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Impact of forest thinning on the dynamics of litterfall derived ^{137}Cs deposits in coniferous forest floor after Fukushima accident

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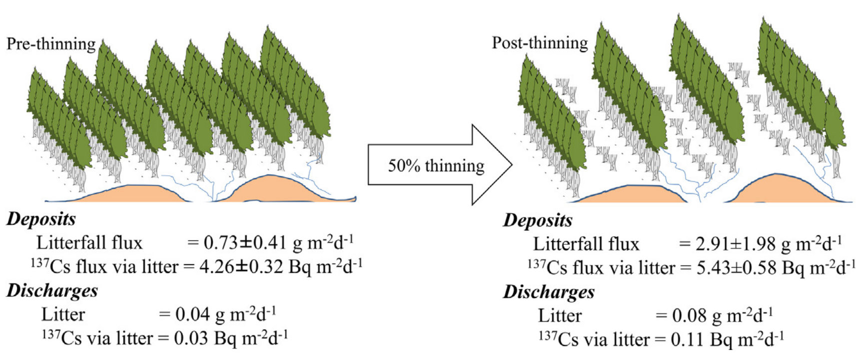
HIGHLIGHTS

- Effect of thinning on litterfall and Fukushima-derived ^{137}Cs dynamics were examined.
- Thinning increased both litterfall by six-fold and ^{137}Cs deposition by two-fold.
- The discharged ^{137}Cs with eroded litter was very small.
- Fukushima-derived ^{137}Cs deposit by litterfall remained on the forest floor.
- Litterfall continued as the main ^{137}Cs depositional pathway.

GRAPHICAL ABSTRACT



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ABSTRACT

The effects of a 50% forest thinning intensity on Fukushima-derived ^{137}Cs deposition by litterfall and its discharge by runoff in hillslope coniferous forest were monitored using four litterfall traps and a hillslope erosion plot. The observation was underway during the pre-and post-thinning periods. Results demonstrated that during the pre-thinning period a total 150 ± 13 g m^{-2} of litterfall deposited about 924 ± 69 Bq m^{-2} of ^{137}Cs. This accounts for 11% of the local ^{137}Cs fallout recorded for the study site in the aftermath of the accident. After thinning, both litterfall and ^{137}Cs increased by more than six- and two-fold, respectively. This is possibly owing to the slow individual tree recovery rate assisted by the change on the running space provided by canopy openings, which can accelerate even the normal gust wind to gain damaging power on the unshielded mechanically injured parts of the contaminated residual trees. In both cases, litterfall generally transferred about 37% (3 ± 0.2 kBq m^{-2}) of the local ^{137}Cs fallout onto the forest floor over the observation period. The eroded litter-associated ^{137}Cs increased by about a factor of two after thinning, which only accounted for less than 1% of ^{137}Cs deposited by litterfall. This implies that the forest floor retains ^{137}Cs and remains contaminated regardless of the size of the eroded litter material. But this could become a potential secondary contamination source for the downstream resources

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such as water bodies and villages, especially at the time of flooding, which in turn calls a serious attention in designing decontamination schemes.

1. Introduction

Following the Fukushima accident, several researchers have reported on the behavior and distribution of the released radioactive elements into the surrounding environments (e.g., Kato et al., 2012; Teramage et al., 2014a, 2014b; Coppin et al., 2016; Evard et al., 2016; Gonze and Calmon, 2017; Teramage et al., 2016; Kato et al., 2017, 2018). Radiocesium, specifically the ^{137}Cs species becomes the element of concern by dominating the long-term radioactive contamination in the environment due to its long half-life (30.2 y). The forest ecosystem surrounding the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) is the major land use types mainly composed of evergreen coniferous tree species (e.g., Onda et al., 2010; Hashimoto et al., 2012). It is also the one among highly contaminated terrestrial ecosystems due to its higher atmospheric pollutants interception capacity provided by the large surface canopy areas (Allen, 1984; Bonnett and Anderson, 1993; Fesenko et al., 2005; Calmon et al., 2015).

It has been well documented that the introduction of silvicultural interventions into the forest ecosystem such as thinning can alters ecosystem structure, shifts the biogeochemical processes involving pathways (energy flows and nutrient cycles) both at tree and stand scales, changes litterfall dynamics, microclimates and soil condition. Forest thinning generally stimulates the growth of the remaining tree by reducing competition for limited resources. It also improves the light conditions that enhance the understory vegetation and modifies the forest floor condition (e.g., Yanai et al., 1998; Juodvalkis et al., 2005; Zhang et al., 2006; Gradel et al., 2017). To benefit from this effect, however, the forest stand must pass through the recovery and stabilization phases from the direct and indirect short-term thinning-derived disturbances such as mechanical and aerodynamics-induced juries and damages. Several studies have evaluated the short and long term effects of thinning on different parameters such as on throughfall (Sun et al., 2015a), on foliage and forest floor properties (Wollum and Schubert, 1975), on forest floor evaporation (Sun et al., 2016), on litterfall, litter decomposition and nutrient fluxes (Novak and Slodicak, 2009; Lado-Monserrat et al., 2016), and on rainfall interception, tree transpiration and hydrological connectivity (Sun et al., 2014, 2015b; Lopez-Vicente et al., 2017). More specifically, studies conducted by Navarro et al. (2013) five years and Jimenez and Navarro (2016) eight years after thinning operation in Pinus afforestation area, have reported that thinning reduced the annual litterfall at the stand level but increased the total litterfall at tree level. This indicates that unlike to other parameters such as rainfall interception, throughfall and the like, studies related to the effect of thinning on litterfall are mostly conducted five to several years after the introduction of the management intervention. However, information regarding the effect of thinning on litterfall dynamic starting from immediately to the first few years after thinning is limited.

Therefore, this study provided and presented the small temporal scale effects of thinning on litterfall dynamic, associated Fukushima-derived ^{137}Cs deposits and their discharged rate in a hillslope Japanese cypress forest floor at the very early period of the Fukushima accident.

2. Materials and methods

The detailed information on the study site, the initial contamination density, litterfall sampling scheme and radioactivity determination is described elsewhere (Teramage et al., 2014a). Briefly, the study was conducted in a 30-year old Japanese cypress (*Chamaecyparis obtusa* Endl.) hillslope plantation forest stand located in Tochigi prefecture of central Japan (Fig. 1). Following the FDNPP accident, the radioactive plume that moved over the study area has left about <10 kBq m^{-2} radiocesium deposits, which accounted for 0.03–10% of the contamination density of the heavily affected (100 - <3000 kBq m^{-2}) zones (MEXT, 2011). Note that all the radiocesium activity measurements reported in this study are decay corrected to the reference date of 11 March 2011. This is mainly done to fully evaluate the effects of forest thinning on litter-derived ^{137}Cs dynamics by avoiding any irregularities that might be caused by sampling date dependent decaying process. Fig. 2 illustrates the monthly rainfall and daily gust wind data measured both during per-and post-thinning observation periods. According to the observation, about 1229 and 1330 mm of rainfall, 5.8 and 3.2 m s^{-1} of mean gust wind during the pre- and post-thinning periods were recorded, respectively.

2.1. Litter traps, erosion plot and thinning regime

Four litter traps (1 m^2 each) were installed 1 m above the ground to monitor the litterfall and associated ^{137}Cs deposition (for detail see Teramage et al. (2014a)). Also, at the same time, a hillslope plot (erosion plot) with a size of 40 m^2 (4 m (across the slope) x 10 m (along the slope)) to measure the erosion-derived discharges was established at the representative place of the study site several days before the Fukushima accident. The plot was constructed in such a way to trap and capture the eroded materials in a gutter located at the lower end of the plot (Fig. 1). The plot has an effective running slope of about 30°.

Strip thinning with a single cycle and a 50% thinning intensity was conducted between 11 October to 4 November 2011, which reduced the stand density by half as well as sat-off both litter traps and erosion plot observations for about 26 days. The detailed change in the stand structure and properties to the response of thinning operation is described by Sun et al. (2016). Immediately after the completion of thinning operation, the litter traps and hillslope plot were reinstalled and maintained at their respective pre-thinning places, and the observation has been resumed.

2.2. Sampling scheme

To evaluate the dynamic of litterfall flux and associated Fukushima-derived ^{137}Cs deposit, seven and six litterfall samplings before thinning (11 March to 11 October 2011, covers a total of 217 days) and after thinning (4 April 2011 to 13 November 2012, covers a total of 376 days) were conducted, respectively. The hydrological observation data reported by Kato et al. (2012), for the pre-thinning period were used for comparison for pre-thinning phase.

From erosion plot, a total of six samplings were conducted during the pre- and post-thinning periods (three each) which covered 195 days (11 March to 11 October 2011) and 152 days (4

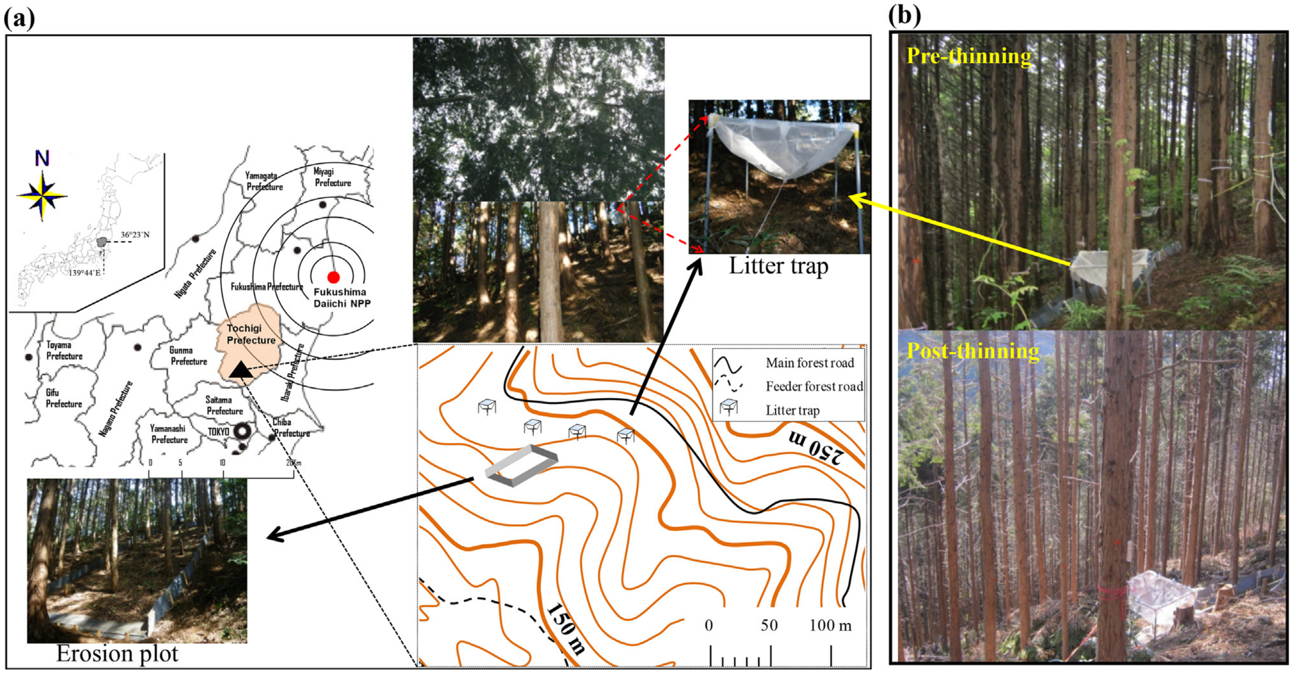

Fig. 1. Map, location and photographs of (a) erosion plot, litter traps; and (b) the forest condition before and right after thinning in the study area.

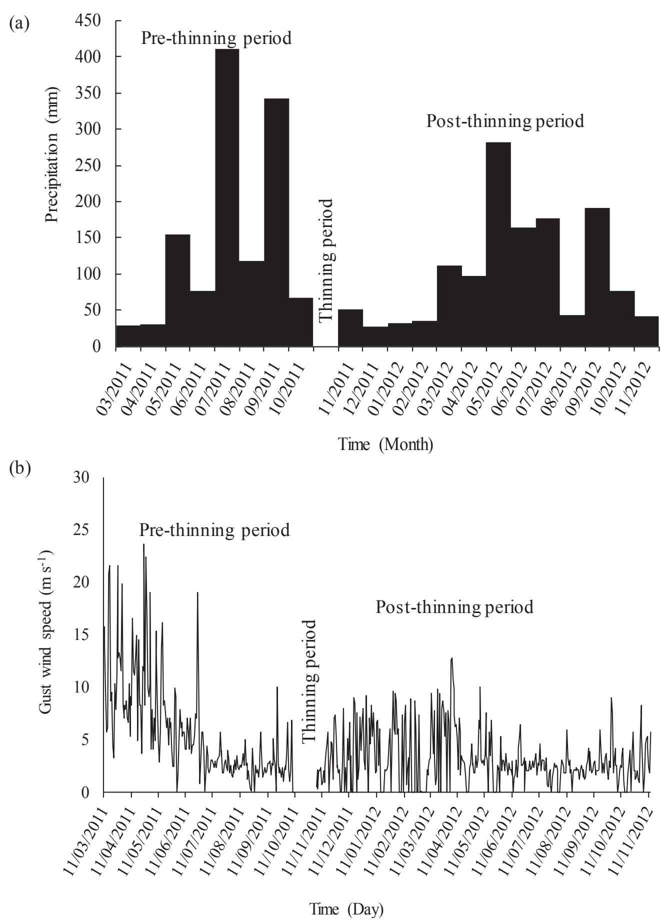

Fig. 2. Meteorological data for the study site and period. (a) Monthly precipitation; (b) daily gust wind speed during the per-and post-thinning observation periods.

November 2011 to 6 April 2012) of observations, respectively. After the sample collection, fully and partially visible litter materials were carefully separated from the rest of the sample portion by hand with the help of small stainless-steel spoon and tong in the laboratory. Then, both sample categories were dried, and their radioactivity were measured according to the standard procedures described by Teramage et al. (2014a). The results were statistically evaluated by an ANOVA test at the 0.05 significant level. Also, the propagation of measurement errors were taken in to account in the calculation wherever appropriate and necessary.

3. Results and discussion

3.1. Litterfall dynamics and associated ^{137}Cs activity

The temporal distribution of litterfall and associated ^{137}Cs deposition fluxes onto the forest floor during the entire observation period is provided in Table 1 and Fig. 3. The total amount of litter deposited onto the forest floor during pre-thinning and post-thinning period was 150 ± 13 g m^{-2} and 935 ± 106 g m^{-2}, respectively (Table 1). According to the length of each observation period, the daily litterfall flux ranged from 0.43 ± 0.14 to 0.95 ± 0.17 g m^{-2} d^{-1} (mean: 0.73 ± 0.41) for pre-thinning and 0.31 ± 0.12 to 6.9 ± 1.0 g m^{-2} d^{-1} (mean: 2.91 ± 1.98) for post-thinning periods (Fig. 3b). The difference in season and the span of the observation period included in the two observation categories could contribute on the variation of the results. However, it can highlight and help to deduct the general trends of which the following discussion focus on.

Accordingly, the litterfall rate observed before thinning is well agreed with data reported by Miyamoto et al. (2013) from the same tree species, which ranged from 0.64 to 1.42 g m^{-2} d^{-1}. Apart from this, statistically, the post-thinning litterfall amount and daily flux were significantly higher than that of the pre-thinning phase (Single factor ANOVA, $P = 0.01036$; $P = 0.03929$, respectively). However, study related to the impact of canopy structure by Penne et al. (2010) have demonstrated that the needle litterfall is

Table 1
Litterfall and associated radiocesium deposit onto the forest floor during pre- and post-thinning periods after FDNPP accident.

	Sampling period	Litterfall (g m^{-2})	Litterfall-derived deposit	
			^{137}Cs (Bq m^{-2})	^{134}Cs (Bq m^{-2})
Pre-thinning	2011/3/11–3/28	15 ± 3	76 ± 19	88 ± 22
	2011/3/28–4/13	14 ± 3	72 ± 18	84 ± 21
	2011/4/13–5/20	32 ± 6	169 ± 43	191 ± 48
	2011/5/20–6/13	23 ± 4	118 ± 30	139 ± 35
	2011/6/13–7/22	30 ± 3	234 ± 56	243 ± 18
	2011/7/22–8/19	12 ± 4	40 ± 8	95 ± 1
	2011/7/22–10/11	23 ± 9	78 ± 16	83 ± 2
Post-thinning	2011/11/4–12/28	205 ± 52	582 ± 144	753 ± 198
	2011/12/28–2012/2/19	87 ± 8	140 ± 30	177 ± 46
	2012/02/19–4/6	331 ± 48	503 ± 49	646 ± 70
	2012/4/6–5/31	220 ± 77	304 ± 28	335 ± 37
	2012/5/31–8/28	28 ± 11	30 ± 14	33 ± 17
	2012/8/28–11/13	63 ± 14	90 ± 24	97 ± 26

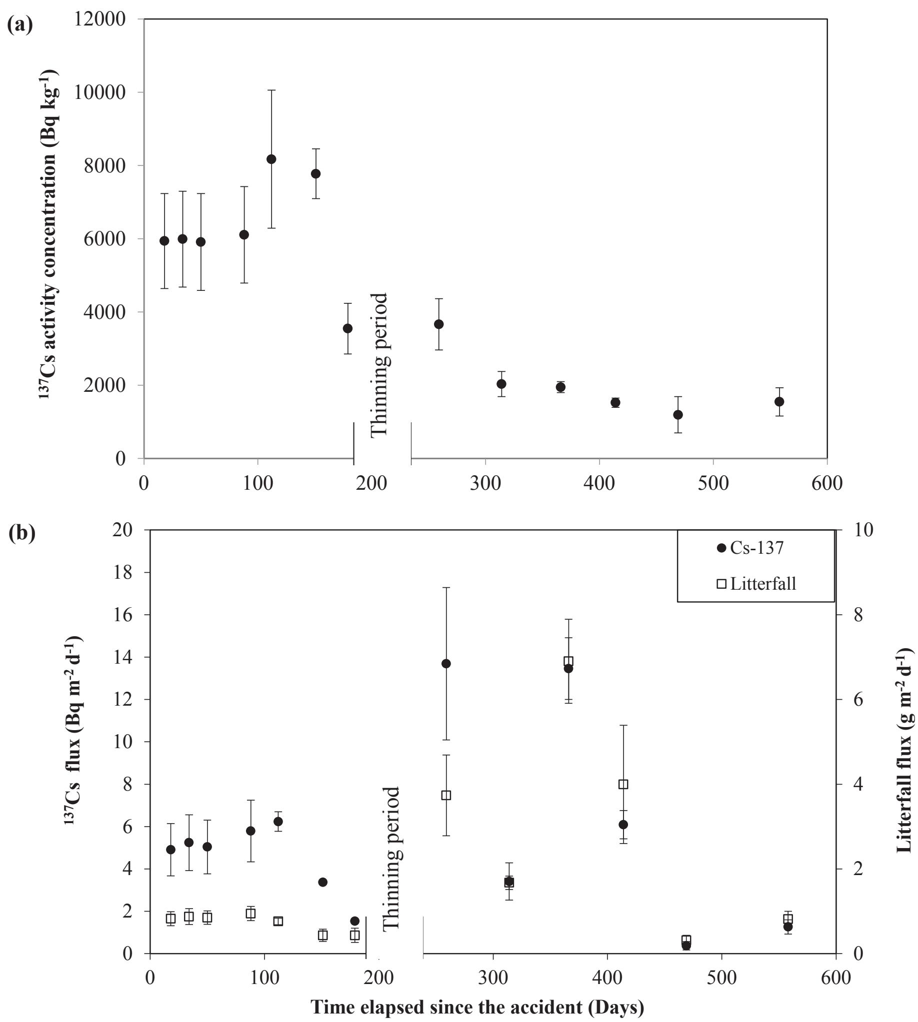

Fig. 3. The temporal distribution of (a) ^{137}Cs concentration in litterfall, and (b) the depositional fluxes of both litterfall and associated ^{137}Cs onto the forest floor during pre and post-thinning observation periods.

significantly higher in area under crown than that of without canopy, indicating litterfall reduces in open canopy forest ecosystem. Specifically, Roig et al. (2005) have reported that the mean litterfall is lower in the stand that received heavy thinning (1520 kg ha^{-1} y^{-1}) than the stand received moderate thinning (5700 kg ha^{-1} y^{-1}), confirming thinning definitely reduces the amount of litterfall. Also, several studies related to thinning indicate that the amount of litterfall reduces after thinning mainly owning to the reduction of stand basal area, which gives the remaining trees more growing space and resources (e.g., Kunhamu et al., 2009; Navarro et al., 2013; Jimenez and Navarro, 2016; Lado-Monserrat et al., 2016).

Note, unlike to our study, these studies are conducted at least five years after thinning, in which the remaining trees can be able to recover, adapt to the new condition and utilize the light access, space and resources opportunities to stabilize their physiological process including those governing the phenology pattern. Twelve years after thinning, for example, Lado-Monserrat et al. (2016) have reported that litterfall production in *Pinus halepensis* forest stand decreased by 33.5% and 96% for 60% and 100% thinning intensities, respectively as compared to the untreated forest. Indeed, thinning increases the light flux (solar radiation) access to the lower branches by opening the forest canopies. Specifically, from our study site, Sun et al. (2016) reported that the canopy cover fraction hardly changed in the first (0.758) and second (0.764) years after thinning. This implies that during the early phase of thinning, the presence of canopy opening-induced extra solar radiation access, and this can increase leaf longevity and reduce litterfall production unlike to that of pre-thinning condition. But this is not the case in our study that the observed higher litterfall amount and rate after thinning may not directly attributed to the results associated to the change in the stand basal area and solar radiation intensity. Moreover, the daily mean gust wind speed records (Fig. 2b) in the post-thinning period was relatively lower ($3.16\,m\,s^{-1}$) than that of the per-thinning ($5.84\,m\,s^{-1}$). Given the unshielded remaining trees due to the canopy openings, the existing aerodynamics forces and the slow tree recovery momentum, the possible reason instead could be that the mechanical induced damages by friction and abrasion by failing trees during the thinning operation may lead to the already weakened branches and leaves to easy fall apart onto the forest floor. In agreement, for example, Inagaki et al. (2010) have observed larger litterfall production in the thinned than untreated cypress forest plot after a typhoon event, implying the aerodynamic and shielding effect are key factors at least for the first few years of thinning until the canopy cover get improved.

The dry weight activity of the deposited radiocesium concentrations associated with the litterfall showed a sort of exponential decreasing trend ($y\ {}^{-1}_{(Bq\ kg)} = 7942.1e^{-0.004t}$, $R^2 = 0.8467$) regardless of the thinning and litterfall dynamics (Fig. 3a). In the ^{137}Cs contamination dynamics, Coppin et al. (2016) have suggested two phases i.e. “early” which lasts for 4–5 years and an apparent “steady state” representing the stabilization of radioactivity transfer between soil and tree. Connected to this, our study was conducted within a year after thinning and within two years after the accident. Accordingly, the decline magnitude of the ^{137}Cs activity concentrations in our observation can be stated as in the phase of “early” depuration process where the rapid deposition of the canopy-trapped ^{137}Cs by throughfall and litterfall routes dominates. Moreover, as reported by Kato et al. (2012), the hydrological pathways became insignificant specially at the last pre-thinning observation periods, confirming our observation is at the “early” phase process characterized by rapid deposition. However, studies indicated that re-suspended ^{137}Cs containing soil particles in to the atmosphere have been observed following mechanized faming activities during spring season (e.g., Igarashi et al., 2015; Kanai, 2012; Yamaguchi et al., 2012). Given the need of further investigation, in connection to this particular case, relatively higher ^{137}Cs activity concentrations in the June/July (5th/6th sampling periods) of litterfall samples (Fig. 3a) were observed. This, could be due to the re-contamination of the tree canopy by ^{137}Cs coded soil particles being blown up in to the air by wind from the nearby farming practices, though not detected in the rain water samples. Nevertheless, it appears that the remaining radiocesium in the canopy components at the end of pre-thinning period is possibly water insoluble (Bonnett and Anderson, 1993), and litterfall is the only route to reach the forest floor governed by the pattern of tree phenology and unforeseen weather conditions (typhoon, storms, etc) particularly in the post-thinning period where the wind running space is high due to canopy openings.

3.2. ^{137}Cs transfer into the forest floor by litterfall

3.2.1. Pre-thinning period

Following 12 open rainfall measurements (a total of 719 mm of rain) at the nearby of the study site, the total local radiocesium fallout was estimated about of 8030 Bq m^{-2} (Kato et al., 2012). They have reported that after July 2011 ^{137}Cs activity was not detected in the rainfall water, indicating the atmospheric ^{137}Cs deposition was completed within five months of the accident.

Based on Kato et al. (2012) report on the ^{137}Cs deposit by hydrological pathways during the pre-thinning period, throughfall and stemflow deposited 2910 Bq m^{-2} and 120 Bq m^{-2} of radiocesium on the forest floor, respectively. Teramage et al. (2014a) have reported that the contribution of litterfall route was estimated up to 31%. Connected to this, Calmon et al. (2015) have commented that the ^{137}Cs depositional flux via this pathway was somewhat higher than the estimates by their model simulation results. After the re-measurement of ^{137}Cs concentrations in the litterfall on dry weight bases, its deposition on the forest floor reduced to about 924 ± 69 Bq m^{-2} during the pre-thinning period. Hence, during the per-thinning period, a total of approximately 4 kBq m^{-2} of Fukushima-derived ^{137}Cs was deposited on the forest floor via the throughfall (74%), stemflow (3%) and litterfall (23%) routes. The ratio of deposited radiocesium to that of the total local fallout via the three depositional routes during pre-thinning period, and the extended litterfall route observation data during post-thinning period are illustrated in Fig. 4. Of the total local fallout (8030 Bq m^{-2}), throughfall, stemflow and litterfall deposited about 36%, 1.5% and 11%, respectively. This implies that about half of the local fallout have already reached the forest floor within five months following the accident.

Statistically, ^{137}Cs deposited via throughfall and litterfall routes were significantly different from the stemflow pathway (ANOVA single factor, $P = 0.0015$ and 0.00145, respectively), whereas the litterfall and throughfall depositional routes were statistically indifferent (ANOVA single factor, $P = 0.067$). Generally, during the pre-thinning period, the following ^{137}Cs depositional order can be identified: throughfall>litterfall>>>stemflow. In close agreement, a similar pattern was also reported by Rafferty et al. (2000), implying throughfall and litterfall are the dominant depositional pathways in which litterfall will gradually take over in the later period as the water soluble ^{137}Cs diminishes over time. Similarly, several studies have also acknowledged that litterfall is the main and prolonged transfer pathways for canopy trapped atmospheric pollutants to the forest floor (e.g., Coppin et al., 2016; Gonze and Calmon, 2017; Kato et al., 2017; Yoschenko et al., 2017).

3.2.2. Post-thinning period

During post-thinning period, the ^{137}Cs deposit data by throughfall route was lacking and this limited to conduct further analysis and comparison as we did for pre-thinning period. Indeed, the trends at the end of the pre-thinning observation periods have indicated that the hydrological routes became less important, and their radiocesium contributions to the forest floor were very low (Fig. 4). For these reasons, our discussion limits to only for litterfall data. Accordingly, the transfer of ^{137}Cs onto the forest floor by litterfall after thinning was more than two-fold higher than pre-thinning phase though statistically indifferent both in its total deposition as well as its daily flux (ANOVA single factor, $P = 0.0965$; $P = 0.4552$, respectively). As discussed above, although the ^{137}Cs activity concentration exponentially decreased, high ^{137}Cs inventory observed after thinning could be partly originated from

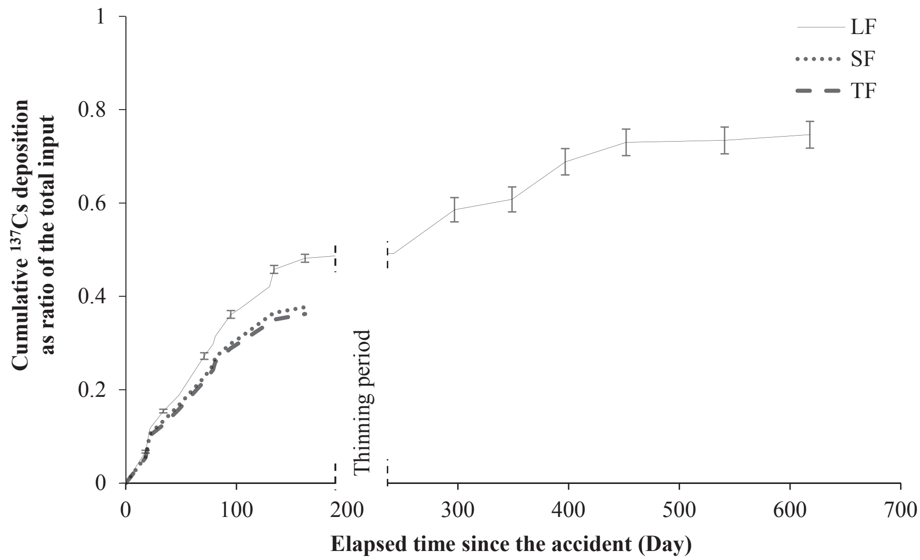

Fig. 4. Comparison on the cumulative ^{137}Cs deposition by Throughfall (TF), Stemflow (SF) as reported by Kato et al. (2012) and Litterfall (LF) routes onto a Japanese cypress forest before thinning and only by LF after thinning following the FNPP accident.

Table 2
The rate of discharged litter, sediment and associated Fukushima-derived ^{137}Cs from the Japanese cypress forest floor during the pre- and post-thinning periods.

	Observation period	Discharged litter and associated ^{137}Cs			Discharged sediment and associated ^{137}Cs		
		Dry weight ($g\ m^{-2}$)	$Bq\ kg^{-1}$	$Bq\ m^{-2}$	Dry weight ($g\ m^{-2}$)	$Bq\ kg^{-1}$	$Bq\ m^{-2}$
Pre-thinning	2011.3.11–6.22	2.1	1168 ± 103	2.5 ± 0.2	4.3	862 ± 80	3.7 ± 0.3
	2011.6.22–7.21	0.2	693 ± 57	0.1 ± 0.0	2.1	728 ± 37	1.5 ± 0.1
	2011.7.21–10.11	5.1	825 ± 33	4.5 ± 0.2	19.4	559 ± 17	10.8 ± 0.3
	Sub-total	**7.4**		**7.2 ± 0.3**	**25.8**		**16.1 ± 0.5**
Post-thinning	2011.11.4–12.4	5.3	1960 ± 79	10.3 ± 0.4	17.3	614 ± 33	10.6 ± 0.6
	2011.12.4–2012.3.7	6	700 ± 33	4.1 ± 0.2	7.4	614 ± 21	3.3 ± 0.2
	2012.3.7–4.06	1.7	1328 ± 47	2.3 ± 0.1	3.2	614 ± 19	1.3 ± 0.1
	Sub-total	**12.8**		**16.7 ± 0.5**	**27.8**		**15.2 ± 0.6**

large amount of litter mass deposition, and partly due to the relatively longer observation time than the pre-thinning period.

Generally, the total contribution of the litterfall in transferring radiocesium onto the forest floor was about 3 ± 0.2 kBq m^{-2} (37% of the local fallout) during the entire observation period, of which pre- and post-thinning accounted for 31% and 69%, respectively. Note that the majority of litterfall-derived ^{137}Cs deposition was occurred in the post-thinning period which mainly associated with large amount of litter mass flux that compensated the exponentially declining ^{137}Cs activity concentrations observed in the falling litter. Indeed, the observation time frames are different in terms of encompassed seasons and duration lengths which in fact could directly or indirectly affect our observation. For example, Hisadome et al. (2013) clearly indicated that the litterfall flux increased in November and December, and this might be the same for our study site. Although the temporal variation of canopy contamination due to self-decontamination and seasonal effects associated to the tree physiology are highly expected, our observation data suggests that the litterfall amount and flux have shown an increasing trend and thereby higher ^{137}Cs deposit specially at the very early periods after thinning operation.

3.3. *Discharged litter and associated ^{137}Cs by runoff from the forest floor*

The eroded materials and associated discharged Fukushima-derived ^{137}Cs from the hillslope forest floor during the pre- and post-thinning periods are given in Table 2. As indicated, the highest ^{137}Cs activity concentrations in the eroded litter was observed at the first observation period both in pre-thinning (1168 ± 103 Bq kg^{-1}) and post-thinning (1960 ± 79 Bq kg^{-1}) periods. Compared to the ^{137}Cs activity concentrations in the litterfall (Fig. 3a), the activity in the eroded litter was reduced by a factor of five and two during pre- and post-thinning periods, respectively. From the laboratory experiment, Teramage et al. (2018) have reported that the extractable ^{137}Cs fraction from the contaminated litter by water seems negligible. Hence, the possible reason for lower ^{137}Cs concentration in the eroded litter would be the result of dilution and normalization by pre-deposited and already existed uncontaminated litters prior to the accident. In agreement, after thinning, where the amount of litter deposited prior to the accident was expected to be highly diminished, the ^{137}Cs concentration in both the fallen and eroded litter was almost closed enough, confirming the transfer of ^{137}Cs from litter to soil is very low.

As indicated in Table 2, a total of about 33 and 41 g m^{-2} soil materials (including litter) were eroded during pre- and post-thinning periods, respectively. Out of these, the eroded litter component accounted for 22% (7.4 gm^{-2}) during pre-thinning and 32% (12.8 gm^{-2}) during post-thinning period while the rest soil component accounted for 78 and 68%, respectively (Table 2). Despite statistically insignificant (ANOVA-Single factor: $P = 0.396$ for eroded litter mass and $P = 0.288$ for eroded ^{137}Cs) and higher monthly rainfall during pre-thinning than post-thinning (Fig. 2a), our observation revealed that the amount eroded litter and associated ^{137}Cs increased from 7.4 g m^{-2} to 6.8 ± 0.3 Bq m^{-2} during pre-thinning period to 12.8 g m^{-2} and 16.7 Bq m^{-2} during the post-thinning period. Previously, it has been reported (e.g., Onda et al., 2010; Razafindrabe et al., 2010) that the nature of the cypress needle is easily disintegrable and movable. Connected to our eroded litter observation, this phenomenon could potentially have contributed to the loss of additional needle litter after thinning where the chance of knocking the needle litters by direct rain drops due to the space created by canopy openings is high. However, the amount and ^{137}Cs content in the rest of the eroded materials were almost similar both in the pre-thinning (25.8 g m^{-2} and 16.1 ± 0.5 Bq m^{-2}) and post-thinning (27.8 g m^{-2} and 15.2 ± 0.6 Bq m^{-2}) periods.

Of the total ^{137}Cs deposited by litterfall, the discharged ^{137}Cs along with litter was less than 1% during the pre-, post-thinning as well as from the entire observation periods, implying the ^{137}Cs deposit by litterfall tends to stay in the forest floor. Nevertheless, form hillslope Japanese cypress forest, Dung et al. (2011) have reported that 50% thinning intensity increased the mean overland flow within two years after intervention which mainly associated with canopy opening (i.e. reduction in canopy interception). In this context, our observation result implies that thinning-induced surface soil erosion dominated on the litter layer while the response of subsurface erosion appeared insensitive for thinning (Table 2). Such information would helpful in designing decontamination strategies for hillslope forest and also to manage the downstream connected environments such as water bodies (rivers, reservoirs, lakes, etc) and villages particularly during flooding events.

4. Conclusion

Note that the seasons covered, and the time length observed between pre-and post-thinning periods were different. However, it highlighted the trends on the short-time scale (within <5 years of thinning) effects of thinning on the litterfall and associated ^{137}Cs deposition in the studied hillslope coniferous forest. Hence, the main conclusion of this investigation is that in short time scale, thinning significantly increased the litterfall amount onto the forest floor. This is possibly owing to the slow individual tree recovery rate assisted by the change on the wind running space due to canopy openings resulting even for the normal gust wind to gain damaging forces on unshielded and mechanically injured parts of the residual trees. The associated ^{137}Cs amount also increased after thinning due to large amount of litterfall deposition which compensated the exponentially declined activity concentrations in the falling litter in time. Regard to erosion, the discharged ^{137}Cs associated with litter by runoff was almost negligible, indicating the forest floor and the connected systems remained net contaminated. This pattern most likely influences the concentrations and distributions of ^{137}Cs in the soil and the growing understory vegetation encouraged by thinning-induced light access for considerable time periods. In connection with managing the nutrient dynamic, such silvicultural intervention could at the same time be associated to design possible decontamination schemes in the forest and connected ecosystem niches, to estimate radiation doses and to assist the related planning and decision-making procedures.

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