when annual mean values for SF were lower by 12% (YWR) and 32% (KND). Among the different fertilizer treatments, the mean values in 2014 were highest for 0K at both fields and lowest for in 3BK at KND. The values in each section and subsection mostly decreased from year to year. The ANOVA results for the 2013–2014 dataset showed significant influences of water management and year without any interaction (Table 5). The Tukey's post hoc test indicated that the differences between LF and the other two kinds of water management were significant.

Concentration of ^{137}Cs in brown rice was also higher for LF than for MF and SF in most cases at YWR and in most 2014 cases at KND (Fig. 2b). At YWR, the annual mean values for LF were higher by 33%–57% than those for MF. The mean value for SF was lower than that for MF by 29% in 2012, but in 2013 and 2014 the mean values for SF and MF were almost equal. At KND in 2013, the annual mean value for brown rice ^{137}Cs was higher for SF than for LF and MF, contrary to the straw ^{137}Cs results. Among the different fertilizer treatments, the mean values in 2014 were highest for 0K at both fields and lowest for 3BK at KND, in accordance with the straw results. The annual grand mean (white bars in Fig. 2) for each field decreased from the first experimental year to the second year. The ANOVA results for the

2013–2014 dataset did not show significant influence of water management but revealed interactions of water management with year (fixed effect) and with field (random effect) (Table 5). It also showed significance or significant tendency ($p < 0.10$) for fertilizer, year, and their interaction. The separate Tukey's post hoc test detected no significant difference in 2013, but it showed that ^{137}Cs in brown rice was significantly higher for 0K than for three other fertilizer treatments in 2014.

Concentration of ^{133}Cs in straw was higher for LF than for MF and SF in most cases after 2012 (Fig. 2c). At YWR, the differences in annual mean values for the different types of water management were negligible in 2012 but increased from year to year. Among the different fertilizer treatments, the values in 2014 were highest for 0K and lowest for 3BK at both fields. The ANOVA results for the 2013–2014 dataset showed significant tendencies for the effects of water management and fertilizer along with a significant interaction between fertilizer and year (Table 5). The separate Tukey's post hoc test for each year detected no significant difference for 2013, but it showed that ^{133}Cs concentration in straw was significantly lower for 3BK than for 0K and 3TK in 2014.

Concentration of ^{133}Cs in brown rice exhibited trends similar to ^{133}Cs concentration in straw (Fig. 2d). Additionally, the annual grand mean for each field was higher for 2014 than for earlier years. The increase from 2013 to 2014 is most evident in LF among water management treatments. At KND in 2013, the annual mean values were higher in LF than in MF and SF, which was consistent with both ^{137}Cs and ^{133}Cs in straw but not with ^{137}Cs in brown rice. The ANOVA results for the 2013–2014 dataset showed significant influence of water management, fertilizer, and year (Table 5). However, it is not feasible to follow multiple comparison tests for any factor because there was also significant interaction within each pair of these three factors.

The relationship between ^{133}Cs and ^{137}Cs concentrations in each plant component (straw and brown rice) are exhibited in Fig. 3, separately for each field and each year. There was no significant correlation in the first experimental year for each site but positive correlation was observed in the subsequent year(s).

The exchangeable NH_4^+ and K contents of soil from selected subsections before and during rice cultivation in 2014 at YWR are exhibited in Fig. 4. Exchangeable NH_4^+ content was higher for IN than for CR on the day before transplanting (Fig. 4a). After that, the exchangeable NH_4^+ content became consistently low, regardless of the difference in application amount of N fertilizer. Midsummer drainage in the MF and SF sections did not change the values. During the grain-filling period, the NH_4^+ content increased with no clearly evident difference between different types of water management or different fertilizer treatments. Exchangeable K content decreased from before transplanting to after the heading stage (Fig. 4b). After the end of flooding, exchangeable K values increased in SF sections.

4. Discussion

4.1. Influence of water management

Except the case of brown rice in 2013 at KND, the ^{137}Cs concentrations of straw and brown rice showed highly significant correlation (YWR in 2012–2014, r=0.786, p<0.001; KND in 2014, r=0.900, p<0.001) and average ^{137}Cs concentrations for water management sections were ordered in the same way in the sense that the highest ^{137}Cs concentrations were in the LF sections (Fig. 2a, b). The average ^{133}Cs concentrations of straw and brown rice for the water management sections were in the same order as the average ^{137}Cs concentrations (highest in the LF sections) except at YWR in 2012 (Fig. 2c, d). In these field experiments, the soil ^{137}Cs concentrations of the water management sections in the two fields were in about the same range (Table 2). The exchangeable K content was also closely similar among the sections of each field at the end of the first experimental year. Therefore, the relatively high ^{137}Cs concentrations in rice plants in the LF sections are not attributable to spatial differences of soil quality in terms of either ^{137}Cs concentration or K fertility. Variations of plant yields were small and insignificant (Table 3) indicating negligible effect of carbohydrate dilution. These results indicate as a whole that the enhanced rice plant Cs (both ^{137}Cs and ^{133}Cs) concentrations in LF sections (LF effect) was the outcome of the long-flooding treatment itself. The interaction between water management and fertilizer was not significant except for brown rice ^{133}Cs (Table 5), and the LF effect was consistent across the different fertilizer treatments in most cases (for all cases in 2014, Fig. 2). Thus the LF treatment seems to have been influential regardless of fertilizer management and field. On the other hand, the effect of doubling the drainage period (i.e., the difference between the treatments in SF and MF) was not significant.

Possible causes of the LF effect on Cs uptake are discussed hereafter. Tensho et al. (1961) suggested that NH_4^+ exchanges with radiocesium selectively absorbed in soil particles to enhance its availability to the plant under submerged conditions. Ammonium also has been reported to play an important role in radiocesium release from submerged sediments (Comans et al., 1989; Evans et al., 1983); also, liberal application of NH_4^+ enhances plant uptake of radiocesium (Jackson et al., 1965; Lasat et al., 1997; Ohmori et al., 2014; Prister et al., 1992). It should be investigated whether or not NH_4^+ derived from mineralization or a practical amount of fertilizer does contribute to Cs mobility, and whether oxidation by drainage treatment could suppress this NH_4^+ contribution. In this study, application of 1.3 times more N to the IN subsections than to the control subsections produced no appreciable difference in Cs concentration in the plants (Fig. 2). The differences in exchangeable NH_4^+ content among soils that experienced different water management treatments were small in the observation at YWR in 2014 (Fig. 4). Ammonium is not necessarily considered to be the cause of the LF effect at this moment.

Secondarily, the possibility of exogenous ^{137}Cs entry from irrigation water might be considered. However, Suzuki et al. (2015) found that irrigation with water containing dissolved ^{137}Cs at a concentration of 0.10 Bq L^{-1} did not or did only slightly (by less than 20%) increase the ^{137}Cs concentration of brown rice grown in pot culture using soil containing ^{137}Cs at 200 Bq kg^{-1}. Although ^{137}Cs concentrations of irrigation water were not measured in our experiment, they were assumed to be lower than 0.10 Bq L^{-1}. In the investigation of Tsuji et al. (2014) in four rivers located in Fukushima Prefecture in 2012 and 2013, dissolved ^{137}Cs concentrations in river water were less than 0.20 Bq L^{-1} in the river where deposited ^{137}Cs is highest, and these were less than 0.05 Bq L^{-1} in the other three revers. Additionally, the differences in total duration of flooding among the water management sections were four weeks or less in this study. Thus the differences of ^{137}Cs inflow load among the water management sections are considered not to be a main cause of the LF effect. Similar enhancements of radiocesium uptake by flooding were reported in pot experiments with no exogenous radiocesium entry (D’Souza and Mistry, 1980; Tensho et al., 1961).

Thirdly, D’Souza and Mistry (1980) suggested that shoot-base absorption of radiocesium in standing water can be a major means by which flooding increases radiocesium uptake, in reference to a report by Myttenaere (1972) that absorption of radiocesium by rice plants is greater through a shoot base dipped in water than through a root dipped in nutrient solution. However, the nutrient solution in the hydroponic experiment seems different from natural soil solution in the point of salt concentration. To estimate the realistic contribution of shoot-base radiocesium absorption to rice plants, the composition of the test solutions (K, NH_4^+, ^{133}Cs etc.) should be modified according to that of soil solution and standing water in the actual field.

A fourth possibility is that K availability can be changed with longer flooding to influence Cs uptake. Reductive conditions reportedly decrease K release (Chen et al., 1987; Horikawa and Kawaguchi, 1963), and oxidation of paddy soil by drainage decreases K-deficient symptoms in rice plants (Ogihara, 1960). At YWR in 2014, the exchangeable K content increased after the end of flooding where drainage had started earlier (Fig. 4b). This increase may have been caused by soil oxidation and related to lower Cs uptake in the SF section. Other causes are possible, but no clear mechanism for the LF effect is evident yet.

Results of ^{133}Cs measurements for the different water management treatments at YWR show a trend not shared by ^{137}Cs results; LF treatment did not change ^{133}Cs concentrations in rice plants (both straw and brown rice) in 2012 but increased these in later years (Fig. 2c, d). We propose a two-fold hypothesis to explain the trend specific to ^{133}Cs. First, the discordance in variation between ^{133}Cs and ^{137}Cs could have been caused by ^{133}Cs uptake from the subsoil. Unlike ^{137}Cs, ^{133}Cs uptake in rice plants comes from not only topsoil but also subsoil, where water and nutrient conditions are different from those. If ^{133}Cs uptake in subsoil was substantial, ^{133}Cs concentration in rice plant would not have reflected LF treatment. Second, repeated LF treatments might gradually have suppressed vertical growth of rice root into the subsoil. Consequently, ^{133}Cs uptake would be enhanced by LF treatment in a manner similar to ^{137}Cs uptake when root activity was predominant in topsoil. Straw samples in the LF section showed significant correlation between ^{133}Cs and ^{137}Cs concentrations among six subsections in 2013 ($r = 0.905$, $p < 0.01$) and 2014 ($r = 0.802$, $p < 0.05$), indicating that the uptake sources of both ^{137}Cs and ^{133}Cs were the same. In contrast, in the cases of MF and SF, there are no significant correlation in each year. Midsummer drainage reportedly promotes vertical growth of rice root (Kawata and Katano, 1977) and nutrient uptake from subsoil (Kaneda, 1995). In the plow sole and subsoil, rice roots grow along with cracks and tubular macro-pores (Kaneda, 1995; Kawata et al., 1980). These macro-pores are formed by drying and previous root activity, whereas they are clogged by clay particles deposited during puddling (Inoue and Tokunaga, 1995). Therefore, repeatedly skipping midsummer drainage should decrease macro-pores in plow soles and subsoil and suppress vertical growth of rice root. Compared with MF and SF sections, the LF section at YWR had a low yield of rice plants in 2014 (Table 3), and became lower in exchangeable K contents in topsoil year by year (Table 2). These results are consistent with the hypothesis that repeated LF treatment concentrated root activity within topsoil. At KND, the trend specific to ^{133}Cs uptake discussed above was not obvious. However, the increase in ^{133}Cs concentrations in brown rice grown in the LF section from 2013 to 2014 (Fig. 2d) can be explained by this hypothesis.

4.2. Influence of K fertilizer application

The effect of K fertilizer is significant or has a significant tendency for brown rice and straw ^{133}Cs, and there are significant interactions with year in all cases (Table 5). In 2014, plants under 0K treatments had the highest Cs concentrations in both straw and brown rice of all fertilizer treatments (Fig. 2), and Tukey's post-hoc test indicated some significant differences from other subsections (Table 5). Conversely, the lowest values for Cs concentrations were commonly observed in plants under the 3BK treatment, especially at KND. However, neither treatment significantly changed K concentration in the rice plants (Table 4). These results indicate that K availability was sufficient for rice plant requirements in all subsections, but its variation within this range affected Cs uptake by rice plant. Increase of the K basal dressing would more effectively enhance K availability at KND than YWR because the former site was poorer in exchangeable K (Table 2). However, the order of Cs uptake for different K application treatments (3BK < other subsections < 0K) was not observed before 2013 even at KND. The temporally broadening range of exchangeable K content across the subsections suggests that K application cumulatively affected soil K availability over the years of the experiment (Table 2). This accumulation would explain the changes in response to K fertilizer treatments. Although application timing of K fertilizer (i.e., basal dressing or top-dressing) is reportedly important to suppress radiocesium concentration in rice plants (Nobori et al., 2014; Saito et al., 2015), the effect of the 3BK treatment on Cs uptake observed in this study is mainly attributed to cumulative enhancement of soil K fertility by application of high amounts of K.

4.3. Influence of time

Plant ^{137}Cs values were expected to decrease over the years of the experiment along with aging of soil ^{137}Cs (Rigol et al., 1999; Roig et al., 2007). Accordingly, these decreases were observed (Fig. 2a, b, Table 5), but the decrease from 2013 to 2014 at YWR was very small. In this study, however, soil ^{137}Cs aging might not be the only cause of these decreases. The grand means of exchangeable K content increased by 9% at YWR and by 11% at KND from the first year to the second year. The increasing K availability in the entire field also might have contributed to the difference of ^{137}Cs uptake between experimental years.

The ^{137}Cs and ^{133}Cs concentrations in rice plants over the elapsed years became correlated during the experimental period (Fig. 3). The observation that ^{137}Cs concentrations gradually began to follow those of ^{133}Cs over time can be explained by the aging of soil ^{137}Cs. As shown in Fig. 3, however, the variation range of stable ^{133}Cs becomes wider to fit that of ^{137}Cs, except in the case of straw at KND. The widening variation of ^{133}Cs was caused by the repetition of water management methods and fertilizer treatments. Repeated LF treatments increased ^{133}Cs uptake by rice plant, which might be attributed to concentration of root activity within topsoil (Section 4.1). Repeated K fertilizer treatments cumulatively affected K availability, and resulted in a significant difference in ^{133}Cs uptake by rice plants between the 0K and 3BK treatments (Section 4.2). Although ^{133}Cs uptake from subsoil might reflect K availability not in topsoil but in subsoil, repeated K fertilization might promote leaching from topsoil, and thereby enhance K availability in subsoil. The convergence of ^{137}Cs and ^{133}Cs concentrations over the elapsed years can be attributed to both aging of soil ^{137}Cs and the cumulative effects of repetitive water management practices and fertilizer treatments.

4.4. Effectiveness of water management and K fertilization treatments in reducing ^{137}Cs transfer to rice

The enhancement of ^{137}Cs uptake by the LF treatment was observed in both of the experimental fields, which had differing K status, site location, and soil taxa. The similar enhancement of natural ^{133}Cs concentration in rice plants after 2012 implies that LF treatment could be influential on ^{137}Cs transfer to rice plants even after long-term aging of soil ^{137}Cs, but the absence of an LF effect on ^{133}Cs in 2012 needs explanation. That is, the changing water management from LF to MF could be an effective, long-term method to reduce ^{137}Cs transfer to rice. On the other hand, extending the drainage period in midsummer and grain-filling period to more than that of MF appears to be fruitless. In rice cropping systems in Japan, midsummer drainage is commonly practiced, and the total flooding period is shorter than that in the LF section of this study. Therefore, changing the practice of LF might be applicable only in fields where drainage treatment is skipped or imperfectly practiced due to low water permeability, inflow of mountain runoff, or other reasons. In such fields, efforts to practice midsummer drainage and/or to terminate flooding earlier in the grain-filling period could decrease ^{137}Cs transfer to rice. However, the effects of these two practices were not individually investigated in this study. Additionally, the cause and the extent of generalization of the phenomenon should be examined in subsequent studies.

Increased K fertilization (3BK) treatment significantly decreased Cs concentration in rice plants, but the effect was not immediately observed, especially at YWR. Kato et al. (2015) reports a negative correlation between exchangeable K content after harvest and transfer factor (the ratio of radiocesium concentration in brown rice to that in soil), but it was not clear when exchangeable K content was higher than 3.8 mmol kg^{-1}. In previous experiments to investigate the effect of K fertilizer on radiocesium uptake by rice plants, exchangeable K contents in used soil were often low (for example, <1 mmol kg^{-1}, Fujimura et al. (2014) and Saito et al. (2012)). It is unclear whether K fertilization is effective in reducing Cs uptake by rice plants in fields where exchangeable K content is moderate or rich. The exchangeable K content in the first year was, on average, 4.7 mmol kg^{-1} at YWR and 2.6 mmol kg^{-1} at KND. This experiment shows that regular application of high amount of K is effective in reducing Cs uptake by rice plants, even where exchangeable K content is not low and the first K fertilization seems to have no effect.

5. Conclusion

The rice cultivation experiments in two fields in southern Ibaraki Prefecture exhibited the following results.

1. Cs uptake in rice plants was significantly affected in many cases by water management treatments; omitting midsummer drainage and/or delaying drainage during the grain filling period (LF) mostly enhanced Cs concentration. The phenomenon was observed to be independent of fertilizer application treatment type.

2. High K fertilization over successive years had a cumulative effect on Cs uptake by rice plants. The difference of K fertilizing was not recognized in plant Cs concentrations in 2012 and 2013 but exhibited a significant influence in 2014. By 2014, the cumulative effect of applying no K clearly enhanced plant Cs concentrations, while the cumulative effect of tripling the K basal dressing had the opposite effect, especially in a field with lower K status.

3. The correlation between ^{137}Cs and ^{133}Cs uptakes was insignificant at first and became close and significant with elapsed years. The convergence between ^{137}Cs and ^{133}Cs is attributed to the aging of soil ^{137}Cs and the cumulative effects of repeated water management methods and

fertilizer treatments.

4. Efforts to practice midsummer drainage and/or terminate flooding earlier in the grain-filling period could be an effective countermeasure to suppress ^{137}Cs transfer to rice plants in fields where drainage is skipped or imperfectly practiced. The effect would be promising even after long-term aging of ^{137}Cs.

Acknowledgments

This study was partly supported by grants from the Japanese Ministry of Agriculture, Forestry and Fisheries ("Development of Radioactive Materials Removal and Reduction Technology for Forests and Farmland" in 2012 and "Development of Decontamination Technologies for Radioactive Substances in Agricultural Land" in 2013–2014). We are grateful to Mr. Y. Takahashi (NARO Tohoku Agricultural Research Center, Agricultural Radiation Research Center) for the measurement of ^{137}Cs and Dr. T. Mitsunaga (NARO Agriculture Research Center) for statistical expertise. We also thank Mr. I. Ameta, Mr. M. Kosuge, Mr. K. Satou, Ms. Y. Nemoto, and Ms. C. Fuse (NARO Agriculture Research Center) for field and laboratory assistance.

References

Chen, S.Z., Low, P.F., Roth, C.B., 1987. Relation between potassium fixation and the oxidation state of octahedral iron. Soil Sci. Soc. Am. J. 51, 82–86. doi:10.2136/sssaj1987.03615995005100010017x

Comans, R.N.J., Middelburg, J.J., Zonderhuis, J., Woittiez, J.R.W., De Lange, G.J., Das, H.A., Van Der Weijden, C.H., 1989. Mobilization of radiocaesium in pore water of lake sediments. Nature 339, 367–369.

D'Souza, T.J., Mistry, K.B., 1980. Absorption of gamma-emitting fission products and activation products by rice under flooded and unflooded conditions from two tropical soils. Plant Soil 55, 189–198. doi:10.1007/BF02181798

Evans, D.W., Alberts, J.J., Clark III, R.A., 1983. Reversible ion-exchange fixation of cesium-137 leading to mobilization from reservoir sediments. Geochim. Cosmochim. Acta 47, 1041–1049.

Fujimura, S., Ishikawa, J., Sakuma, Y., Saito, T., Sato, M., Yoshioka, K., 2014. Theoretical model of the effect of potassium on the uptake of radiocesium by rice. J. Environ. Radioact. 138, 122–31. doi:10.1016/j.jenvrad.2014.08.017

Horikawa, Y., Kawaguchi, K., 1963. Studies on the potassium-adsorption caused by soil-reduction part I. Soil Sci. Plant Nutr. 9, 15–22. doi:10.1080/00380768.1963.10431050

Inoue, H, Tokunaga, K, 1995. Soil and water management, in: Tabuchi, T., Hasegawa, S. (Eds.), Paddy Fields in the World. The Japanese Society of Irrigation, Drainage and Reclamation Engineering, Tokyo, pp. 303–325.

International Union of Soil Sciences Working Group WRB, 2014. World reference base for soil resources 2014. World Soil Resources Reports 106, Food and Agriculture Organization of the United Nations, Rome.

Jackson, W.A., Craig, D., Lugo, H.M., 1965. Effect of various cations on cesium uptake from soils and clay suspensions. Soil Sci. 99, 345–353.

Japan Meteorological Agency, 2015. Past meteorological data search, Tsukuba (Tateno) http://www.data.jma.go.jp/obd/stats/etrn/index.php?prec_no=40&block_no=47646 (June, 2015).

Kaneda, Y., 1995. Soil management and paddy rice root by non-tilled farming. Root research 4, 47–51. (in Japanese)

Kato, N., Kihou, N., Fujimura, S., Ikeba, M., Miyazaki, N., Saito, Y., Eguchi, T., Itoh, S., 2015. Potassium fertilizer and other materials as countermeasures to reduce radiocesium levels in rice: Results of urgent experiments in 2011 responding to the Fukushima Daiichi Nuclear Power Plant accident. Soil Sci. Plant Nutr. 61, 179–190. doi:10.1080/00380768.2014.995584

Kawata, S., Katano, M., 1977. Effect of water management of paddy fields on the direction of crown root growth and the lateral root formation of rice plants. Japanese Journal of Crop Science 46, 543–557. (in Japanese with English summary)

Kawata, S., Katano, M., Yamazaki, K., 1980. The root system development of rice plants in the worked- and sub-soils of actual paddy field. Japanese Journal of Crop Science 49, 311–316. (in Japanese with English summary)

Lasat, M.M., Norvell, W.A., Kochian, L.V., 1997. Potential for phytoextraction of ^{137}Cs from a contaminated soil. Plant Soil 195, 99–106. doi:10.1023/A:1004210110855

Nobori, T., Kobayashi, N.I., Tanoi, K., Nakanishi, T.M., 2014. Effects of potassium in reducing the radiocesium translocation to grain in rice. Soil Sci. Plant Nutr. 60, 772–781. doi:10.1080/00380768.2014.947617

Myttenaere, C., 1972. Absorption of radiocaesium by flooded rice: relative importance of roots and shoot base in the transfer or radioactivity. Plant Soil 36, 215–218. doi:10.1007/BF01373473

Obara, H., Ohkura, T., Takata, Y., Kohyama, K., Maejima, Y., Hamazaki, T., 2011. Comprehensive Soil Classification System of Japan—First Appoximation. Bulletion of National Institute for Agro-environmental Sciences 29. (in Japanese with English summary)

Ogihara, T., 1960. Studies on the potassium deficiency of rice plant. Special Report in Fukuoka Prefecture Agricultural Experimental Station 15. (in Japanese)

Ohmori, Y., Kajikawa, M., Nishida, S., Tanaka, N., Kobayashi, N.I., Tanoi, K., Furukawa, J., Fujiwara, T., 2014. The effect of fertilization on cesium concentration of rice grown in a paddy field in Fukushima Prefecture in 2011 and 2012. J. Plant Res. 127, 67–71. doi:10.1007/s10265-013-0618-7

Prister, B., Loshchilov, N., Perepelyatnikova, L., Perepelyatnikov, G., Bondar, P., 1992. Efficiency of measures aimed at decreasing the contamination of agricultural products in areas contaminated by the Chernobyl NPP accident. Sci. Total Environ. 112, 79–87. doi:10.1016/0048-9697(92)90240-S

Rigol, A., Roig, M., Vidal, M., Rauret, G., 1999. Sequential extractions for the study of radiocesium and radiostrontium dynamics in mineral and organic soils from Western Europe and Chernobyl areas. Environ. Sci. Technol. 33, 887–895. doi:10.1021/es980720u

Roig, M., Vidal, M., Rauret, G., Rigol, A., 2007. Prediction of radionuclide aging in soils from the Chernobyl and Mediterranean areas. J. Environ. Qual. 36, 943–952. doi:10.2134/jeq2006.0402

Saito, T., Ohkoshi, S., Fujimura, S., 2012. Effect of potassium application on root uptake of radiocesium in rice. in: Proceedings of international symposium on environmental monitoring and dose estimation of residents after accident of TEPCO's Fukushima Daiichi Nuclear Power Station. Kyoto University Research Reactor Institute Press, Kyoto, pp. 165–169. doi:10.1007/s10967-014-3609-9

Saito, T., Takahashi, K., Makino, T., Tsukada, H., Sato, M., Yoshioka, K., 2015. Effect of application timing of potassium fertilizer on root uptake of ^{137}Cs in brown rice. J. Radioanal. Nucl. Chem. 303, 1585–1587. doi:10.1007/s10967-014-3609-9

Shaw, G., Bell, J.N.B., 1991. Competitive effects of potassium and ammonium on caesium uptake kinetics in wheat. J. Environ. Radioact. 13, 283–296. doi:10.1016/0265-931X(91)90002-W

Smolders, E., Van den Brande, K., Merckx, R., 1997. Concentration of ^{137}Cs and K in soil solution predict the plant availability of ^{137}Cs in soils. Environ. Sci. Technol. 31, 3432–

3438. doi:10.1021/es970113r

Smolders, E., Tsukada, H., 2011. The transfer of radiocesium from soil to plants: Mechanisms, data, and perspectives for potential countermeasures in Japan. Integr. Environ. Assess. Manag. 7, 379–81. doi:10.1002/ieam.236

Suzuki, Y., Yasutaka, T., Fujimura, S., Yabuki, T., Sato, M., Yoshioka, K., Inubushi, K., 2015. Effect of the concentration of radiocesium dissolved in irrigation water on the concentration of radiocesium in brown rice. Soil Sci. Plant Nutr. 61, 191–199. doi:10.1080/00380768.2014.1003192

Tensho, K., Yeh, K.-L., Mitsui, S., 1961. The uptake of strontium and cesium by plants from soil with special reference to the unusual cesium uptake by lowland rice and its mechanism. Soil and Plant Food 6, 176–183. doi:10.1080/00380768.1961.10430944

Tsuji, H., Yasutaka, T., Kawabe, Y., Onishi, T., Komai, T., 2014. Distribution of dissolved and particulate radiocesium concentrations along rivers and the relations between radiocesium concentration and deposition after the nuclear power plant accident in Fukushima. Water Res. 60, 15–27. doi:10.1016/j.watres.2014.04.024

Tsukada, H., Hasegawa, H., Hisamatsu, S., Yamasaki, S., 2002. Rice uptake and distributions of radioactive ^{137}Cs, stable ^{133}Cs and K from soil. Environ. Pollut. 117, 403–409. doi:10.1016/S0269-7491(01)00199-3

Uchida, S., Tagami, K., 2007. Soil-to-plant transfer factors of fallout ^{137}Cs and native ^{133}Cs in various crops collected in Japan. J. Radioanal. Nucl. Chem. 273, 205–210. doi:10.1007/s10967-007-0737-5

Verfaillie, G., Myttenaere, C., Bourdeau, P., 1967. Factors involved in the accumulation of fallout radionuclides in irrigated rice and meadow plants, in: Aberg, B., Hungate, F.P. (Eds.), Radioecological Concentration Processes: Proceedings of an International Symposium Held in Stockholm, April, 1966. Pergamon Press, NewYork, pp. 429–436.

Figure captions

Figure 1. Field experimental designs. CR, control; 0K, no K fertilizer application; 3BK, triple basal dressing of KCl; 3TK, triple top-dressing of KCl; KS, K_2SiO_3 application instead of KCl; 0TK/IN, no K top-dressing in 2012 and increased N fertilizer application in 2013–2014.

Figure 2. ^{137}Cs concentrations in straw (a) and brown rice (b) and ^{133}Cs concentrations in straw (c) and brown rice (d). Fertilizer treatments: CR, control; 0K, no K fertilizer application; 3BK, triple basal dressing of KCl; 3TK, triple top-dressing of KCl; KS, K_2SiO_3 application instead of KCl; 0TK, no K top-dressing; IN; increased N fertilizer application. Gray and white rectangle bars represent the averages between water management treatments for each fertilizer subsection and overall, respectively. Error bars in (a) and (b) represent counting errors. The short-flooding, 3TK value for brown rice ^{137}Cs (b) at KND in 2013 (2.03 Bq kg^{-1}) was an outlier and hence excluded from data.

Figure 3. Relationships between ^{137}Cs and ^{133}Cs concentrations in straw (upper panels) and brown rice (lower panels). The significances of the correlation coefficients (r) by t-test is indicated with asterisks: $^{**}p < 0.010$, $^{***}p < 0.001$. Regression lines are shown when significant correlation was observed at $p < 0.050$.

Figure 4. Exchangeable NH_4^+ (a) and K (b) contents in control (CR) and increased N fertilizer (IN) subsections at the YWR field for samples collected five times in 2014: the days before transplanting (15 May), before midsummer drainage (23 Jun), after midsummer drainage in the medial- and short-flooding sections (16 Jul), after heading stage (6 Aug), and after drainage in the long-flooding section (5 Sep). Rectangles and error bars respectively represent

the averages and standard deviations of triplicates.

Table 1. Schedule of paddy field management during the experiment

	2012		2013				2014			
Field management	YWR		YWR		KND		YWR		KND	
Basal dressing fertilizer application and soil mixing	1	May	7	May	13	May	7	May	12	May
Start of flooding and puddling	9		13		10–12[a]		14		14	
Transplanting	11		15		15		16		19	
Starting midsummer drainage in MF and SF sections	29	June	24	June	24	June	25	June	25	June
Re-flooding in MF section	6	July	2	July	2	July	15	July	15	July
Re-flooding in SF section	13		9		10		15		15	
Top-dressing fertilizer application	18		18		18		22		25	
Drainage in SF section	20	August	15	August	15	August	15	August	15	August
Drainage in MF section	27		23		22		22		22	
Drainage in LF section	5	September	30		30		4	September	3	September
Harvesting	26		10	September	11	September	19		16	

[a] In the case of 2013 in KND field, flooding started before basal dressing although the exact starting date was unfortunately not recorded. LF, MF and SF in the table mean as long-, medial- and short-flooding, respectively.

Table 2. Annual mean of soil ^{137}Cs and exchangeable K contents after harvest in experimental sections and subsections.

		Soil ^{137}Cs (Bq kg^{-1})					Exchangeable K (mmol kg^{-1})				
Sections		YWR			KND		YWR			KND	
or subsections		2012	2013	2014	2013	2014	2012	2013	2014	2013	2014
Water management	LF	160	136	167	167	173	4.7	4.4	4.6	2.5	2.9
	MF	164	135	154	148	183	4.8	5.3	5.2	2.7	2.9
	SF	174	147	161	147	169	4.8	5.5	5.8	2.7	3.0
Fertilizer	CR	164	133	155	151	152	4.9	5.4	5.3	2.5	2.7
	0K	157	156	161	138	185	4.4	4.5	4.3	2.5	2.2
	3BK	160	139	166	161	182	5.3	5.7	6.5	2.9	3.8
	3TK	171	122	153	166	181	4.8	4.7	4.7	2.6	3.0
	KS	174	138	177			4.4	5.0	5.1		
	0TK/IN	171	147	154			4.9	5.0	5.2		

Water management sections: LF, long flooding; MF, medial flooding; SF, short flooding. Fertilizer subsections; CR, control; 0K, no K fertilizer application; 3BK, triple basal dressing of KCl; 3TK, triple top-dressing of KCl; KS, K_2SiO_3 application instead of KCl; 0TK/IN, no K top-dressing in 2012 and increased N fertilizer application in 2013 and 2014.

Table 3. Annual mean yields of straw and brown rice in experimental sections and subsections.

Sections or subsections		Straw yield ($g\ m^{-2}$) YWR 2012	YWR 2013	YWR 2014	KND 2013	KND 2014	Brown rice yield ($g\ m^{-2}$) YWR 2012	YWR 2013	YWR 2014	KND 2013	KND 2014
Water management	LF	685	792	664	551	694	438	460	388	417	423
	MF	661	801	759	556	682	432	471	470	406	401
	SF	685	817	809	510	717	463	468	479	393	427
Fertilizer	CR	651	814	732	552	708	437	477	431	409	418
	0K	681	786	720	562	700	443	466	451	411	418
	3BK	717	788	729	502	693	461	485	437	395	411
	3TK	608	762	680	540	689	402	429	425	407	421
	KS	743	834	811			482	497	485		
	0TK/IN	662	834	792			440	444	447		

Values are based on dry matter mass. Water management sections: LF, long flooding; MF, middle flooding; SF, short flooding. Fertilizer subsections; CR, control; 0K, no K fertilizer application; 3BK, triple basal dressing of KCl; 3TK, triple top-dressing of KCl; KS, K_2SiO_3 application instead of KCl; 0TK/IN, no K top-dressing in 2012 and increased N fertilizer application in 2013 and 2014.

Table 4. Annual means of K concentrations in straw and brown rice in experimental sections and subsections.

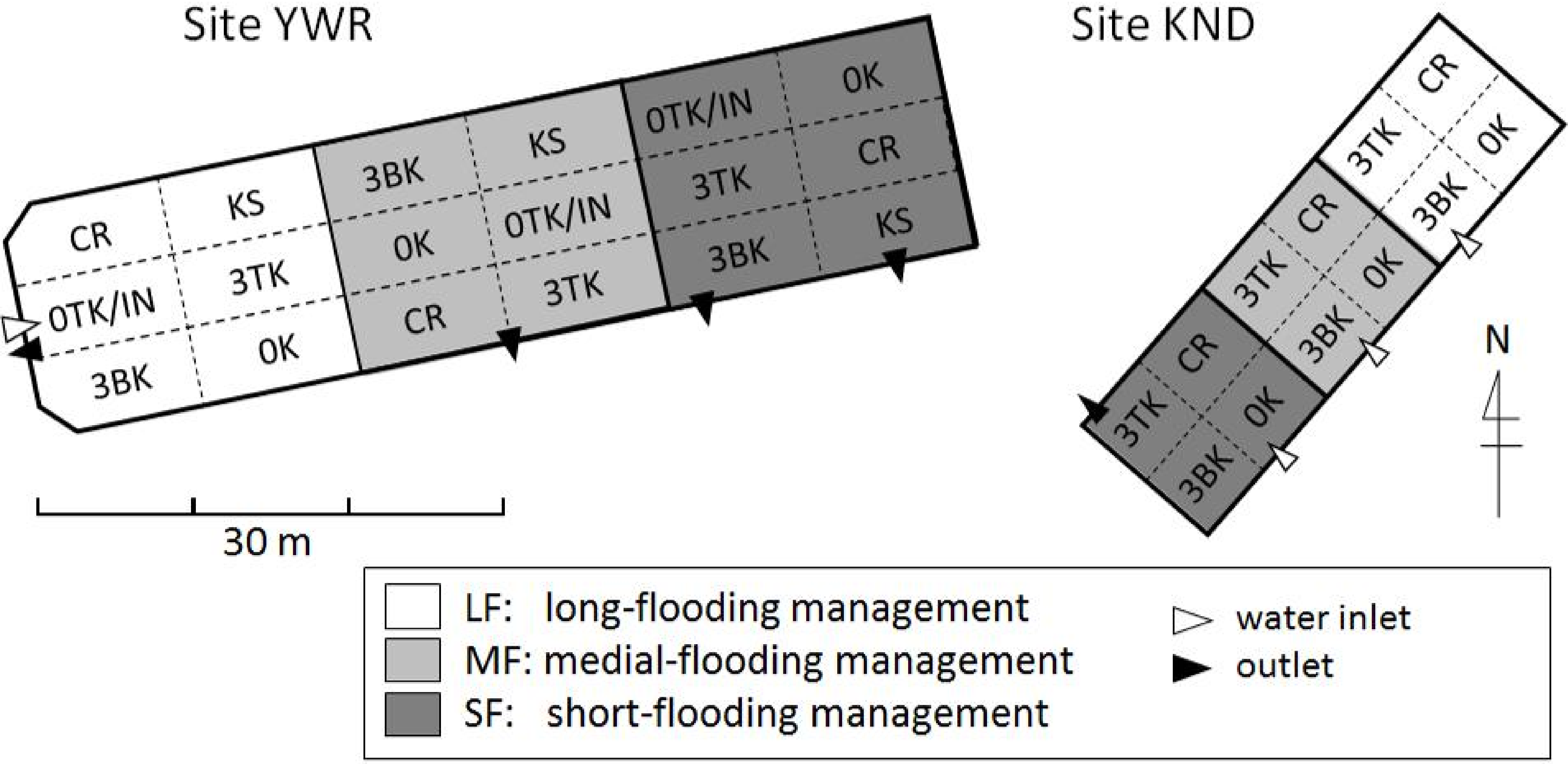
Sections or subsections		Straw K (g kg^{-1})					Brown rice K (g kg^{-1})				
		YWR			KND		YWR			KND	
		2012	2013	2014	2013	2014	2012	2013	2014	2013	2014
Water management	LF	16.0	19.4	18.4	17.3	18.5	2.87	2.82	2.70	2.91	2.64
	MF	16.1	19.1	19.8	16.4	17.3	2.89	2.82	2.74	2.95	2.69
	SF	16.7	18.4	19.3	15.8	17.0	2.98	2.92	2.71	2.95	2.61
Fertilizer	CR	16.1	20.1	19.4	16.3	17.9	2.87	2.90	2.71	2.95	2.66
	0K	16.4	18.8	18.8	16.4	17.1	2.99	2.90	2.72	2.90	2.67
	3BK	16.3	19.4	19.5	16.6	16.9	2.78	2.99	2.70	2.98	2.60
	3TK	16.0	17.2	18.2	16.6	18.7	2.97	2.76	2.80	2.92	2.66
	KS	16.7	20.6	20.3			2.91	2.97	2.68		
	0TK/IN	16.2	17.9	18.7			2.98	2.59	2.68		

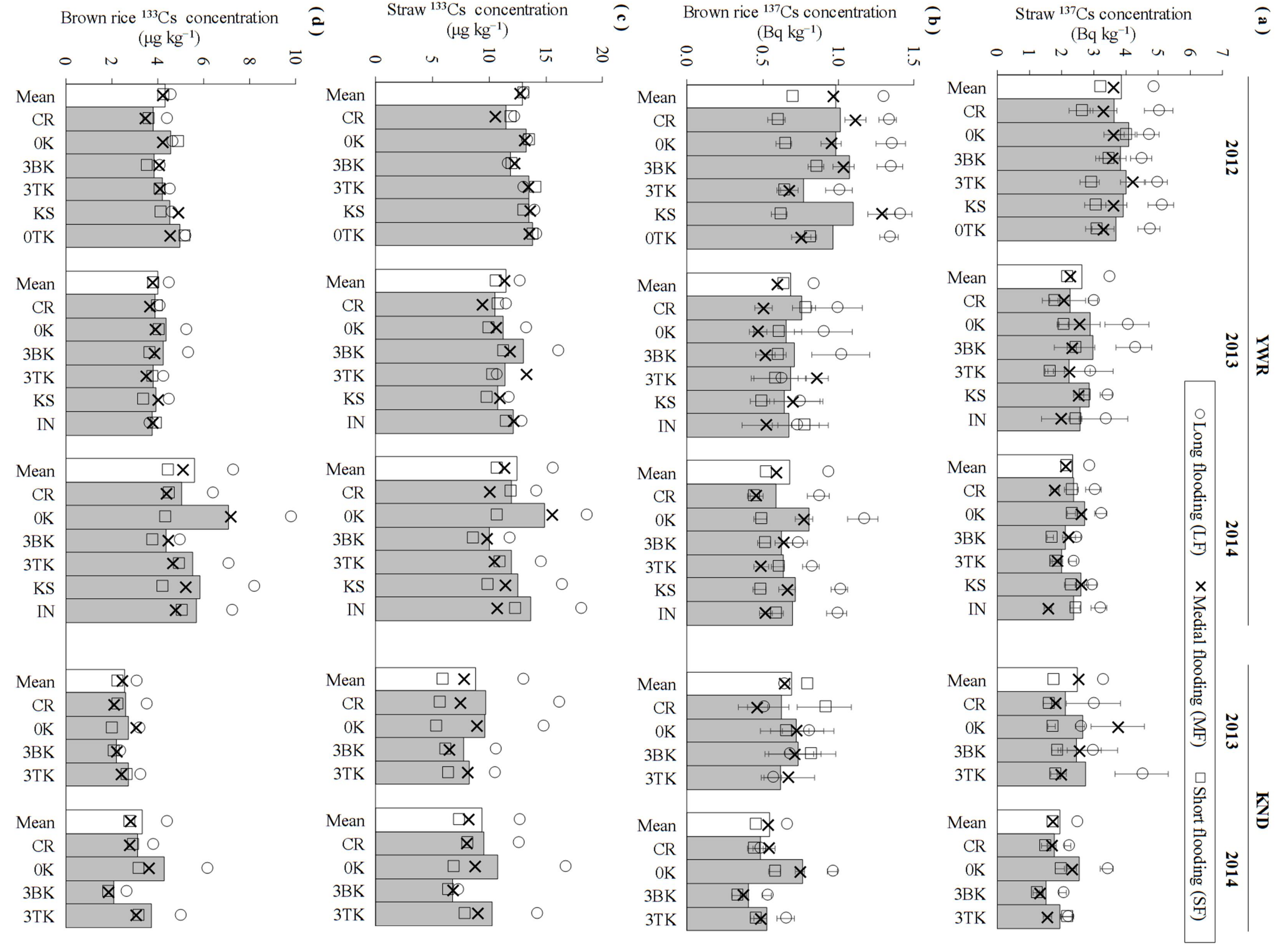
Water management sections: LF, long flooding; MF, middle flooding; SF, short flooding. Fertilizer subsections; CR, control; 0K, no K fertilizer application; 3BK, triple basal dressing of KCl; 3TK, triple top-dressing of KCl; KS, K2SiO3 application instead of KCl; 0TK/IN, no K top-dressing in 2012 and increased N fertilizer application in 2013 and 2014.

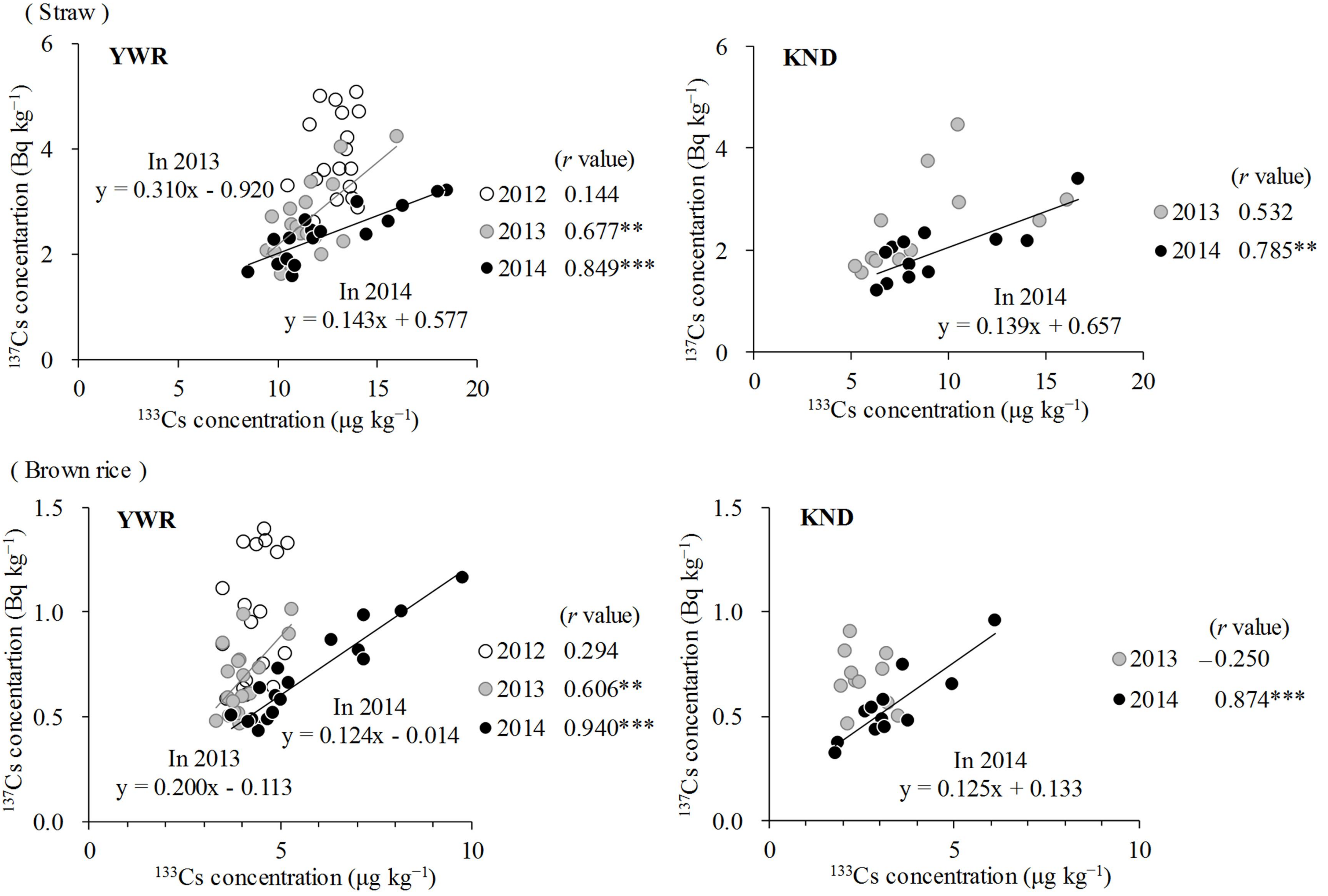
Table 5. Analysis-of-variance table for ^{137}Cs activity and ^{133}Cs concentration in straw and brown rice with results of Tukey's post-hoc multiple comparisons.

Factor	DF[a]	Error term	Straw ^{137}Cs			Brown rice ^{137}Cs			Straw ^{133}Cs			Brown rice ^{133}Cs		
			MS[b]	F	*p*	MS	F	*p*	MS	F	*p*	MS	F	*p*
Fixed effects														
Water management	2	s w	5.61	107.6	0.0092	0.171	2.0	0.3370	98.5	9.6	0.0942	10.2	34.9	0.0279
Fertilizer	3	s w f	0.75	3.0	0.0866	0.045	3.7	0.0572	10.1	3.3	0.0732	4.0	17.7	0.0004
Year	1	Residual	2.11	8.9	0.0114	0.079	6.0	0.0320	4.2	1.9	0.1958	14.2	37.2	0.0001
w f	6	s w f	0.13	0.5	0.7862	0.027	2.2	0.1369	5.0	1.6	0.2455	0.8	3.5	0.0443
w y	2	Residual	0.65	2.7	0.1058	0.057	4.3	0.0414	0.3	0.1	0.8810	1.8	4.7	0.0312
f y	3	Residual	0.41	1.7	0.2179	0.051	3.8	0.0399	10.3	4.6	0.0230	2.4	6.2	0.0087
w f y	6	Residual	0.18	0.8	0.6160	0.023	1.7	0.1946	3.6	1.6	0.2280	0.5	1.2	0.3716
Random effects														
Site	1	s w	0.57	10.8	0.0812	0.068	0.8	0.4672	91.8	9.0	0.0957	41.3	141.2	0.0070
s w	2	s w f	0.05	0.2	0.8154	0.085	7.1	0.0155	10.2	3.3	0.0835	0.3	1.3	0.3235
s w f	9	Residual	0.25	1.1	0.4564	0.012	0.9	0.5462	3.1	1.4	0.2945	0.2	0.6	0.7761
Residual	12		0.24			0.013			2.2			0.4		
Tukey's post-hoc		In 2013–2014		LF > MF, SF			-			-			-	
multiple		In 2013		-			no significance			no significance			-	
comparisons test		In 2014		-			0K > CR, 3BK, 3TK			0K, 3TK > 3BK			-	

[a] Degrees of freedom. [b] Mean square. Interactions between factors were shown as combinations of capital letter for each factor (w: water management, f: fertilizer, y: year, s: site). Data from four subsections (CR, 0K, 3BK and 3TK) in 2013–2014 were used for the analysis. When effects of water management or fertilizer were significant ($p < 0.050$) without any interaction, Tukey's post-hoc multiple comparisons test was used to determine significant differences among water management sections (LF, long flooding; MF, middle flooding; SF, short flooding) or fertilizer subsections (CR, control; 0K, no K fertilizer; 3BK, triple basal dressing of KCl; 3TK, triple top-dressing of KCl) at $p < 0.050$. When significant interactions of year with water management or fertilizer were revealed by ANOVA, the post-hoc test was performed separately for 2013 and 2014 data at $p < 0.025$.


Site YWR
CR
KS
0TK/IN
3TK
3BK
0K
3BK
KS
0K
0TK/IN
CR
3TK
0TK/IN
0K
3TK
CR
3BK
KS
30 m
Site KND
CR
3TK
0K
3BK
CR
3TK
0K
3BK
CR
3TK
0K
3BK
N
LF: long-flooding management
MF: medial-flooding management
SF: short-flooding management
water inlet
outlet


(a)
Straw ^{137}Cs concentration (Bq kg^{-1})
0
1
2
3
4
5
6
7
(b)
Brown rice ^{137}Cs concentration (Bq kg^{-1})
0.0
0.5
1.0
1.5
(c)
Straw ^{133}Cs concentration (μg kg^{-1})
0
5
10
15
20
(d)
Brown rice ^{133}Cs concentration (μg kg^{-1})
0
2
4
6
8
10
YWR
KND
2012
2013
2014
2013
2014
Mean
CR
0K
3BK
3TK
KS
0TK
IN
○ Long flooding (LF)
× Medial flooding (MF)
□ Short flooding (SF)


(Straw)
YWR
KND
In 2013
y = 0.310x - 0.920
In 2014
y = 0.143x + 0.577
(r value)
2012 0.144
2013 0.677**
2014 0.849***
In 2014
y = 0.139x + 0.657
(r value)
2013 0.532
2014 0.785**
^{137}Cs concentartion (Bq kg^{-1})
^{133}Cs concentration (μg kg^{-1})
0
2
4
6
0
5
10
15
20
(Brown rice)
YWR
KND
In 2014
y = 0.124x - 0.014
In 2013
y = 0.200x - 0.113
(r value)
2012 0.294
2013 0.606**
2014 0.940***
In 2014
y = 0.125x + 0.133
(r value)
2013 –0.250
2014 0.874***
0.0
0.5
1.0
1.5
0
5
10