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Highlights

- Depth migration of ^{137}Cs were investigated in soil cores collected on contaminated paddy field.
- Major part of ^{137}Cs remain in the uppermost 5 cm even 30 months after the accident.
- More than 50% of contamination could remain in tilled soil after decontamination.
- Radiocesium migrate in the uppermost 3 cm after grass cutting.

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Abstract

Large quantities of radiocesium were deposited across a 3000 km² area northwest of the Fukushima Dai-ichi nuclear power plant after the March 2011 accident. Although many studies have investigated the fate of ^{137}Cs in soil in the months following the accident, the depth distribution of this radioactive contaminant in rice paddy fields requires further examination after the typhoons that occurred in this region. Such investigations will help minimize potential human exposure in rice paddy fields. Radionuclide activity concentrations, organic content and particle size were analysed in 10 soil cores sampled from paddy fields in November 2013, 20 km north of the Fukushima power plant. Our results demonstrate limited depth migration of ^{137}Cs with the majority concentrated in the uppermost layers of soils (<5 cm). More than 30 months after the accident, between 46.8 to 98.7% of the total ^{137}Cs inventories was found within the top 5 cm of the soil surface, despite cumulative rainfall totalling 3300 mm. Furthermore, there were no significant correlations between ^{137}Cs depth distribution and the other parameters. We attributed the maximum depth penetration of ^{137}Cs to grass cutting (73.6-98.5% of ^{137}Cs in the upper 5 cm) and farming operations (tillage – 46.8-51.6% of ^{137}Cs in the upper 5 cm). As this area is exposed to erosive events, ongoing decontamination works may increase soil erodibility. We therefore recommend the rapid removal of the uppermost – contaminated – layer of the soil after removing the vegetation to avoid erosion of contaminated material during the subsequent rainfall events. Further analysis is required to thoroughly understand the impacts of erosion on the redistribution of radiocesium throughout the Fukushima Prefecture.

1 Introduction

The Tohoku earthquake and the subsequent tsunami on March 11, 2011 resulted in the Fukushima Dai-Ichi Nuclear Power Plant (FDNPP) accident and the significant corresponding atmospheric release of radionuclides, such as ^{137}Cs ($T_{1/2}$ = 30 years) (Saunier et al., 2013). Approximately 80% of the release was transported over the Pacific Ocean with the remainder predominantly deposited on Fukushima Prefecture soils as a result of wet atmospheric fallout

(Kawamura et al., 2011). Estimations of ^{137}Cs total activity in the Fukushima Prefecture soils range between 10 PBq and 50 PBq, with deposition characterized by strong spatial heterogeneities (Koo et al., 2014). The highest activities are concentrated within a 70 km long radioactive plume where initial ^{137}Cs contamination exceeded 300 $kBq.m^{-2}$ covering an area of 3000 km^2. Therefore it is crucial to understand and monitor the fate of the initial radioactive deposits in order to protect the local population against exposure to high dose rates due to gamma radiation that may prevail in areas accumulating contamination.

In the coastal catchments affected by the FDNPP accident, Chartin et al. (2013) showed that paddy fields are one of the major sources of ^{137}Cs mobilization and export by soil erosion. A significant proportion of paddy fields are located in the upstream area of the contaminated catchments and they were shown to supply large quantities of contaminated sediment to rivers during typhoons and snowmelt events (Evrard et al., 2013; Evrard et al., 2014). Dispersion of contamination originating from paddy fields along the rivers of the region could therefore contaminate downstream areas that were affected to a limited extent by the initial fallout. In this region, background levels of ^{137}Cs from fallout from atmospheric nuclear weapons testing were estimated to be under $100Bq.kg^{-1}$ (Fukuyama et al., 2005).Several studies have shown that ^{137}Cs has a low mobility in most soils (Beck 1966, Ivanov et al., 1997) and is rapidly fixed to fine particles, especially clay minerals (Sawhney, 1972; He & Walling, 1996). These findings were confirmed in the vicinity of the main contamination plume in the Fukushima Prefecture where Saito et al. (2014) reported that ^{137}Cs was concentrated in the silt and clay fractions. Also, it was reported that the majority of ^{137}Cs remained in the first centimetre of the soil profile (Fujiwara et al., 2012; Kato et al., 2012; Koarashi et al., 2012; Lepage et al., 2014). However, it was also shown that in soils with high levels of organic matter, radiocesium may migrate down the soil profile as organic matter may reduce its affinity with clay minerals (Kamei-Ishikawa et al., 2008; Koarashi et al., 2012; Staunton et al., 2002; Szenknect et al., 2003). Koarashi et al. (2012) analysed several soil profiles sampled in the vicinity of Fukushima City and showed that clay content and Total Organic Carbon (TOC) were the main factors controlling radiocesium depth migration. They also found a strong negative correlation ($r = -0.79$, $p < 0.005$) between TOC content divided by clay content (TOC/Clay) and the percentage of retention of ^{137}Cs suggesting that the presence of organic matter inhibits the adsorption of ^{137}Cs on clay minerals.

Thirty months after the accident, it is important to investigate the depth distribution of ^{137}Cs in a selection of paddy fields located within the main contamination plume of Fukushima Prefecture. The concentration of ^{137}Cs in the uppermost layers of the soil could make it available for erosion and delivery to nearby rivers. This investigation of ^{137}Cs depth distribution in paddy fields is particularly timely in the current post-accidental phase characterised by the implementation of large-scale remediation efforts targeting paddy fields. The implications of these findings for potential soil erosion will be specifically discussed.

2 Materials and methods

2.1 Study area

The study was conducted in Fukushima Prefecture, located in North-Eastern Japan, 30 km northwest of FDNPP (Fig. 1). We focused our work on two coastal catchments (i.e. Mano and Niida River catchments - 450km^2) draining the main part of the radioactive plume. These catchments extend from the coastal mountain range (approximately 30 km from the coast) to the Pacific Ocean, and their elevation ranges from 0 to 900 m. Mean annual rainfall was 1320 mm according to Japanese Meteorological Agency (2014) measured over 37 years at the rainfall station located in the upper part of the Nitta catchment (Fig. 1). Our study was conducted in November 2013 and cumulative rainfall reached 3300mm (max = 35$mm.h^{-1}$) between the accident and our field survey (32 months) with the occurrence of 4 typhoons (Songda and Roke in 2011, Man-Yi and Wipha in 2013). In these catchments, paddy fields are predominantly located along the rivers (Tanaka et al., 2013).

Remediation works implemented since July 2012 under the supervision of the Japanese Ministry Of Environment, Government of Japan (MOE, 2012a; MOE, 2013) are concentrated in upper parts of the Nitta River catchment and consist of removing the five uppermost centimetres of the soil (Mizoguchi, 2013; Sakai et al., 2014) to decrease the radioactive dose level in order to avoid exceeding the permissible level (1 mSv y^{-1}) determined by Japanese authorities (MOE, 2012b).

2.2 Sample collection and preparation

A radiameter (LB123 D-H10, Berthold Technologies) was used to measure radiation dose rates at the ground level in the paddy fields (Table 1). To be representative, dose levels were measured at 5 different locations on each field within 10m^2. The formula Eq. (1) proposed by

the Ministry of Environment MOE (2012b) was then applied to convert these data into annual dose rates.

$$D_{an} = \frac{(D_{amb} - 0.04) * (8 + 16 * 0.4) * 365}{1000} \quad (1)$$

Where D_{amb} is the ambient dose rate, and D_{an} is the annual dose rates.

Soil cores (Table 1) were collected in paddy fields across the two selected catchments (Fig 1). We selected the fields to cover a range of dose rates (low, medium and high) in order to investigate migration of ^{137}Cs in fields with different levels of contamination (Table 1).

A soil auger (diameter 45 mm) was used to sample soil cores to a depth of 10 cm from 10 fields. The soil cores were sub-sectioned into 1 cm increments for the uppermost 5 cm (0-1; 1-2; 2-3; 3-4; 4-5 cm) and an additional 5 cm increment was taken from 5 cm to 10 cm (5-10 cm). Because of the very high radioactive dose rate measured at the location where core P9 was sampled (5.5 $\mu sv.h^{-1}$), two additional layers were sampled at greater depths (10-15 cm and 15-20 cm). Density of the soil was determined by dividing the dry soil mass in each layer by its volume determined from the diameter of the soil auger and the thickness of the layer. Mean compaction in the cores was estimated to be 13% using soil density. Soil TOC content was measured with the dry combustion method (VarioTOC, Elementar, LAME, IRSN, Fontenay aux Roses, France) and clay content (particle size < 10µm) of the samples was measured using a laser diffraction system (Malvern Mastersizer 2000) coupled to a liquid dispersing unit (Hydro 2000G, University of Paris Sud, Orsay, France). XRD measurement were performed on a diffractometer (INEL XRG 3000, L3MR, CEA, Saclay, France) equipped with a curved position sensitive detector CPS 120 and radiation were produced at 30 kV and 30 mA.

2.3 Gamma spectrometry measurements

Before measurement, samples were dried in an oven at 40°C for a week, ground to a fine powder in an agate mortar, and then packed into 15 mL polyethylene specimen containers. Cesium-137 activities were determined by gamma spectrometry using low-background coaxial N- and P-types HPGe detectors (Canberra/Ortec). Counting times of samples varied between 80 000 s and 150 000 s. The ^{137}Cs activities were measured at the 661 keV emission peak. Counting efficiencies and energy calibration were monitored using internal, national (IRSN) and certified International Atomic Energy Agency (IAEA) reference materials (i.e., IAEA-135, IAEA-375, IAEA-CU-2006-03, IAEA-Soil-6, RGU-1, and RGTh-1) prepared in the same specimen

containers as the samples. Uncertainties were estimated by combining counting statistics and calibration uncertainties. Summing and self-absorption effects were taken into account by measuring reference materials with similar densities and characteristics as the collected samples. All activities were decay corrected to the date of 14 March 2011 corresponding to the date of the main radionuclide deposits on soils (Kinoshita et al., 2011; Shozugawa et al., 2012).

2.4 Distribution of ^{137}Cs with depth

Radiocesium profiles in undisturbed soils are expected to display an exponential decline with depth (He & Walling, 1997; Walling & He, 1999), which can be described by the following function (Beck, 1966):

$$C_{(x)} = C_0 * \exp^{-\alpha.x} \quad (2)$$

Where C(x) is the concentration activity of a radionuclide in $Bq.kg^{-1}$ at the depth x (cm) and C_0 at x=0, and α (cm^{-1}) is a coefficient representing the characteristics of the radionuclide distribution and depends on different characteristics of the soil (e.g. pH, CEC, TOC, clay content).

In addition, a more specific model can be used to describe ^{137}Cs mobility in soils (Kato et al., 2012; Koarashi et al., 2012; Miller et al., 1990):

$$I_{(x)} = I_t \, (1 - \exp^{-z/h_0}) \quad (3)$$

Where $I_{(z)}$ is the ^{137}Cs inventory ($Bq.m^{-2}$) at the z ($kg.m^{-2}$) depth, I_t is the total ^{137}Cs inventory and h_0 is the relaxation mass depth ($kg.m^2$), an index characterising the ^{137}Cs penetration in the soil. The greater the value of the relaxation mass depth h_0, the deeper the ^{137}Cs penetrates into the soil profile (Kato et al., 2012).

In order to use this formula, we calculated the ^{137}Cs inventory using ^{137}Cs activities ($Bq.kg^{-1}$) (Lee et al., 2013) at the successive (x) depths (Eq. 4):

$$I(x) = \rho(x) * h(x) * A(x) \quad (4)$$

Where ρ is the dry bulk density ($g.m^{-3}$), h is the thickness (cm) of the layer and A the activity ($Bq.kg^{-1}$) of this layer.

3 Results and discussion

3.1 Depth distribution

Based on the distribution of ^{137}Cs activity with depth, soil cores were classified into four groups (undisturbed, decontaminated, tilled and managed) (Table 2 - Fig 2) :

- Undisturbed: distribution shown an exponential decrease of ^{137}Cs activity with depth (Fig 3),
- Decontaminated: very low level of ^{137}Cs activity in all layers,
- Tilled: similar level of ^{137}Cs activity in each layer,
- Managed: similar level of contamination in the upper 2-3cm then exponential decrease with depth of the ^{137}Cs activity.

The group of undisturbed fields (P6, P7 and P9) remained abandoned by the end of 2013 as they were protected by a dense grass cover (Fig 4a) and they showed an exponential decrease of ^{137}Cs activities with depth (Fig 3). Furthermore, our results on relaxation mass depths h_0 in undisturbed soils (Table 2) varied from 5.4 to 8.3 and remained in the same range as previous results found for soils collected in this area (Table 3). Although this result indicates a limited migration of ^{137}Cs, contamination from the FDNPP accident could still be found at the 10-15 cm and 15-20 cm layers in P9 (respectively 370 and 170 $Bq.kg^{-1}$, Fig 2). This is likely due to the natural migration of ^{137}Cs as this soil core was heavily contaminated (155 $kBq.kg^{-1}$) and contained 8.5% of TOC. Nevertheless, level of contamination corresponded to less than 10% of total contamination of P9, as observed in the other undisturbed soil cores.

The core P5 did not show evidence of additional contamination of ^{137}Cs due to Fukushima accident (Fig 2) as at this site the ^{137}Cs concentration levels remained similar to pre-accident conditions, which were estimated not to exceed 100 $Bq.kg^{-1}$ in Japanese soils (Fukuyama et al., 2005). However, the detection of ^{134}Cs confirms that this field was contaminated by the Fukushima fallout and subsequently decontaminated by remediation efforts (Fig 4b - Mizoguchi, 2013; Sakai et al., 2014).

P2 and P4 were disturbed after the initial radionuclide deposition, resulting in a homogenization of activities in successive soil layers (Fig 2; Fig 3). These fields were most likely tilled by farmers (Endo et al., 2013; Matsunaga et al., 2013; Yamaguchi et al., 2012) and now around

51% of the total contamination inventory is found deeper in the soil (i.e. 5-10 cm) (Table 2). This percentage could be higher (≈66%) as tilled soils generally showed a similar level of contamination until 15 cm (Endo et al., 2013; Yamaguchi et al., 2012). Thus, a greater sampling depth should be considered for future investigations on ^{137}Cs migration in Fukushima soils. The ongoing farming operations in this area can be explained by the fact that those fields are not located in the evacuation-prepared area and that cultivation is allowed (Fig 1).

In contrast, managed fields (P1, P3, P8 and P10) showed a similar level of contamination in the upper 2-3 centimetres and then a decrease (Fig 2). These four fields have been continuously managed since the accident, as illustrated by our field observations during previous campaigns (Nov. 2011, April 2012 and May 2013). Grass was cut each year using heavy machinery (Fig 4c), which may explain the mixing of soil and associated ^{137}Cs in these fields due to the compaction of the first few centimetres of the soil (Jagercikova et al., 2014; Matsunaga et al., 2013). Takahashi et al. (2014) also reported the same migration in the uppermost 3-centimetres and concluded that it was caused by the repeated formation and melting of needle ice in the surface soil during winter and spring. Further investigation is required to clarify the process involved in this migration. However, our results demonstrated that 73.6 to 98.5% of the ^{137}Cs contamination was concentrated in the upper 5 cm (Table 2).

Contrary to the results obtained by Koarashi et al. (2012), no significant correlation was found between TOC, clay content, TOC/Clay and both the α coefficient and the relaxation mass depth h_0 (Table 4) in both managed and undisturbed soils (number of samples = 7). As the depth distribution of ^{137}Cs in soils does not vary with the soil parameters, the different ^{137}Cs migration observed between undisturbed and managed fields is most likely explained by the type and frequency of farming operations carried out between the nuclear accident and the sampling campaign. The limited migration of ^{137}Cs could be attributed to the presence of phyllosilicate minerals as identified by XRD analyses (data not presented). These results confirm those found for undisturbed soils located under different land uses in the vicinity of the FDNPP by previous studies (Table 3). Most of these studies concluded that ^{137}Cs was exclusively found in the upper 5 cm for undisturbed soil in forests (mean of ^{137}Cs inventory = 94.8±2.5%) and in fields (98.7±1.8%). Our results on tilled soils are also consistent with those from previous publications (Endo et al., 2013; Koarashi et al., 2012; Matsunaga et al., 2013; Tanaka et al., 2013).

To complement the published research conducted a few months after the accident (Fig 5 – Table 4), our results showed that even more than 30 months after the accident and after the occurrence of several typhoons (Fig 5), the depth migration of ^{137}Cs was very limited with the majority (73.6 – 98.7%) of this radionuclide still found in the upper 5 centimetres of undisturbed and managed soils. These results are complementary with the study of Mastunaga et al. (2013) who concluded that radiocesium did not migrate with depth even after rainfalls, 5 months after the accident. Tilling is the main contributor of the migration of radiocesium in soil as the main part of contamination is under the first layers (48.4 – 53.2%) in tilled fields (Table 3).

3.2 Implications for contamination redistribution across the catchments

In most of the investigated soil cores, contamination was concentrated in the upper layers of the soils and is therefore potentially available for soil erosion (Motha & Wallbrink, 2002; Walling & Woodward, 1992). However, in abandoned fields, the dense grass cover will protect the soil against erosion as soil erodibility is mainly controlled by the vegetation cover, surface roughness and crusting characteristics (Evrard et al., 2008; Le Bissonnais et al., 2005). During decontamination operations, the grass is cut and vegetation is removed leaving the soil bare and exposed to the erosive impact of intense rainfall. The specific supply of contaminated sediment from fields where remediation efforts were concentrated to nearby rivers was demonstrated by Evrard et al (2014) who showed an increase of radioactive dose rates in recent sediment drape deposits collected in upper parts of the Nitta River catchment after the heavy typhoons that occurred during summer in 2013.

In this context, we recommend rapidly removing the first few centimetres of the soil immediately after removing the vegetation to avoid erosion of contaminated material during the subsequent rainfall events. Alternatively, remediation efforts could be concentrated before July or after October, when typhoons are unlikely to occur. We do not recommend mixing soil with water (puddling) in contaminated fields, as this could export the contamination contained in the uppermost layers of the soil (Wakahara et al., 2013). Furthermore, contaminated soils that have been eroded and transported by the river could be deposited on top of already decontaminated soil (Sakai et al. 2014). To avoid this recontamination, we recommend to start the decontamination works in the catchment headwaters and to proceed downstream.

4 Concluding remarks

Depth distributions of ^{137}Cs investigated in 10 paddy fields varied with land management. The maximum depth penetration of ^{137}Cs collected in November 2013 was attributed to maintenance and farming operations in paddy fields contaminated after the FDNPP accident (March 2011). In tilled fields, the contamination showed a similar level in each layer (0-10cm) while in managed field, where vegetation was removed, contamination only migrated down the first 2-3 cm. In undisturbed soils, ^{137}Cs inventory decreased with depth following an exponential function. Our results confirm the overall limited migration of ^{137}Cs concentrated in the first few centimetres (<5 cm) of soil in undisturbed and managed paddy fields located within the main Fukushima contamination plume.

Author contribution

H.L. and O.E. wrote the main manuscript; O.E. and Y.O. designed research; H.L. and O.E. conducted field sampling; H.L. and I.L. conducted laboratory measurements. Y.O., J.P. L. and S.A. participated to the redaction and reviewed the manuscript.

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Figure captions

Figure 1. Map of the study area with location of the soil cores collected within Mano and Nitta River catchments including ^{137}Cs soil inventory decay corrected to the date of 14 June 2011 based on the Japanese Ministry of Education, Culture, Sports, Science and Technology data (MEXT, 2012) and April 2014 restricted access areas delineated by Ministry of Economy, Trade and Industry (METI, 2014).

Figure 2. Depth distribution of ^{137}Cs activity in soil cores. Data on the 4-5 cm layer for P6 were not available (n/a).

Figure 3. Depth distribution of ^{137}Cs inventory in the different groups of contaminated soil cores.

Figure 4. Pictures taken during the sampling campaign (November 2013) and illustrating the difference of land management practices in the field, a) P9 - dense cover of grass on the field showed an absence of land management, b) P5 – land management in the field showed by tractor tracks and c) P8 - grass recently cut and presence of straw residues on the field.

Figure 5. Daily rainfall between FDNPP accident and this sampling campaign. Occurrence of typhoons is indicated on the graph. Timing of sampling campaigns of previous studies dealing with ^{137}Cs migration in soils is also indicated. Takahashi et al. (2014) also sampled at (1) (2) and (3).

Figure1
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Figure 1.

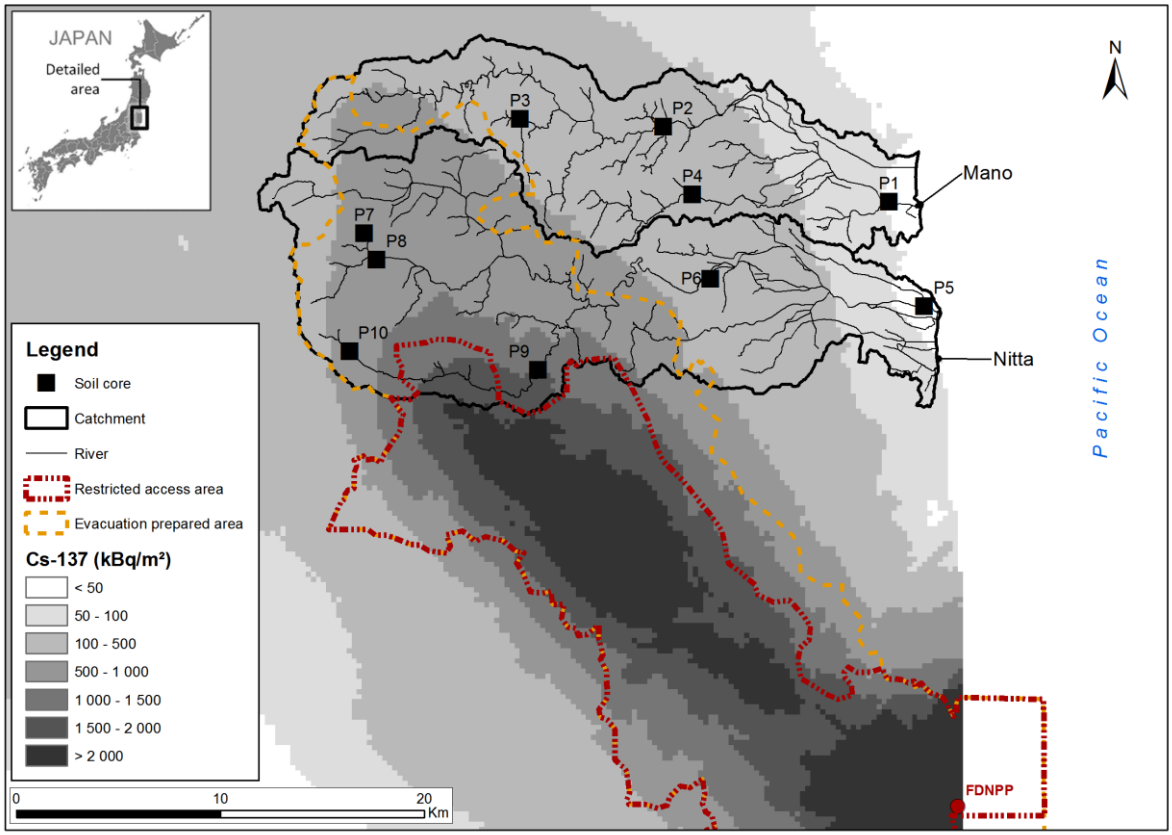

Figure2

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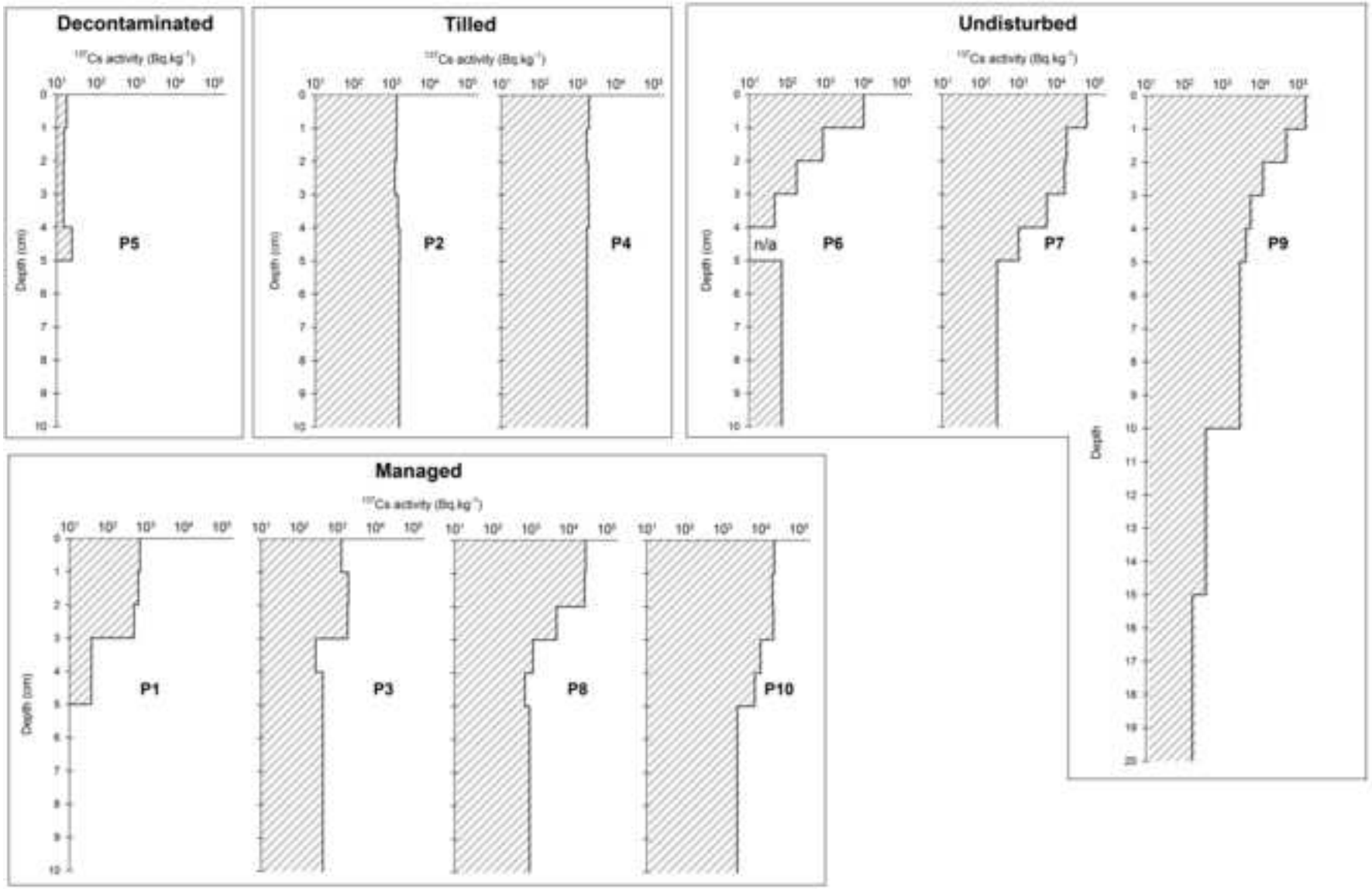

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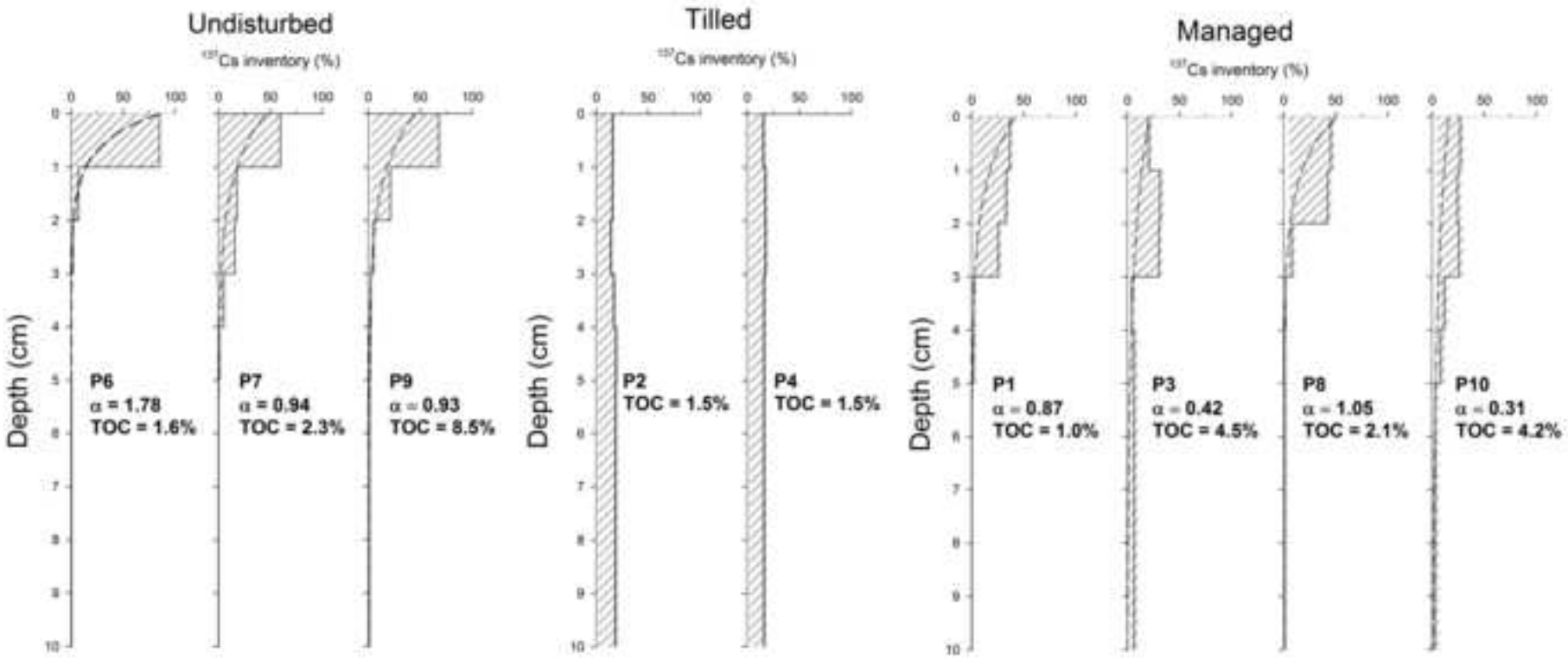

Figure4

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Figure 4.

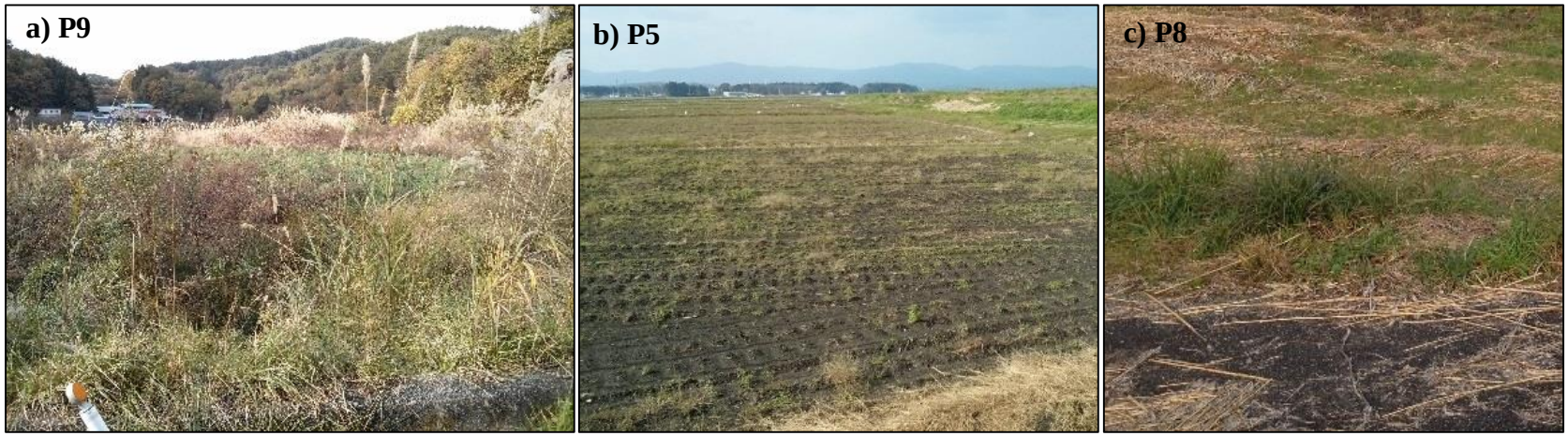

Figure5

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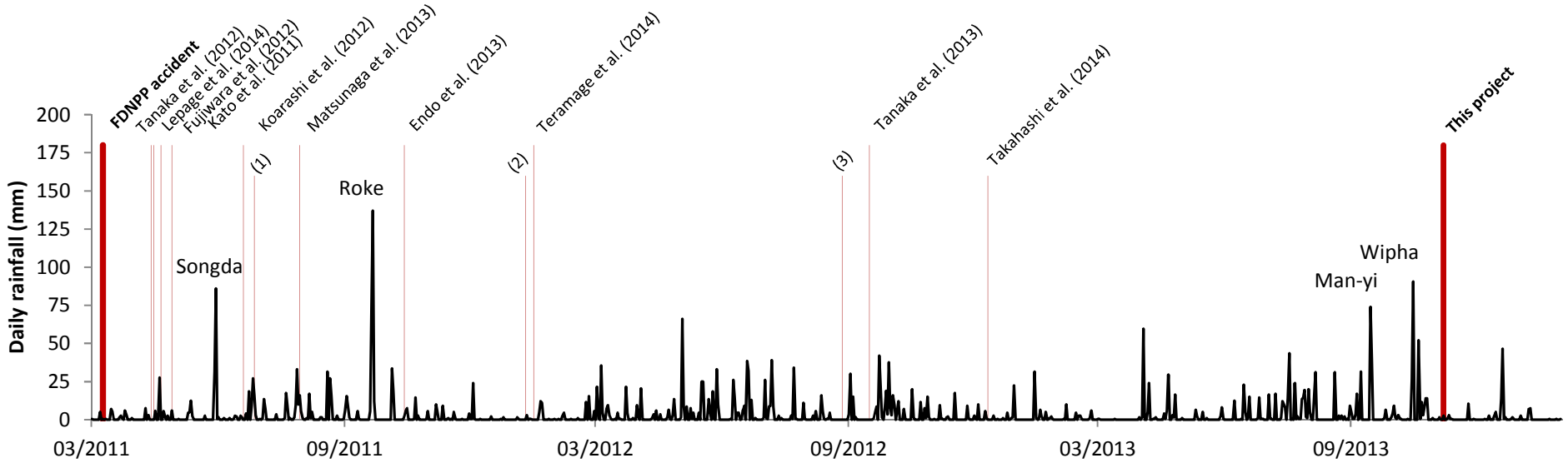

Table1
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Table 1. Location of investigated soil cores and ambient radioactive dose rates measured at the ground level. Annual dose rates exceeding the permissible level of 1mSv.y^{-1}are indicated in bold (MOE, 2012b).

Latitude	Longitude	Profile label	Dose rate (µSv.h^{-1})	Annual dose rate (mSv.y^{-1})	Japanese soil type (WRB)*
37.688264	140.995708	P1	0.2	0.8	Unknown
37.721432	140.870119	P2	0.4	**1.9**	Gray lowland soil (Gleyic Fluvisol)
37.724665	140.790469	P3	1.2	**6.1**	Gray lowland soil (Gleyic Fluvisol)
37.691504	140.886210	P4	0.5	**2.4**	Gray lowland soil (Gleyic Fluvisol)
37.642013	141.015405	P5	0.1	0.3	Unknown
37.654186	140.896448	P6	1.5	**7.7**	Gray lowland soil (Gleyic Fluvisol)
37.674029	140.703817	P7	2.7	**14.0**	Peat soil (Histosol)
37.662245	140.710906	P8	2.3	**11.9**	Gray lowland soil (Gleyic Fluvisol)
37.613850	140.800832	P9	5.5	**28.7**	Gray lowland soil (Gleyic Fluvisol)
37.621797	140.695852	P10	2.5	**12.9**	Gley soil (Gleysol)

* Determined using National Institute for Agro-Environmental Sciences (NIAES) cropland soil map (NIAES, 1996; NIAES)

Table2

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Table 2. Characteristics of the soil cores calculated for the uppermost 5 cm incremental layers. More detail is provided in the Supplementary material

Core	Class	^{137}Cs inventory (%)	Bulk density (g.cm^{-3})	h0 (kg.m^{-2})	α (cm^{-1})	Mean TOC (%)	Clay (%) d < 10µm
P1	Managed	98.5	1.3 ± 0.3	20.4	0.87	1.0 ± 0.1	14.1 ± 1.1
P2	Tilled	46.8	1.2 ± 0.2	n/a	n/a	1.5 ± 0.2	8.2 ± 0.2
P3	Managed	73.6	0.8 ± 0.2	17.4	0.42	4.5 ± 0.2	10.6 ± 0.9
P4	Tilled	51.6	0.8 ± 0.2	n/a	n/a	1.5 ± 0.1	11.9 ± 2.3
P5	Decontaminated	72.9	1.2 ± 0.2	n/a	n/a	n/a	n/a
P6	Undisturbed	97.1	1.2 ± 0.1	6.3	1.78	1.6 ± 0.3	13.7 ± 2.3
P7	Undisturbed	98.7	0.9 ± 0.2	8.3	0.94	2.3 ± 0.2	10.8 ± 1.1
P8	Managed	92.9	1.1 ± 0.2	10.4	1.05	2.1 ± 0.4	8.3 ± 0.2
P9	Undisturbed	92.8	0.7 ± 0.1	5.4	0.93	8.5 ± 0.3	14.6 ± 1.2
P10	Managed	87.1	0.8 ± 0.1	16.8	0.31	4.2 ± 0.4	16.2 ± 0.6

n/a : not available

Table 4. Literature review of studies investigating evolution of radiocesium activities with depth in soils contaminated by FDNPP radioactive fallout.

Shape	Reference	Sampling period (mm/yy)	Number of samples	Type of land use investigated	Mean of % upper 5 cm	α (cm^{-1})	h_0 ($kg.m^{-2}$)
Disturbed (Tilled)	Endo et al. (2013)	10/11	3	Paddy field	≈50	n/a	n/a
	Koarashi et al. (2012)	06/11	6	Croplands (with one paddy field)	81	n/a	n/a
	Matsunaga et al. (2013)	07/11	6	Croplands (with one paddy field)	80	n/a	n/a
	Tanaka et al. (2013)	09/12	3	Cultivated paddy field	55	n/a	n/a
	This study	11/13	2	Paddy field	49	n/a	n/a
Disturbed (managed, grazing)	Takahashi et al. (2014)	06/11	2	Land	99	0.3	n/a
			3	Field	98	1.0	n/a
		01/12	2	Land	99	0.5	n/a
			3	Field	98	0.6	n/a
		08/12	2	Land	100	0.7	n/a
			3	Field	94	0.5	n/a
		12/12	2	Land	98	0.4	n/a
			3	Field	88	0.6	n/a
	This study	11/13	4	Paddy field	88	0.7	18.2
Undisturbed	Fujiwara et al. (2012)	04/11	1	Brown forest soil	n/a	0.7	n/a
			1	Fluvisol	n/a	0.9	n/a
	Kato et al. (2011)	04/11	1	Vegetable field	n/a	2	n/a
			1	Cultivated soil (home garden)	99	1.2	9.1
	Koarashi et al. (2012)	06/11	6	Croplands (with one paddy field)	99	1.3	5.3
			4	Grassland	99	1.2	4.9
	Lepage et al. (2014)	04/11	5	Forest	97	0.6	8.4
			1	Cropland	n/a	1,9	7.1

Matsunaga et al. (2013)	07/11	6	Croplands (with one paddy field)	99	n/a	n/a
		4	Grassland	99	n/a	n/a
		5	Forest	97	n/a	n/a
Takahashi et al. (2014)	06/11	3	Forest	98	0.7	n/a
		2	Land	100	2.0	n/a
	01/12	3	Forest	92	0.6	n/a
		2	Land	100	1.7	n/a
	08/12	3	Forest	96	0.7	n/a
		2	Land	100	1.4	n/a
	12/12	3	Forest	94	0.7	n/a
		2	Land	100	1.3	n/a
Tanaka et al. (2012)	04/11	2	Field	95	n/a	n/a
		2	Fruit trees field	92	n/a	n/a
Teramage et al. (2014)	01/12	1	Coniferous forest	92	0.6	11.1
This study	11/13	3	Paddy field	96	1.2	6.7

n/a : not available

Table 4. Correlation coefficients (r) obtained between the vertical distribution parameters and soil properties measured in samples collected in both undisturbed and managed fields

	α	h_0	TOC (%)	Clay (%)	TOC/Clay
α	1				
h0	-0.66	1			
TOC (%)	-0.35	-0.30	1		
Clay (%)	-0.11	0.13	0.30	1	
TOC/Clay	-0.38	-0.29	0.95*	-0.01	1

* Significant at the 0.01 probability level