

**The factor analyses concerning the infiltration of radioactive Cs
for the effect of forest decontamination activities
and the development of the evaluation method
for the residual radioactive Cs on surfaces**

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Abbreviations

CEC	Cation Exchange Capacity
CDE	Calculation system for Decontamination Effect
FA	Forestry Agency
FES	Frayed Edge Site
F layer	Fermented layer
GIS	Geographic Information System
GM survey meter	Geiger-Mueller survey meter
H layer	Humus layer
ICSA	Intensive Contamination Survey Area
IAEA	International Atomic Energy Agency
INES	International Nuclear Event Scale
IQR	Interquartile Range
JAEA	Japan Atomic Energy Agency
JCAC	Japan Chemical Analysis Center
JFTA	Japan Forest Technology Association
JGS	Japanese Geotechnical Society
JRIA	Japan Radioisotope Association
L layer	Litter layer
MOE	Ministry of the Environment
NERH	Nuclear Emergency Response Headquarters
NISA	Nuclear and Industrial Safety Agency
NRA	Nuclear Regulation Authorities
RA	Reconstruction Agency
RIP	Radiocaesium Interception Potential
RPC	Reconstruction Promotion Council
SDA	Special Decontamination Area
SRI	Surface Residual Index
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
U.S. NRC	United States Nuclear Regulatory Commission
VBA	Visual Basic for Applications

Chapter 1 Introduction

1.1 Background and objectives of this research

The Fukushima dai-ichi nuclear power plant accident, caused by March 11th earthquake and following tsunami disaster, released the huge amount of radioactive substances and led to the environmental pollution in the vast area in eastern Japan, from Kanto to Tohoku area, including Chiba, Saitama, Gunma, Ibaraki, Tochigi, Fukushima, Miyagi and Iwate prefecture.

This is the huge, indescribable disaster and we have never experienced such sort of disaster, including forcing the residents to evacuate from their living area, due to the high radiation, as well as the earthquake and Tsunami.

The vast contamination caused by scattered radioactive substances in the living area, including houses, parks, schools, roads, farmlands, forests were remediated according to the land categories, based on the The Act on Special Measures Concerning the Handling of Radioactive Pollution and related laws, guideline for the decontamination activities, prioritizing to eliminate the influence to the living area (MOE, 2013).

The Japanese government has completed the “dimensional”, or full-scale decontamination activities in the end of the fiscal year 2016, or the end of Mar. 2017, and continuously conducted the follow-up works to check the backlog of their works or re-contamination.

Regarding the forest area mainly focused in this research, occupies around 70 % of dimension in Fukushima prefecture or Japanese land. Forest area has been basically decontaminated within 20 m from the edge of the forest mainly by removing the organic matter on the top of the forest ground.

The measurement of rest of the area has been tackled from the long-term perspective and comprehensive policies such as research and development, risk communication, the reconstruction of forestry, the prevention of soil runoff to living area and so forth. SATOYAMA model project, one of these measures, is a group of mixed policies by Reconstruction Agency, Ministry of the Environment and Forestry Agency to revitalize the forest area familiarly used by people in pre-accident life, including raising mushrooms and camping (RA, 2016).

It isn't realistic to remove all organic matters from the forests, in terms of a great deal of waste management, second disaster (e.g. landslide) by removing organic matter or soil, economic efficiency and so on.

Taking the fact that half time of ^{137}Cs is around 30 years into account as well, the countermeasures for forest contamination would last for a long time, and it is crucial to study the behavior of radioactive substances and its influence to the effect of forest decontamination that would contribute to the review of the comprehensive measures mentioned above.

It has been well known that radioactive Cs had accumulated in the above-ground part in forests, for example, branches, leaves, trenches, at the early term after the accident, according to the various kinds of researches or monitorings.

These radioactive substances moved towards the below-ground part, or organic or soil layers relatively early after the accident through falling leaves or water flow (FA, 2015).

Given the actual work processes that forest decontamination activities has been conducted by removal of organic matters, distribution of radioactive Cs in forest with different types of vegetation or other properties, would provide the suggestion for the effective strategies.

Concretely speaking, if the radioactive Cs still remains on the surface of the ground, continuous removal

would be effective for decreasing the influence. On the other hand, if these substances have already penetrated downward, the prevention of runoff of soil or continuous monitoring, instead of removal, would be prioritized.

Generally, it is well known that the radioactive Cs is easily adsorbed to the negative charge in the soil particles (Yamaguchi, 2011). However, if the difference of infiltration is observed in the forests with different vegetation, it would help clarify the mechanism from the deposition, migration, and adsorption, by comparing the characteristics of organic matter and soil in each place.

This research was conducted, bearing in mind the application to the actual decontamination activities, because I have been in charge of decontamination policy for a long time as a government employee since the accident happened, as well as a doctoral student with support from the government.

At the last part of this research, the method for evaluation of residual condition of radioactive Cs on the surface without bring any samples to laboratory is proposed, in order to make this way more applicable on site.

1.2 Contents of this research

After describing the background of this research and events or progresses regarding the decontamination activities in Chapter 1 and 2, the results of 3 researches are described in Chapter 3, 4, 5 respectively (Fig. 1-1).

- Factor analyses concerning the effect of forest decontamination using statistic and depth profile investigation (Chapter 3)
- Analysis of the influence of forest soil characteristics on radioactive Cs infiltration (Chapter 4)
- Evaluation of residual radioactive Cs on surfaces by monitoring surface dose rates and surface contamination concentrations (Chapter 5)

Air dose rate (monitoring point: 1 cm and 100 cm from the ground) and surface contamination concentration (hereinafter referred to as “radiation dose”) have been monitored, before and after the decontamination activities, to evaluate its effect.

In Chapter 3, the correlation between the decontamination effect and “pre-decontamination radiation dose” and “monitoring term of pre-decontamination” were statistically analyzed.

In addition, publicly available GIS data on vegetation information was incorporated and superimposed with geological data obtained during decontamination works, to evaluate the relation between the vegetation and decontamination effect.

Moreover, the investigation for depth profile of radioactive Cs in organic and soil layer was conducted, in the five forests with different types of vegetation, taking advantage of scraper plate.

As a result of these investigations, the relation between the infiltration of radioactive Cs and decontamination effect was analyzed.

In Chapter 4, in the wake of the results in Chapter 3, that is, the different effect of decontamination was observed, in the forests with different types of vegetation, soil cores were obtained to investigate the relation between the depth profile and “saturated hydraulic conductivity”, “field capacity”, “voidage” and “cation exchange capacity (CEC)”. The ignition loss, the index of the amount of organic matter was also monitored

in each layer. Among these index describing the soil characteristics, the ignition loss was focused to simulate the depth profile of radioactive Cs by the compartment model, because it had high positive correlation with CEC, which describes the amount of negative charge.

The results of analyses in Chapter 3 and 4 implied that the depth profile of radioactive Cs differed from places to places with different types of vegetation and that would make an impact on the reduction rate of radiation dose, as well as the possibilities that phenomena occurred in the early stage after the accident.

In Chapter 5, in the wake of these results, the simple method to evaluate the residual condition of radioactive Cs on surfaces was proposed, using the NaI scintillation survey meter and GM survey meter, usually used during the decontamination activities.

Detailed depth profile can be clarified by analyses using scraper plate and Ge semiconductor detector, used in Chapter 3 and 4. It is, however, relatively expensive, time-consuming and short-handed, when all points are to be studied. Finally, the simple, instant and inexpensive way was proposed which could be applicable on site, though some improvement is still necessary.

In the last Chapter 6, these achievements were integrated as conclusions.

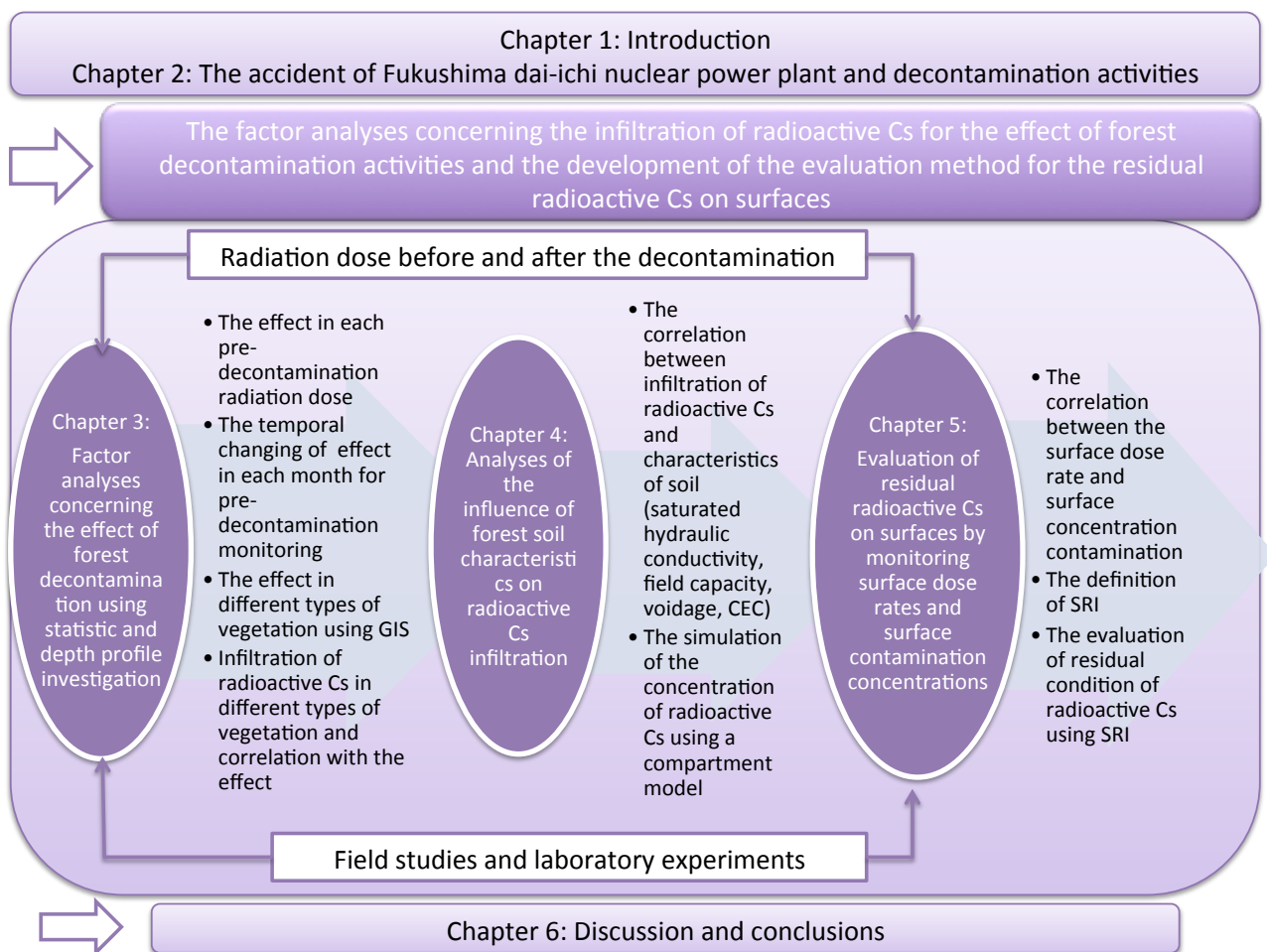


Fig. 1-1 The contents of this research.

References (Chapter 1)

Forestry Agency, 2015. The result of distribution survey of radioactive substances in forest (Fiscal year 2014). Available at: <http://www.rinya.maff.go.jp/j/press/kaihatu/150327.html> (in Japanese).

Ministry of the Environment, 2013. Guideline for decontamination (ver.2), pp.116-125 (In Japanese).

Reconstruction Agency, 2016. The project team's 3rd meeting of related Ministries for reconstruction of forest and forestry in Fukushima. Available at: <http://www.reconstruction.go.jp/topics/main-cat1/sub-cat1-4/forest/20160906091020.html> (in Japanese).

Yamaguchi, N., 2011. Adsorption mechanism of radiocesium on soil. J. Jpn. Soc. Soil Phys. 126, 11-21 (in Japanese).

2.1 Background and timeline of measures for radioactive contamination

The environmental pollution caused by radioactive substances released by Fukushima nuclear power plant accident was expanded in broad area, but has been decreasing in line with physical and natural attenuation, according to the periodical aircraft monitoring (NRA, 2016) as well as decontamination activities (Fig. 2-1). The contamination in a great deal of area caused by the accident was unanticipated in advance and no related legislation to tackle this issue was established ahead of time.

The timeline of countermeasures for radioactive substances was listed in this Chapter and Table 2-1, by mainly focusing on the forest decontamination activities, major target of this research.

The countermeasures for these kinds of environmental pollution was first noticed in May 2011 in the “The Immediate Measures to Support the Sufferers by Nuclear Accident*” (NERH, 2011a), that the practical methods to remove the radioactive substances in farmlands were going to be considered and disseminated to the contaminated site. In the very early stage after the accident, the establishment of system to enhance the monitoring and getting rid of wastes generated by Tsunami disaster were prioritized.

“Basic Concept for Cleanup (Decontamination) Activities in Living Area in Fukushima Prefecture (Except

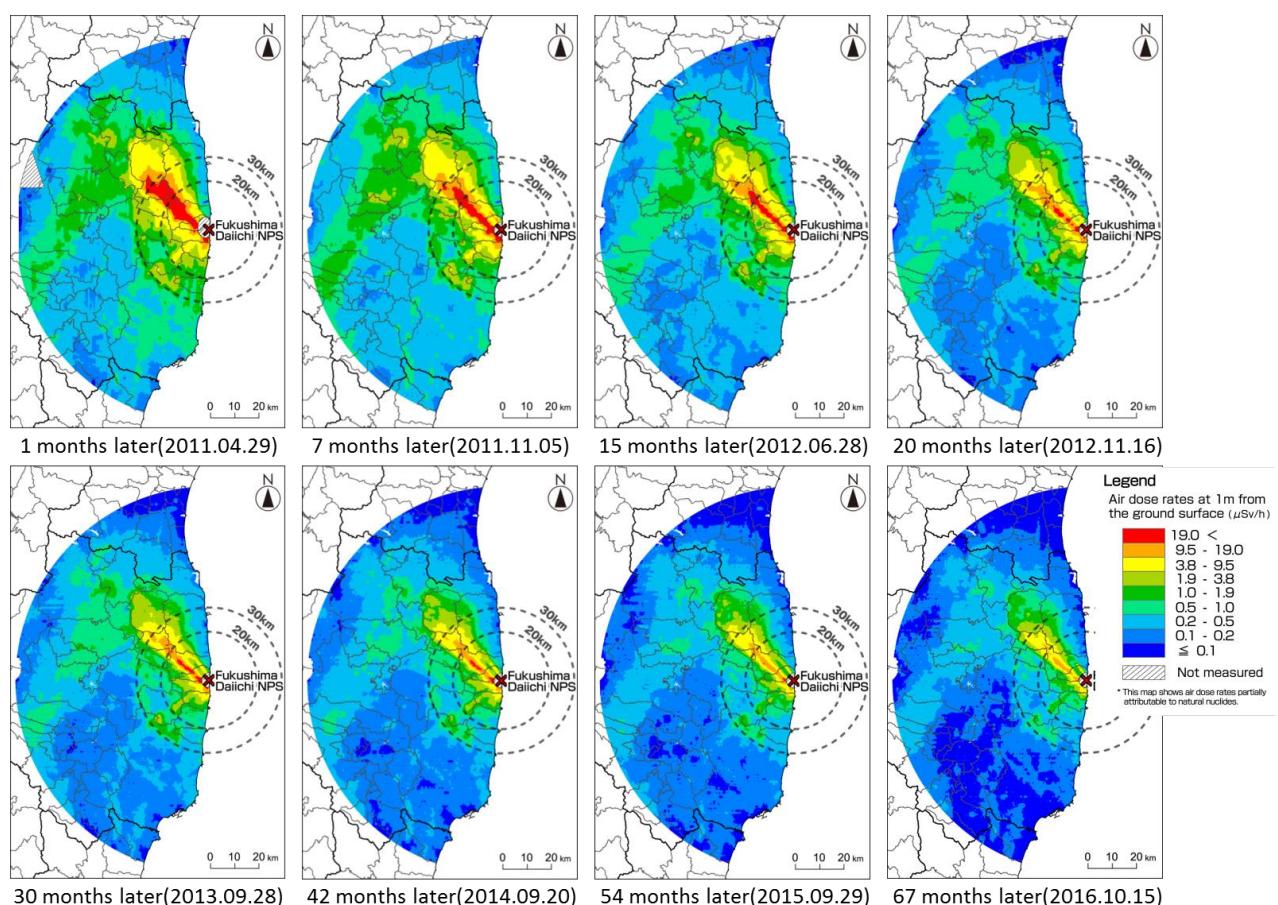


Fig. 2-1 Temporal change of air dose rate in Fukushima and nearby prefectures.

* The translation of the published documents is just provisional version and true to the followings.

for the Caution Zone and the Planned Evacuation Zone)” (NERH, 2011b) in Jul. 2011 was the document which mentioned the concrete measures for decontamination activities, including the evaluation of the effect through demonstration experiments and model activities, points of concern and waste treatment.

The objective of this document was thought to be the guideline for the people, mainly who lived in the contaminated region and voluntarily cleaned up the schools, parks and so on, because the act for tackling decontamination activities was not published yet at that time. There were no specific rules for implementation and authorities in charge of these tasks and all rules for removing and preserving contaminated substances were left entirely to the people at this early stage.

“The Emergent Implication Guideline” (NERH, 2011c) and “The Guideline for Implication of Decontamination Activities by Municipalities” (NERH, 2011d) became open to public at the same term, even after The Act on Special Measures Concerning the Handling of Radioactive Pollution (hereinafter referred to as “the Act”) was published in Aug. 2011. This was because the time was still needed to establish the organized system, including the government ordinance, the ministry ordinance and related guidelines.

In the Emergent Implication Guideline, the basic concept for the authorities, who would conduct the decontamination activities, was mentioned: The government had responsibilities for the area in which additional exposed dose was more than 20 mSv y⁻¹ and each municipality had responsibilities, with financial support from government, for the area in which additional exposed dose was less than 20 mSv y⁻¹.

The goals for the radiation protection were also indicated in the guideline as follow:

- The area under the Emergency Exposure Situation would be decreased in a stepwise approach.
- The additional exposed dose would be made less than 1 mSv y⁻¹ as a long term goal in the area under the Existing Exposure Situation.
- The estimated annual exposed dose would be reduced by 50 % for the ordinary people and 60 % for the children within 2 years.

These goals were inherited to the basic policy under the Act later.

In the Guideline for Implication of Decontamination Activities by Municipalities, the detailed concept for the decontamination activities in the area where the additional exposed dose was 1 - 20 mSv y⁻¹ were represented as examples as follows:

- The establishment of decontamination plan
- The tentative concept of specific measures for decontamination
- The points of concern when conducting the decontamination activities
- The installation and management of temporary storage sites and the correspondence after the decontamination

The basic concept of this guideline was succeeded to the following decontamination guideline and a lot of municipalities had established the implementation plans for decontamination stipulated in the Act, by reference to the plan based on this “The Guideline for Implication of Decontamination Activities by Municipalities”.

In this guideline, the concrete ways for forest decontamination were referred for the first time, such as the removal of bottom weed and mulch, pruning branches in reasonably feasible range. Moreover, it was pointed out that the decontamination in whole area of forests would lead to a large amount of waste and loss

of multilateral functions they originally possessed.

“The Publication of Proper Methods for Forest Decontamination” (NERH, 2011e) was the first document referring to the forest decontamination specifically and in this document, the removal of fallen leaves should be conducted within 20 m from the edge of the forests, though the range would be altered according to the air radiation dose. This basic concept was inherited to the present guideline mentioned later, though this range for forest decontamination, 20 m from the edge, sometimes has attracted the controversy.

It was mentioned in the guideline that the reduction of dose rate should be attained basically through the removal of organic matter, as well as pruning the branches in the range of the half height of the tree, in order not to deteriorate its growth. This technique has been also referred to in the present guideline published by Ministry of the Environment (hereinafter referred to as “MOE”) (MOE, 2013a). The necessity of prevention of soil runoff after the decontamination was also mentioned in the “The Publication of Proper Methods for Forest Decontamination” and the specific manners were considered later as the important measures.

The goals or basic items for decontamination and waste management were described in the basic policy for the Act established in Nov. 2011 (MOE, 2011).

The knowledge and the effect of the decontamination was tried to be accumulated through the model projects begun by Cabinet office around the same time, before the Act was fully come into effect in Jan. 2012.

The guideline for decontamination was established in Dec. 2011 and a series of methods to clean up the radioactive substances were lined up for the first time. Regarding the forest decontamination, the removal of organic matter, pruning branches and other necessary methods were indicated, based on the experience and knowledge obtained through model projects or experiments by academic society (Fig. 2-2) (MOE, 2013a).

11 municipalities in Special Decontamination Area (hereinafter referred to as “SDA”) and 102 (later 104 at maximum) municipalities in the Intensive Contamination Survey Area (hereinafter referred to as “ICSA”) were designated around the same time (Fig. 2-3). In the wake of thorough enforcement of the Act in Jan. 2012, the government got in charge of decontamination in SDA and the municipalities got in charge of decontamination in ICSA, with the aid of financial and technical support of government.



Fig. 2-2 Decontamination activities in forests.

Reference: The Guideline for Decontamination (MOE)

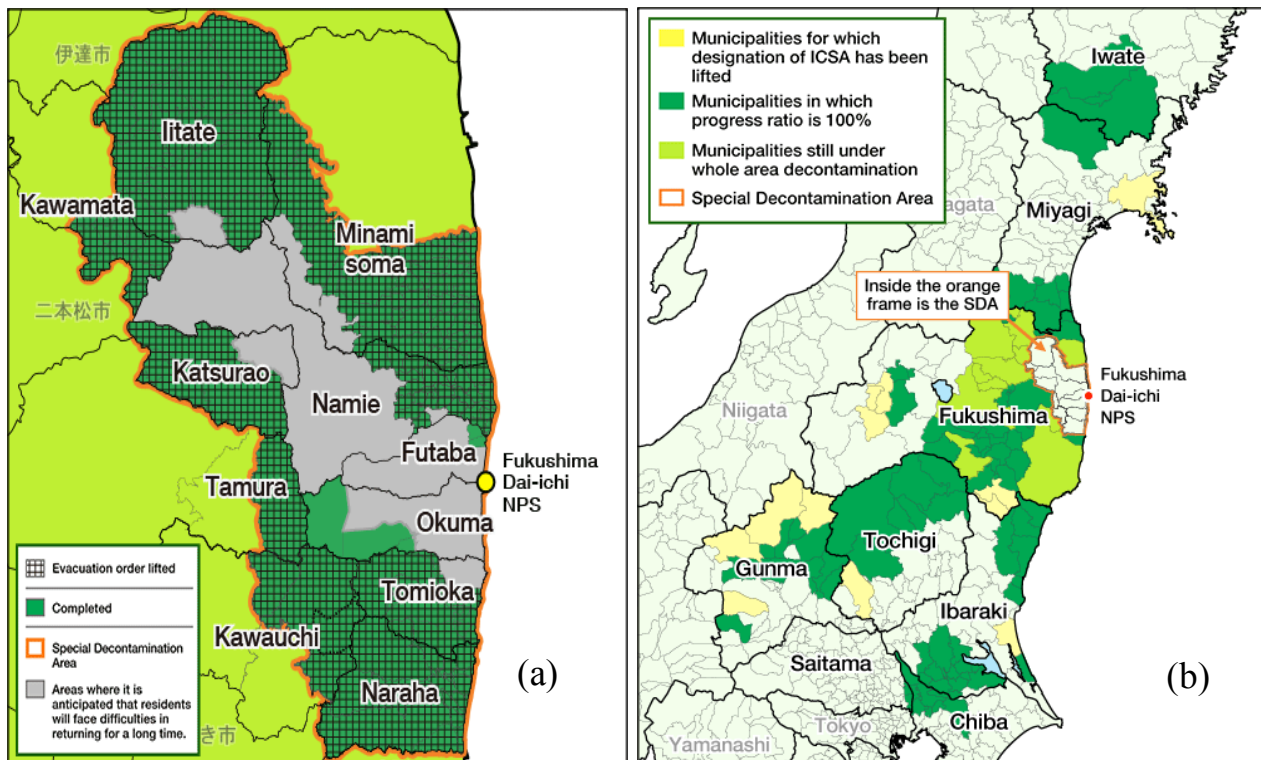


Fig. 2-3 Special Decontamination Area (a) and Intensive Contamination Survey Area (b) (As of the end of Jun. 2017).

Reference: MOE (<http://josen.env.go.jp/en/decontamination/>)

The number of municipality has been still 11 in the SDA as of Jun. 2017. On the other hand, the number in ICSA was 104 at maximum but has been gradually decreasing owing to the progresses of decontamination, as well as physical and natural attenuation, and reached 92 as of Jun. 2017 (Table 2-2).

Table 2-1 The timeline of countermeasures for radioactive contamination
(mainly for forests decontamination)

Month year	and Events
Mar. 2011	The 2011 off the Pacific coast of Tohoku Earthquake Fukushima dai-ichi nuclear power plant accident
May	The Immediate Measures to Support the Sufferers by Nuclear Accident (Nuclear Emergency Response Headquarters)
Jul.	Basic Concept for Cleanup (Decontamination) Activities in Living Area in Fukushima Prefecture (Except for “The Caution Zone” and ”the Planned Evacuation Zone (Nuclear Emergency Response Headquarters)
Aug.	The publication of Act on Special Measures Concerning the Handling of Radioactive Pollution The Emergent Implication Guideline (Nuclear Emergency Response Headquarters) The Guideline for Implication of Decontamination Activities by Municipalities (Nuclear Emergency Response Headquarters) The partial enforcement of the Act on Special Measures Concerning the Handling of Radioactive Pollution
Sep.	The Publication of Proper Methods for Forest Decontamination (Nuclear Emergency Response Headquarters) The Distribution of Radioactive Substance in Forests and the Results of Analyses (interim report) (Forestry Agency)
Nov.	The Basic Policy for the Act on Special Measures Concerning the Handling of Radioactive Pollution The kickoff of model projects by Cabinet office (the projects were to be succeeded to Ministry of the Environment)
Dec.	Order and ordinance for the Act on Special Measures Concerning the Handling of Radioactive Pollution The Guideline for Decontamination (Ministry of the Environment) The designation of Special Decontamination Area (11 municipalities) and Intensive Contamination Survey Area (102 municipalities), based on the Act on Special Measures Concerning the Handling of Radioactive Pollution The Survey Results of Distribution of Radioactive Substance in Forests (second report) (Forestry Agency)
Month year	and Events
Jan. 2012	The Decontamination Policy in Special Decontamination Area (Road map for decontamination) (Ministry of the Environment) The complete enforcement of the Act on Special Measures Concerning the Handling of

	Radioactive Pollution
	The establishment of the Fukushima Office for Environmental Restoration (Ministry of the Environment)
Apr.	The Implication Plan for Decontamination in Special Decontamination Area (Tamura City, Naraha Town, Kawauchi Village, Minamisoma City)
	The Technical Guideline for Removal and Prevention of Diffusion of Radioactive Cs in forest (Forestry Agency)
	The reopening of Minamisoma IC – Soma IC
May	The Implication Plan for Decontamination in Special Decontamination Area (Iitate Village)
	Establishment of 5 branch offices for the Fukushima Office for Environmental Restoration (Ministry of the Environment)
Jul.	The kickoff of full-scale decontamination activities in Tamura City (Ministry of the Environment)
	The 4th Panel for the Environment Recovery (Discussion about the policy of forest decontamination) (Ministry of the Environment)
	The 5th Panel for the Environment Recovery (Discussion about the policy of forest decontamination) (Ministry of the Environment)
Aug.	The Implication Plan for Decontamination in Special Decontamination Area (Kawamata Town)
	The 6th Panel for the Environment Recovery (Discussion about the policy of forest decontamination) (Ministry of the Environment)
	The Technical Guideline for Removal and Prevention of Diffusion of Radioactive Cs in forest (Forestry Agency)
Sep.	The Implication Plan for Decontamination in Special Decontamination Area (Katsurao Village)
	The 7th Panel for the Environment Recovery (Discussion about the policy of forest decontamination) (Ministry of the Environment)
	The Immediate Points of View Regarding the Future Forest Decontamination (Ministry of the Environment)
Nov.	The Implication Plan for Decontamination in Special Decontamination Area (Namie Town)
Dec.	The Implication Plan for Decontamination in Special Decontamination Area (Okuma Town)
	The kickoff of monitoring of radioactive Cs in the freshwater from the mountain used by residents (Ministry of the Environment)
Month and year	Events
Jan. 2013	The Decontamination Effect Implemented by Projects of Government and Municipalities (Ministry of the Environment)

Feb.	The kickoff of model projects to verify the range and effect of forest decontamination to reduce the air dose rate in appropriate ways (Ministry of the Environment)
Mar.	The Survey Results of Distribution of Radioactive Substance in Forests (Forestry Agency)
Apr.	The 8th Panel for the Environment Recovery (the present situation of forest decontamination) (Ministry of the Environment)
May	The Guideline for Decontamination (2nd edition) (Ministry of the Environment)
Jun.	The Implication Plan for Decontamination in Special Decontamination Area (Tomioka Town)
	The completion of decontamination in Tamura City (Special Decontamination Area) as a first case and the kickoff of follow-up process
	The completion of decontamination of Joban Express way (Ministry of the Environment)
Aug.	The 9th Panel for the Environment Recovery (Marshaling the knowledge of forest decontamination) (Ministry of the Environment)
	The Future Direction of Forest Decontamination (the removal of residue of organic matter, the measures for forest surrounding the house in valley terrain with high radiation, measures in mushroom plantation, experiment for verification in Area C) (Ministry of the Environment)
Sep.	The Overhaul of the Progress of Decontamination Activities (Ministry of the Environment)
Oct.	The Guideline for Plantation and Management of Mushroom (Forestry Agency)
	The kickoff of model project concerning the decontamination beyond 20m from the forest edge and the removal of residue of organic matter (Ministry of the Environment)
Nov.	The revision of the Implication Plan for Decontamination in Special Decontamination Area (Minamisoma City, Iitate Village, Kawamata Town, Katsurao Town, Namie Town, Tomioka Town)
Dec.	The 10th Panel for the Environment Recovery (the interim report for the model project at Difficult-to-Return zone, the revision of the guideline for decontamination (the chapter related with forest decontamination), the effect of decontamination activities) (Ministry of the Environment)
	Toward the Acceleration of Fukushima Reconstruction from the Nuclear Disaster (Cabinet Decision)

Month and year	Events
Feb. 2014	Reopening of Hirono IC – Jobantomioka IC
Mar.	The completion of decontamination in Kawauchi Village, Naraha Town and Okuma Town (Special Decontamination Area except for the Difficult-to-Return Zone) and the kickoff of follow-up process (Ministry of the Environment)
	The 11th Panel for the Environment Recovery (the results of model projects for forest decontamination, follow-up decontamination) (Ministry of the Environment)

Apr.	The lift of evacuation order for Tamura City as a first case (Nuclear Emergency Response Headquarters)
	The Survey Results of Distribution of Radioactive Substance in Forests (fiscal year 2013) (Forestry Agency)
Jun.	The report for verification project by decontamination in Difficult-to-Return zone (Ministry of the Environment)
Jul.	The Implication Plan for Decontamination in Special Decontamination Area (Futaba Town)
Aug.	The interim report for measurements for acceleration of decontamination and reconstruction by government and 4 cities (Reconstruction Agency, Ministry of the Environment, Fukushima City, Koriyama City, Soma City, Date City)
	Future Policy for Tackling the Pollution of Rivers and Lakes (Ministry of the Environment)
	The 12th Panel for the Environment Recovery (The introduction of measures by Forestry Agency) (Ministry of the Environment)
Oct.	The partial lift of evacuation order for Kawauchi Village (Nuclear Emergency Response Headquarters)
Dec.	The Guideline for Decontamination (2nd edition) with supplement regarding rivers and lakes (Ministry of the Environment)
	Reopening Namie IC – Minamisoma IC and Soma IC – Yamamoto IC
	The kickoff of model project to grasp the influence to living area by diffusion of radioactive substances on the wind (Ministry of the Environment)

Month and year	Events
Jan. 2015	The revision of the ordinance for the Act on Special Measures Concerning the Handling of Radioactive Pollution (the review of commission standard) (Ministry of the Environment)
	The 13th Panel for the Environment Recovery (the preservation condition of removed soil in Intensive Contamination Survey Area) (Ministry of the Environment)
Mar.	The 14th Panel for the Environment Recovery (the results of model projects for forest decontamination) (Ministry of the Environment)
	The kickoff of the model project to grasp the influence to living area by soil runoff caused by precipitation (Ministry of the Environment)
	The Survey Results of Distribution of Radioactive Substance in Forests (fiscal year 2014) (Forestry Agency)
	Reopening of Jobantomioka IC – Namie IC
	The Report on Decontamination –the summary of experience obtained through decontamination activities conducted in living area by Ministry of the Environment and other authorities
Jun.	The 15th Panel for the Environment Recovery (The result of model project of forest

	decontamination, exposed dose by recreation in forest) (Ministry of the Environment)
	The revision of Toward the Acceleration of Fukushima Reconstruction from the Nuclear Disaster (Cabinet Decision)
Sep.	The lift of the evacuation order for Naraha Town (Nuclear Emergency Response Headquarters)
Dec.	The 16th Panel for the Environment Recovery (the measures for radioactive pollution in forests) (Ministry of the Environment)
	The completion of decontamination in Katsurao Village and Kawamata Town (Special Decontamination Area except for the Difficult-to-Return Zone) and the kickoff of follow-up process (Ministry of the Environment)
	The Direction of Measures for Radioactive Substances in Forests (Ministry of the Environment)

Month year	and Events
Feb. 2016	The 1st Panel for Restoration of Forest and Forestry in Fukushima
Mar.	The 2nd Panel for Restoration of Forest and Forestry in Fukushima
	The Survey Results of Distribution of Radioactive Substance in Forests (fiscal year 2015) (Forestry Agency)
	The completion of decontamination in Futaba Town (Special Decontamination Area except for the Difficult-to-Return Zone) and the kickoff of follow-up process (Ministry of the Environment)
Apr.	The 1st Meeting of related parties for Satoyama Restoration Project
Jun.	The lift of the evacuation order for Katsurao Town and Kawauchi Village except for the Difficult-to-Return Zone (Nuclear Emergency Response Headquarters)
Jul.	The 2nd Meeting of related parties for Satoyama Restoration Project
	The lift of the evacuation order for Minamisoma City except for the Difficult-to-Return Zone (Nuclear Emergency Response Headquarters)
Aug.	The policy of handling Difficult-to-Return Zone (Nuclear Emergency Response Headquarters, Reconstruction Promotion Council)
	The kickoff of the model project to grasp the influence to living area by fallen and residual leaves (Ministry of the Environment)
Sep.	The 3rd Panel for Restoration of Forest and Forestry in Fukushima (the selection of first group of municipalities for implementation of Satoyama Restoration Project)
Dec.	The 17th Panel for the Environment Recovery (the interim report for the model project concerning the measures against radioactive substances in forest) (Ministry of the Environment)
	The 4th Panel for Restoration of Forest and Forestry in Fukushima (the selection of second group of municipalities for implementation of Satoyama Restoration Project)

Month year	and Events
Jan. 2017	The completion of decontamination in Tomioka Town (Special Decontamination Area except for the Difficult-to-Return Zone) and the kickoff of follow-up process (Ministry of the Environment)
Mar.	Decontamination, Interim Storage Site, Waste treatment –Achievements and Prospects (Ministry of the Environment)
	The completion of decontamination in Minamisoma City and Namie Town (Special Decontamination Area except for the Difficult-to-Return Zone) and the kickoff of follow-up process (Ministry of the Environment)
	The lift of the evacuation order for Kawamata Town, Namie Town and Iitate Village except for the Difficult-to-Return Zone (Nuclear Emergency Response Headquarters)
	The Survey Results of Distribution of Radioactive Substance in Forests (fiscal year 2016) (Forestry Agency)
Apr.	The lift of the evacuation order for Tomioka Town except for the Difficult-to-Return Zone (Nuclear Emergency Response Headquarters)
	Forest fire in Namie Town and Futaba Town
Jun.	“Survey result of the land after the forest fire” (Forestry Agency)
Jul.	“Fukushima Office for Environment Restoration” was re-organized as “Fukushima Regional Environment Office” (Ministry of the Environment)
Dec.	The 18th Panel for the Environment Recovery (the interim report for the model project concerning the measures against radioactive substances in forest) (Ministry of the Environment)

Table 2-2 Municipalities designated as SDA and ICSA (as of Jun. 2017)

	SDA	ICSA
Designated municipalities	11 (Dec. 2011) (Okuma Town, Futaba Town, Tomioka Town, Namie Town, Katsurao Village, Iitate Village, Minamisoma City, Kawamata Town, Naraha Town, Kawauchi Village, Tamura City)	102 (Dec. 2011) 2 Yanaizu Town and Watari Town (Feb. 2012)
Undesignated municipalities	0	12 Katashina Village, Minakami Town, Showa Village (Dec. 2012) Ishinomaki City (Jun. 2013) Mishima Town (Nov. 2014) Hokota City, Sano City (Mar. 2016) Yamatsuri Town (Sep. 2016) Hanawa Town, Yanaizu Town (Nov. 2016) Annaka City, Nakanojo Town (Mar. 2017)
Sum	11	92

Note: There are 4 municipalities containing both SDA and ICSA
(Kawauchi Village, Tamura City, Kawamata Town, Minamisoma City)

The Act was fully come into force in Jan. 1st, 2012, and at the same time, MOE established the regional office in Fukushima city named “Fukushima Office for Environmental Restoration”.

Moreover, MOE made open to public the “The Decontamination Policy in SDA” at the same time (MOE, 2012a) to show the specific plan in SDA.

The implementation plan for decontamination in SDA was established in Tamura city, Naraha town and Kawauchi village and Minamisoma city in Apr. 2012, followed by the plan in Iitate village to prepare the actual setout from Jul. 2012.

“The Technical Guideline for Removal and Prevention of Diffusion of Radioactive Cs in Forest” was made open to public by Forestry Agency (hereinafter referred to as “FA”) in Apr. 2016 (FA, 2012). The tree logging and prevention of runoff of surface soil were described, as well as the removal of fallen leaves, branches referred in the decontamination guideline.

MOE, FA, Fukushima prefectural government, Reconstruction Agency (hereinafter referred to as “RA”) and other related organization has been cooperatively involved with these countermeasures regarding the forest decontamination, in the long-term perspective.

From Jul. 2012, the decontamination activities had been conducted on a full-scale operation, and the policy for forest decontamination toward the future has been discussed in “The Panel for the Environment Recovery” at the same time.

In the 4th panel, the evaluation of the amount of the runoff or diffusion of radioactive substances from the whole forest or local area by decontamination activities was discussed.

The forests that should be prioritized to be decontaminated were also raised as one of the agendas (MOE, 2012b).

The evaluation of the amount of the radioactive substances through the air and water, the runoff of soil caused by the removal of leaves, branches, thinning, clear-cutting were discussed in the 5th panel, as well as the specific places to be decontaminated and the preservation of the waste generated through the activities (MOE, 2012c).

The 6th panel was held in the next month, Aug. 2012. The Fukushima prefectural government and Kawauchi village, one of the municipalities containing SDA, were interviewed, and research and development on the forest decontamination which should be conducted continuously was discussed (MOE, 2012d).

In the very next month, Sep. 2012, the 7th panel was held and “The Immediate Points of View Regarding the Future Forest Decontamination” was compiled (MOE, 2012e).

The three types of forests, which have been often referred when the policy regarding the forest decontamination is discussed, were defined for the first time in this document as follows (Fig. 2-4):

Area A: Forests near to the living area

Area B: Forests located apart from the living area but people frequently enter for recreation or businesses

Area C: Forests excluding the Area A and Area B

This is the basic classification to tackle this issue, according to the types of utilization.

In Area A, the range for the decontamination would be decided, according to the step-by-step trial removal of fallen leaves and branches, followed by the action up to the 20 m from the edge of the forest. It was pointed out that it would be appropriate for the branches of evergreen trees at the edge of forest to be pruned, when sufficient effect could not be observed.

In Area B, the cultivation fields for mushrooms or camping site were taken as examples, and the concrete range or methods for decontamination would be further considered, in terms of the radiation exposure to workers or users, and the cost-effectiveness.

The amount of runoff and diffusion of radioactive substances through water and air was thought to be very small from the watershed of Area C, occupying the vast rest of the area. It was also mentioned that the removal of organic matters in the wide range of forests would cause the negative effect for trees by soil outflow or land deterioration. On the other hand, the combination of the forestry and forest decontamination, in the other words, the thinning and removal of radioactive substances simultaneously, was said to be necessary, because that would lead to the safety and security of people.

The monitoring of radioactive Cs in the freshwater from the mountain used by residents had begun from Dec. 2012 mentioned in the document, followed by continuous publication trimonthly from Mar. 2013 (MOE, 2013b).

“The Decontamination Effect Implemented by Projects of Government and Municipalities” was published in Jan. 2013. The reduction rate of surface contamination concentration was adopted to evaluate the each type of decontamination technique conducted by government and municipalities under the relatively high radiation area in Fukushima prefecture during the early stage after the accident, though the effect of forest decontamination wasn’t considered due to the shortage of data (MOE, 2013c). This was the first document to assess the decontamination effect utilizing a great deal of data.

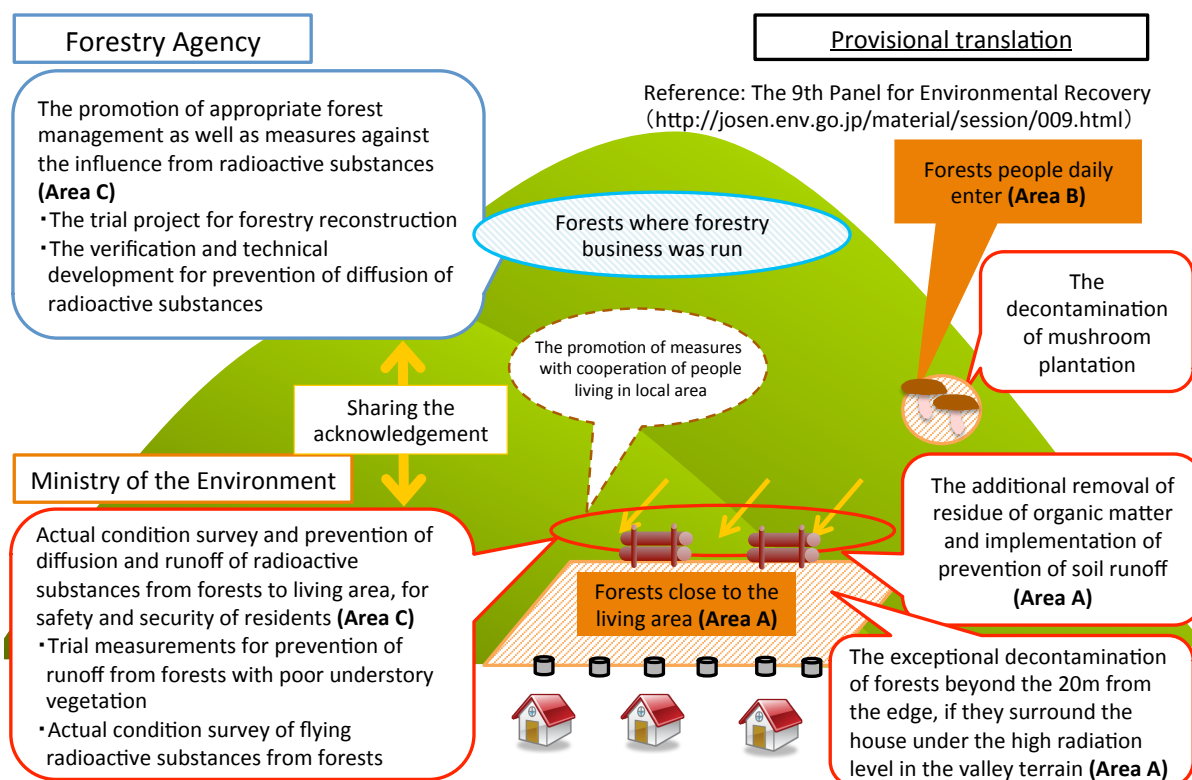


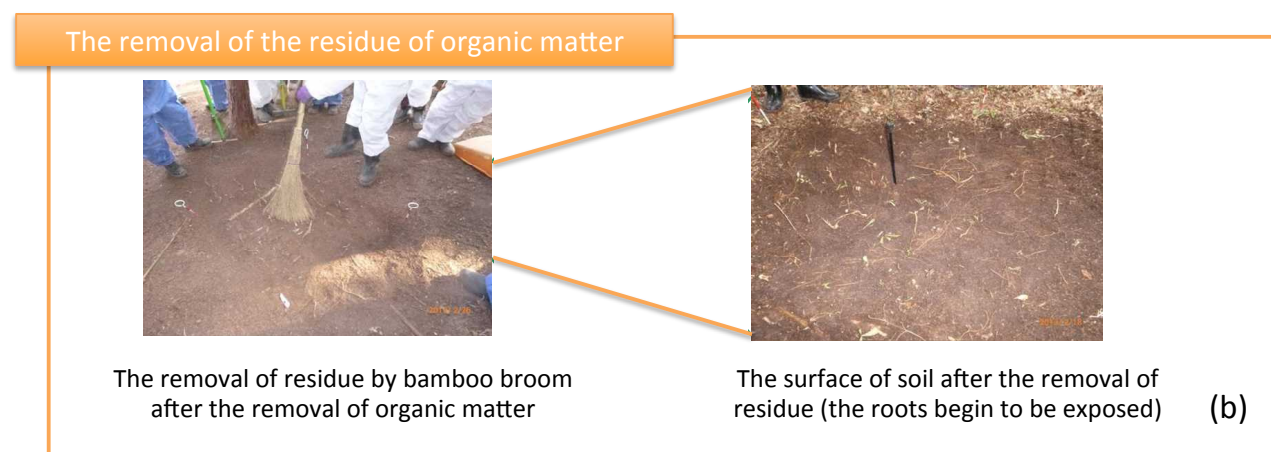
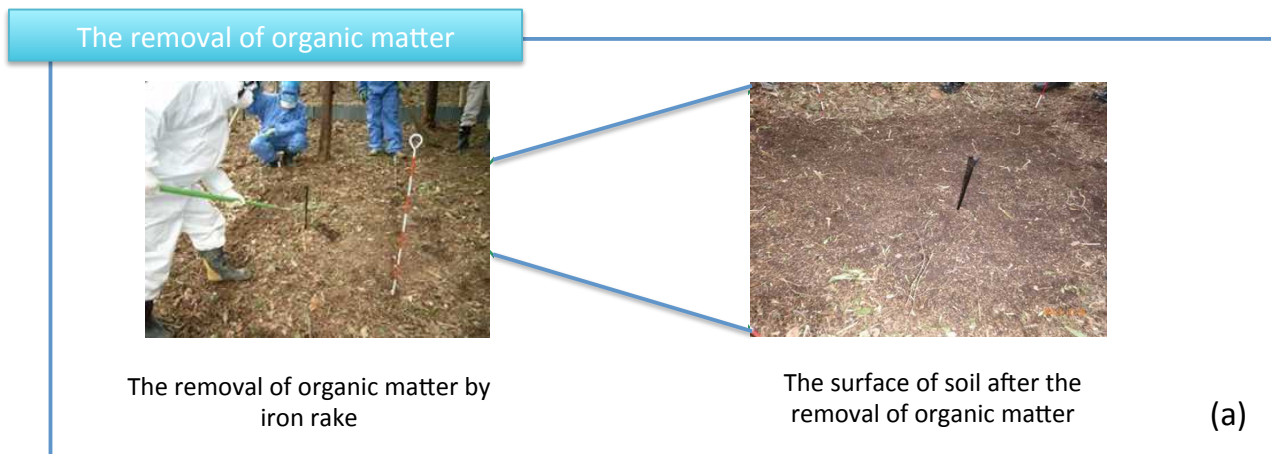
Fig. 2-4 Countermeasures for forest radioactive contamination in “Area A, B and C”.

Model projects to verify the range and effect of forest decontamination to reduce the air dose rate in appropriate ways started from Feb. 2013, at Ogawara district in Okuma Town, one of the municipalities containing SDA. Concretely, the effect was analyzed, when the range for the decontamination was expanded from the 20 m to 40 m from the edge of the forest, or the residue of the organic matter plus organic matter itself was removed within the 20 m from the edge of the forest.

As a result of these trial activities, it was revealed that the expansion of the range of the decontamination didn't lead to the more effective results, and that the removal of residue of organic matter should be conducted within 5 m from the edge to reduce the air dose rate in living area.

The forest decontamination has been conducted, according to the results of these activities, in terms of reducing the influence to living area, as well as protecting the forest environment.

In the 8th Panel for the Environment Recovery held in Apr. 2013 (MOE, 2013d), the efforts in Area A, B and C were introduced, followed by the 9th panel in Aug. 2013 (MOE, 2013e) in which “The Future Direction of Forest Decontamination” was proposed. In this proposal, in Area A, it was made possible to remove additionally the residue of organic matter within the 5 m from the edge of the forest, if the enough effect couldn't be observed after the removal of organic matter (Fig. 2-5). The installation of workpiece including sandbags to tackle the soil runoff from forests with steep slope was also approved.



Reference: Edited version based on the decontamination guideline p 2-121 (MOE)

Fig. 2-5 Removal of organic matter (a) and residue of organic matter (b).

Moreover, the forest decontamination more than 20 m would be admitted, when the house located in the valley terrain was surrounded by forests and suffered from relatively higher radiation. It was regarded as an exceptional measure and model project began from Oct. 2013 to determine the specific condition.

The forest decontamination in Area B adopted nearly the same ways as that of Area A, that is, the removal of organic matter in the places (e.g. mushroom plantation) and the area spreading 20 m from the edge of the places.

In the Area C, two different kinds of trial experiments were decided to start. First, the prevention of runoff of radioactive substances from forests using wood fences would be conducted in a few fields. Second, the monitoring of flying radioactive substances, using dust samplers, anemoscope and automatic monitoring device for radiation to evaluate the fluctuation of air dose rate according to the direction or condition of winds.

The decontamination of Joban Highway and Tamura city had finished in Jun. 2013.

“The Overhaul of the Progress of Decontamination Activities” was made open to public in Sep. 2013. In this document, it was mentioned that the implementation plan for decontamination would be revised until the end of 2013, according to the actual condition in each municipality (MOE, 2013f).

In Oct. 2013, FA published “The Guideline for Plantation and Management of Mushroom” for preventing the concentration of radioactive Cs in mushrooms from exceeding the standard (FA, 2013a). In the “Q & A for Decontamination Activities”, the decontamination of mushroom plantation was recommended to follow

this guideline (MOE, 2013g).

In the 10th Panel for the Environment Recovery held in Dec. 2013, the interim results for model projects including the forest decontamination in “Difficult-to-Return Zone” were reported.

The chapter of forest decontamination guideline was revised, reflecting the new knowledge for dynamics of radioactive substances (e.g. the transition to the forest floor, the fact that the runoff of radioactive substances is relatively limited), and for effective decontamination activities (e.g. the appropriate range for removing the organic matter and its residue, the exceptional removal of organic matter beyond the 20 m from the edge of the forest).

The new reports for decontamination effect was made open to public in Dec. 2015, focusing on the reduction of air dose rate instead of surface contamination concentration, collecting the additional data obtained through subsequent projects in SDA and ICSA (MOE, 2013h).

According to the report, the average of the reduction rate for air dose rate (monitoring points: 1 m from the ground) was around 34.8 %. On the other hand, the reduction rate through forest decontamination was around 21.8 % in SDA and around 16.2 % in ICSA, having the characteristics that the effect was less than other places, influenced by the surrounding environment.

The results of model projects concerning the experimental decontamination beyond the 20 m from the edge of forests, which had been operated since Oct. 2013, were reported in the 11th Panel for the Environment Recovery held in Mar. 2014 (MOE, 2014a).

In this report, new findings were implied as follows:

- The removal of organic matter beyond the 20 m from the edge of forests, surrounding a house with relatively high air dose rate, rarely contributed to its reduction.
- The decontamination beyond the 20 m from the edge of forests could be effective, when the area beyond the 20 m was highly contaminated rather than within 20 m.
- The additional removal of residue of organic matter should be limited up to 5 m from the edge for effective decontamination.

Around the same time, the decontamination in Kawauchi Village, Naraha Town and Okuma Town, municipalities in SDA, has been finished and follow-up remediation has been continuously conducted.

In Apr. 2014, in Tamura city the evacuation order was lifted, for the first time among 11 municipalities. The results of model projects for decontamination in the



Fig. 2-6 Instruments to detect the radioactive substances distributed from forests.

Reference: The 14th Panel for Environment Recovery (MOE)

“Difficult-to-Return Zone” were reported in Jun. 2014. It was true in all categories to be decontaminated including houses, farmlands, roads and so forth, that the reduction rate got efficient under the high radiation circumstances. In the forests, however, the efficiency became lower, or 10 - 20 % compared with other types of land use (MOE, 2014b).

The measures for radioactive pollution by FA were introduced in the 12th Panel for the Environment Recovery in Aug. 2014, such as the distribution survey of radioactive Cs in the each part of the trees (leaves, branches, barks, fallen leaves and soil), which had been continuously conducted as well as the evaluation of reduction effect of air dose rate, the travel distance of soil, the effect of covering of the surface, the effect of workpiece for preventing the muddy water, the introduction of forests restoration projects (MOE, 2014c).

In Oct. 2014, the evacuation order in the part of Kawauchi village was lifted or revised, the second municipality in SDA.

In Dec. 2014, the model project to evaluate the diffusion of radioactive Cs from forests on the wind was kicked off in two places in Tamura City, according to “The Future Direction of Forest Decontamination” opened in Aug. 2013 (Fig. 2-6 and Fig. 2-7).

In the 14th Panel for the Environment Recovery in Mar. 2015, the brief items were introduced, concerning the runoff and diffusion of radioactive Cs (MOE, 2015a). At the same month, the model experimental project regarding the runoff of radioactive Cs and the influence on living area started (Fig. 2-8).

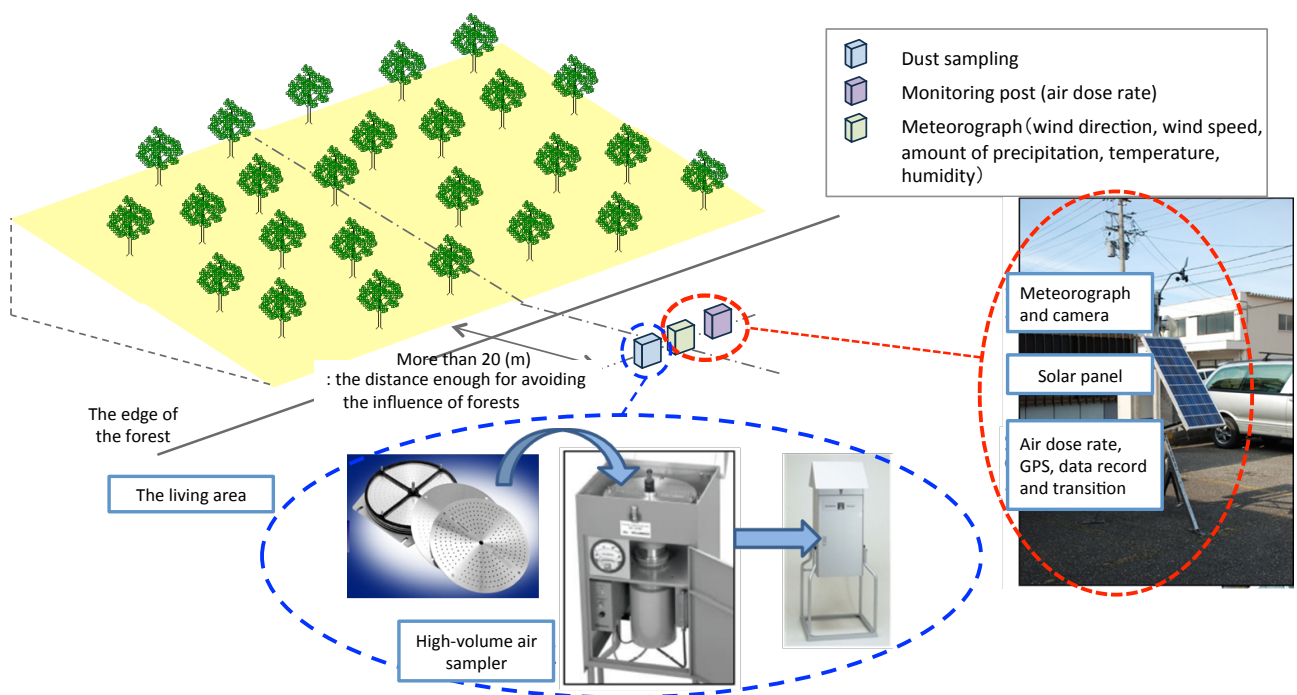


Fig. 2-7 Concept of model project for investigating the radioactive substances flying from forest with winds.

The progresses of the model project to evaluate the diffusion of radioactive Cs on the wind from forest were reported in the 15th Panel for the Environment Recovery in Jun. 2015. According to the report, the explicit correlation wasn't observed between the air dose rate and direction or speed of wind, that is, even when wind blew from the forests to the living area, the increase of air dose rate wasn't confirmed.

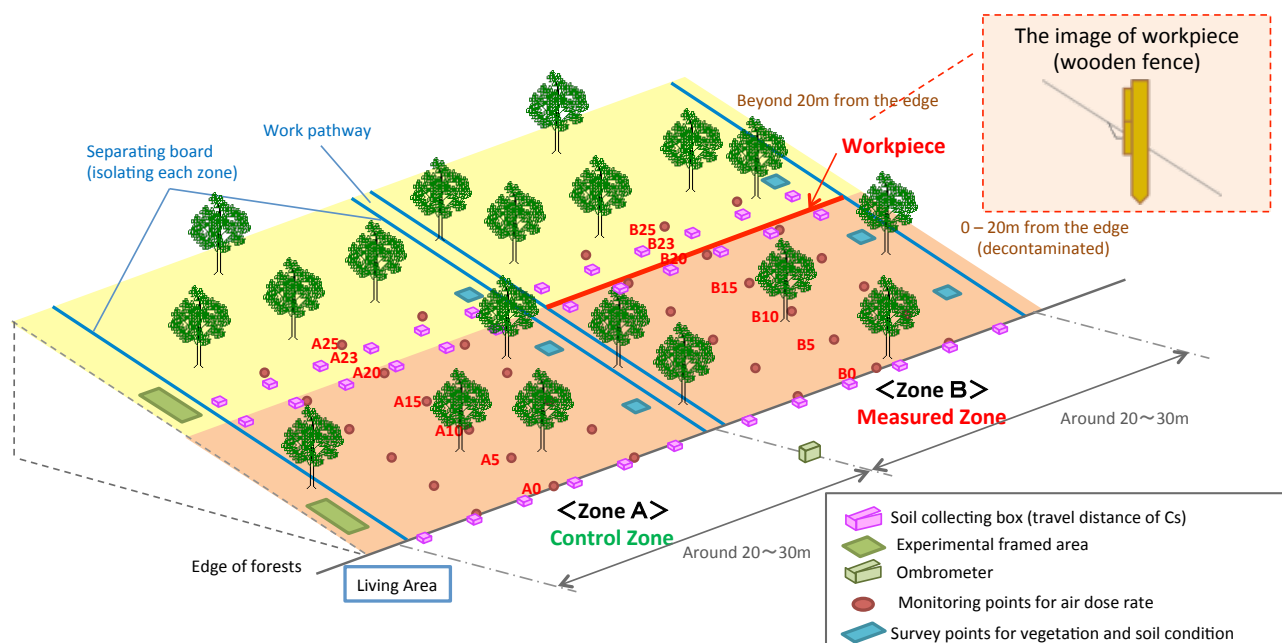


Fig. 2-8 Concept of model project for investigating the effect of wooden rail to prevent the soil from flowing out to living area.

Reference: Edited version based on the 14th Panel for Environment Recovery (MOE)

Moreover, the concentration of radioactive Cs in suspended dust was almost same or slightly larger than the average concentration in Japan before the accident. This might implied that the suspended dust wasn't the major source to contribute the air dose rate and no evidence was provided, for the diffusion of radioactive Cs from forests to influence the increase the air dose rate in living area.

The amount of estimated exposure during recreation activities in forests was also announced showing that it was assumed around 0.060 mSv y^{-1} on average and 0.14 mSv y^{-1} when calculated under conservative condition (MOE, 2015b).

The evacuation order in Naraha town was completely lifted in Sep. 2015.

The decontamination in Katsurao Village and Kawamata Town, municipalities in SDA, has been finished and follow-up remediation has been continuously conducted in Dec. 2015.

The interim reports on the influence on living area, through soil runoff caused by precipitation was made open to public in the 16th Panel for the Environment Recovery in Dec. 2015.

According to the report, the existence of wooden workpiece didn't make any implicit impacts on the change of air dose rate, though the amount of soil runoff had positive correlation with the amount of rainfall, in addition to the fact that the amount of soil transference and accumulation of radioactive Cs in decontaminated place was larger than that of untouched place.

The amount of accumulated radioactive Cs was totally different between places to places, that is, the amount was less in place without wooden workpiece and having steep slope after experiencing the heavy precipitation.

Simulation under the conservative conditions that all of radioactive Cs, which went out of forests was accumulated along the forest edge, led the result that around 2 - 9 % rise on air dose rate would be estimated, if the place experienced large amount of rainfall for 5 consecutive years as much as that of fiscal year 2015.

These experimental projects were decided to be continued, because the results implied that the workpiece

would be effective to tackle the soil runoff, in the terrain with steep slope (MOE, 2015c).

In the wake of a lot of obtained knowledge, “The Future Direction for Measures for Radioactive Substances in Forests” was made open to public at the same time.

In Area A and B, the forest decontamination would be conducted by removing the organic matter within 20 m from the edge, the residue of organic matter within 5 m within the edge respectively, in parallel with trial implementation.

In addition to these existing measures, taking countermeasures beyond the 20 m was approved exceptionally for the first time, in the case of forests surrounding the house located in the valley terrain with high radiation.

Regarding Area C, continuous monitoring and establishment of wooden workpieces would be mainly introduced on site when necessary, in the wake of the results that the runoff or diffusion of radioactive Cs contributing the rise of air dose rate in living area would not be observed, as well as the concerns that the widespread removal of organic matter on the ground would lead to the undesirable soil runoff and deterioration of land capability.

Unified measures of forestry and radioactive substances were regarded as one of the major policies and this concept would last and share for long-term perspective (MOE, 2015d).

There was a certain amount of support for this policy, but thorough forest decontamination was called for mainly from municipalities in Fukushima Prefecture. In response to these opinions, the 1st and 2nd Panel for Restoration of Forest and Forestry in Fukushima, consisting of Minister of RA, MOE and FA were held in Feb. and Mar. 2016. In these panels, the new cooperative project named “Satoyama Restoration Project” was determined to be launched (RA, 2016a and 2016b).

The decontamination in Futaba Town, municipality in SDA, has been finished and follow-up remediation has been continuously conducted in Mar. 2016.

The first municipalities were chosen, or, Kawamata Town, Hirono Town, Katsurao Village and Kawauchi Village in the 3rd Panel for Restoration of Forest and Forestry in Fukushima in Sep. 2016, as first sites to tackle, in the wake of adjustment and field studies by government (RA, 2016c).

The evacuation order for Katsurao Village and Kawauchi Village was lifted in Jun. 2016, as well as for Minamisoma City in Jul. 2016.

“The Policy for the Difficult-to-Return-Zone” was published by government in Aug. 2016 and in this document, the inhabitable strongholds for reconstruction were to be established in each municipality with the zone, by lifting the evacuation order in the wake of the decrease of air dose rate within 5 years (NERH and RPC, 2016).

In the 17th Panel for the Environment Recovery in Dec. 2016, the interim results were reported for 2 types of experimental projects. First, the model project concerning the soil runoff, which has been continuously conducted, partially reported in the 14th and 16th panel (MOE, 2016).

According to the interim report, there was no explicit soil runoff to influence the increase of air dose rate in living area, such as the place or the existence of workpiece, and this was also coherent with the interim report in the 16th panel.

The second project was the succeeding one to evaluate the diffusion on radioactive Cs on wind.

In this project, the influence to living area by falling leaves had been investigated, using litter-fall traps as well as other instruments (Fig. 2-9). According to the interim report, there wasn't any specific change regarding the air dose rate, comparing the summer and autumn, the season for leaves to fall. This project would be continued for a while.

In the same month, the 4th Panel for Restoration of Forest and Forestry in Fukushima was held and 2nd group of municipalities, Iitate Village, Tomioka Town, Nihonmatsu City and Date City were chosen for implementation of Satoyama restoration project (RA, 2016d).

The decontamination in Tomioka Town, a municipality in SDA, has been finished and follow-up remediation has been continuously conducted.

“Decontamination, Interim Storage Site, Waste treatment –Achievements and Prospects” was published by MOE in Mar. 2017 just before the 6th anniversary of the earthquake and end of the full-scale decontamination activities.

The decontamination in Minamisoma City and Namie Town, municipalities in SDA, has been finished and follow-up remediation has been continuously conducted. These are the last two cities where full-scale decontamination activities were conducted in SDA, followed by monitoring and necessary adjustments.

In Mar. 2017, FA released the survey results of distribution of radioactive Cs in different types of forests, including leaves, branches, barks, trenches, organic matters, soil. This monitoring has been continuously conducted right after the accident and made open to public annually (FA, 2011a, FA, 2011b, FA, 2013b, FA, 2014, FA, 2015, FA, 2016, FA, 2017a). According to the investigation, in the early stage after the accident, around 20 – 40 % of radioactive Cs was attached to the above-ground parts, that is, leaves, branches, barks and trenches. Especially, conifer trees including *Cryptomeria japonica* has tended to retain more of radioactive Cs, compared with deciduous trees such as *Quercus serrata*. This might be because more leaves had remained in conifer trees while most leaves of deciduous trees had fallen when the accident happened. It has steeply decreased down to around 10 – 30 % after 1 year passed after the accident. After 3 years passed, the proportions of radioactive Cs in above-ground part had become almost same between the forests, approximately 1 - 10 %. In the wake of these results, it can be assumed that radioactive Cs had dropped to the ground part of forests during relatively earlier stage (Table 2-3).

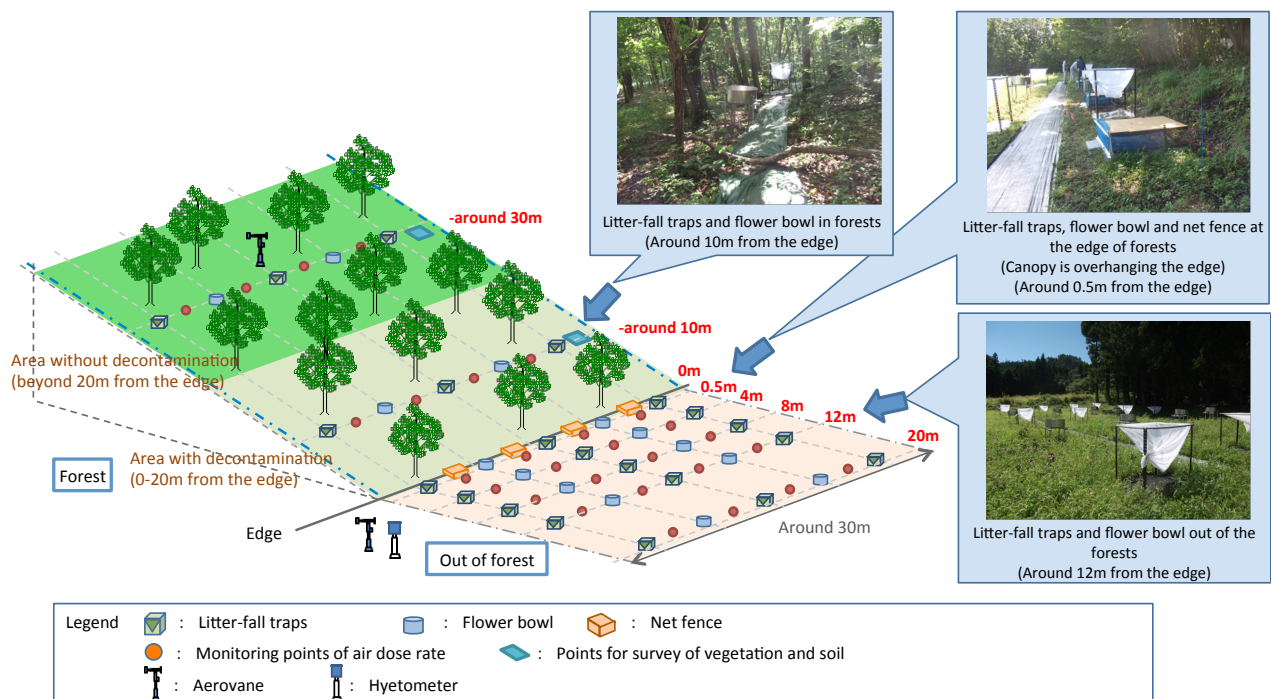
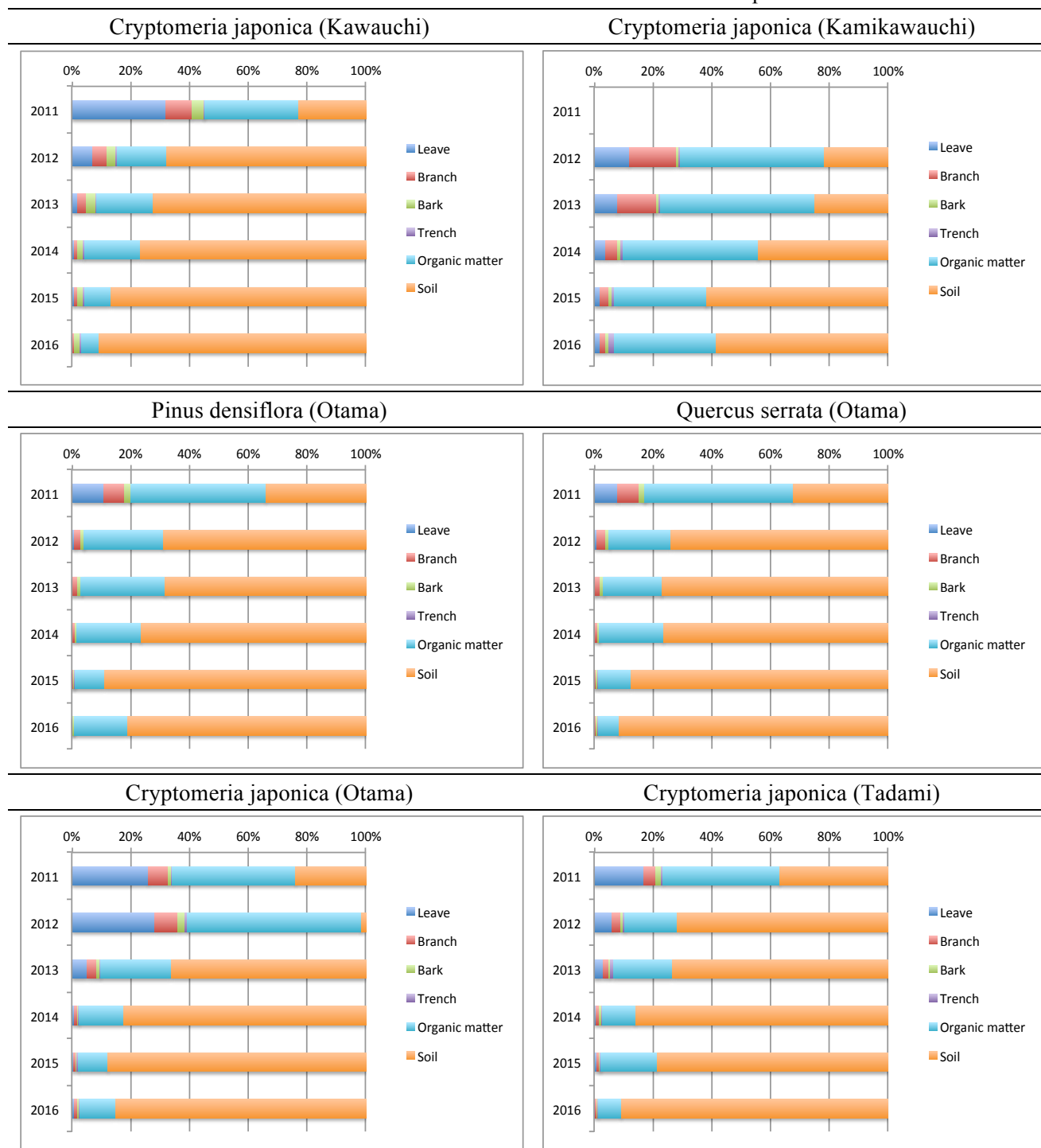


Fig. 2-9 Concept of model project for investigating the influence of fallen leaves to living area.

Reference: Edited version based on the 17th Panel for Environment Recovery (MOE)

Table 2-3 Timeline of distribution of radioactive Cs in each part of forest



The evacuation orders for Kawamata Town, Namie Town and Iitate Village were lifted in Mar. 31 2017 followed by the lift of the order for Tomioka Town in Apr. 1 2017, except for the Difficult-to-Return Zone. All evacuation orders except for the Difficult-to-Return Zone were lifted and government began focusing on the measures in this Zone.

In the end of Apr., forest fire occurred in the mountain and the fire expanded toward both the area of Namie Town and Futaba Town.

Forestry Agency published the survey report on the land after the fire, in response to the people's concern about diffusion of radioactive Cs to the surrounding area (FA, 2017b).

In Jul. 2017, Fukushima Office for Environment Restoration of Ministry of the Environment was re-organized as "Fukushima Regional Environment Office", to comprehensively deal with the complex issues in Fukushima.

These introduced events were focused on countermeasures for radioactive substances mainly in forests by putting them in chronological order, conducted mainly by whole government and MOE in charge of decontamination policy. However, there have been a lot of organizations to tackle this issue, including Fukushima Prefectural Government, universities, other research institutes and obtained knowledge was taken advantage of for related policies.

In the 18th Panel for the Environment Recovery in Dec. 2017, the interim results were reported for the experimental projects to evaluate the diffusion on radioactive Cs on wind.

According to the interim report, the influence to living area by falling leaves had not been observed, but the investigation would be continued and the impact of natural disaster including typhoon would be investigated as well (MOE, 2017a).

2.2 Progresses of decontamination activities

The area widely contaminated by radioactive substances has been categorized into two parts, SDA and ICSA as mentioned above, and decontaminated mainly by MOE and each municipality respectively.

The progress in SDA was announced every month by MOE in charge of decontamination activities (MOE, 2017b).

Regarding the ICSA, Fukushima Prefectural Government has tallied data and continuously published within Fukushima prefecture and MOE has been involved with data out of Fukushima prefecture, that is, Iwate, Miyagi, Ibaraki, Tochigi, Gumma, Chiba, Saitama prefecture (MOE, 2017c). The progresses in each area was aggregated based on these data (Fig. 2-10 - Fig. 2-12).

It should be considered, however, that the starting point for publication, as well as the interval of data publication was different: once every month for SDA and ICSA in Fukushima prefecture and once every three months for ICSA out of Fukushima prefecture.

In some months, the progress rate decreased, but it was due to the increase of the planned number of targeted objects, and generally speaking, the progress in each category has coherently tended to increase both in SDA and ICSA.

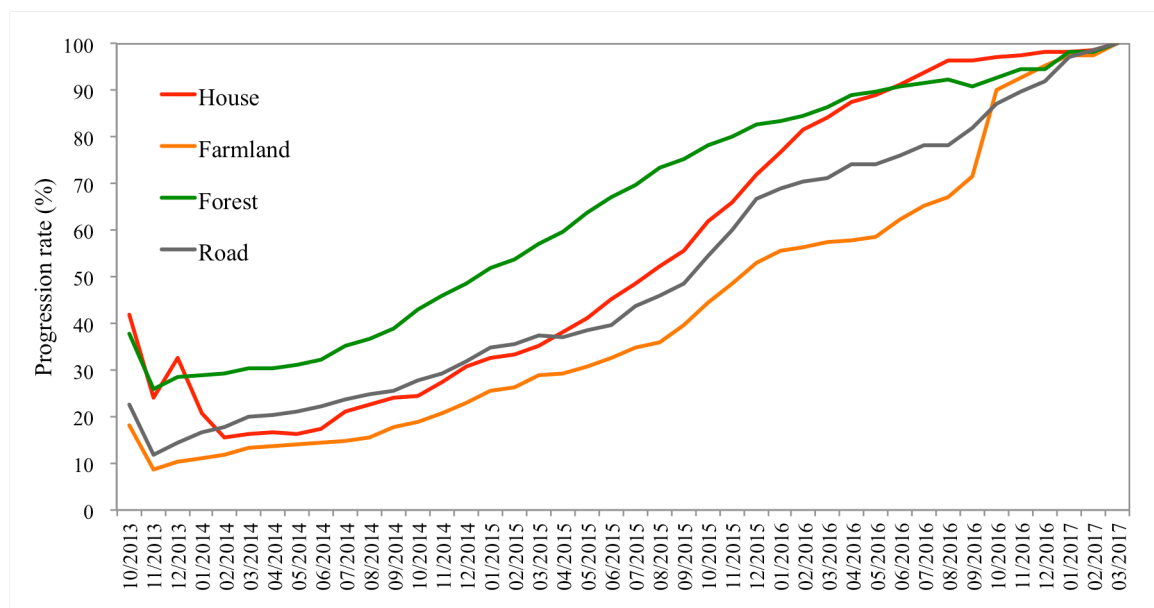


Fig. 2-10 Progression rate of decontamination activities in SDA (Oct. 2013 - Mar. 2017). The rate in SDA was tallied and made open to public by MOE (MOE, 2017a).

In SDA, the full-scale decontamination activities have finished in the end of the Mar. 2017, according to the government goal. Thus, the progress rate in every type of category, house, farmland, forest and road, reached 100 % as of Mar. 2017, though the follow-up activities has been still undertaken. The process to the goal, however, was different between categories: in SDA, according to the statistics, forest seemed to be prioritized to be embarked on, followed by house, road, farmland, though the planned dimension or the number also depends on categories.

In ICSA in Fukushima prefecture, their decontamination activities were initially planned to be finished at the end of Mar. 2017. However, they are still in progress and aimed to be ended until the end of Mar. 2018.

All of the categories including house, public facility, farmland, road and forest, the progression rate reached more than 98 % as of the end of Dec. 2017. In ICSA, children-related facilities including houses, parks, schools, public facilities has been prioritized to be decontaminated, because people have been led their lives, without being evacuated in these area. In SDA, basically the houses had taken priority to be undertaken in order to prepare to sequential lift of the evacuation order completed until Mar. 2017 except for Difficult-to-Return Zone, though the situation differed between each municipality.

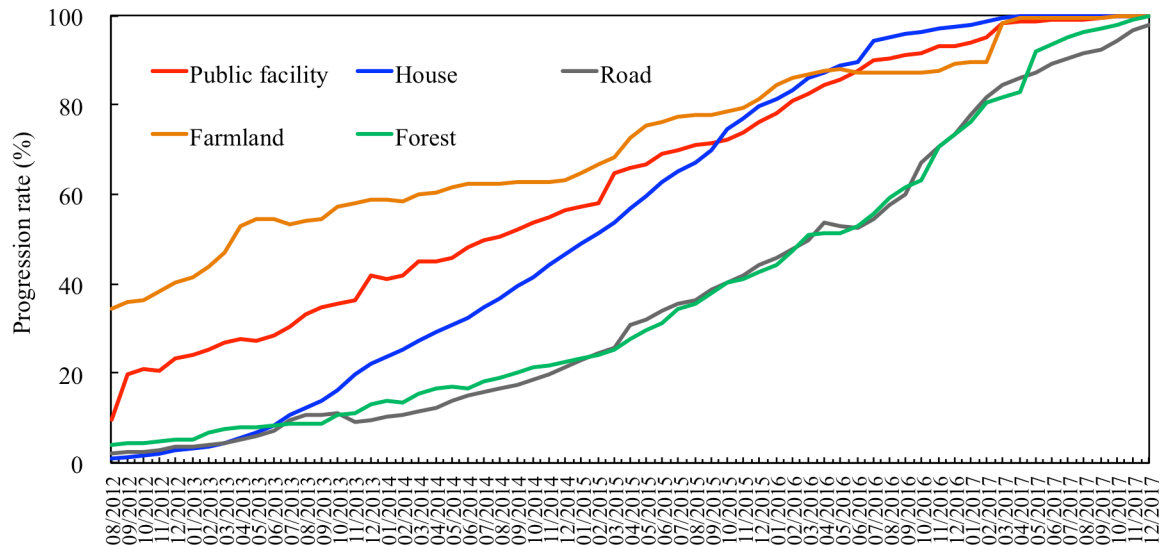


Fig. 2-11 Progression rate of decontamination activities (ICSA in Fukushima Prefecture)(Aug. 2012 – Dec. 2017). The rate in ICSA in Fukushima Prefecture was tallied and made open to public by Fukushima Prefectural government.

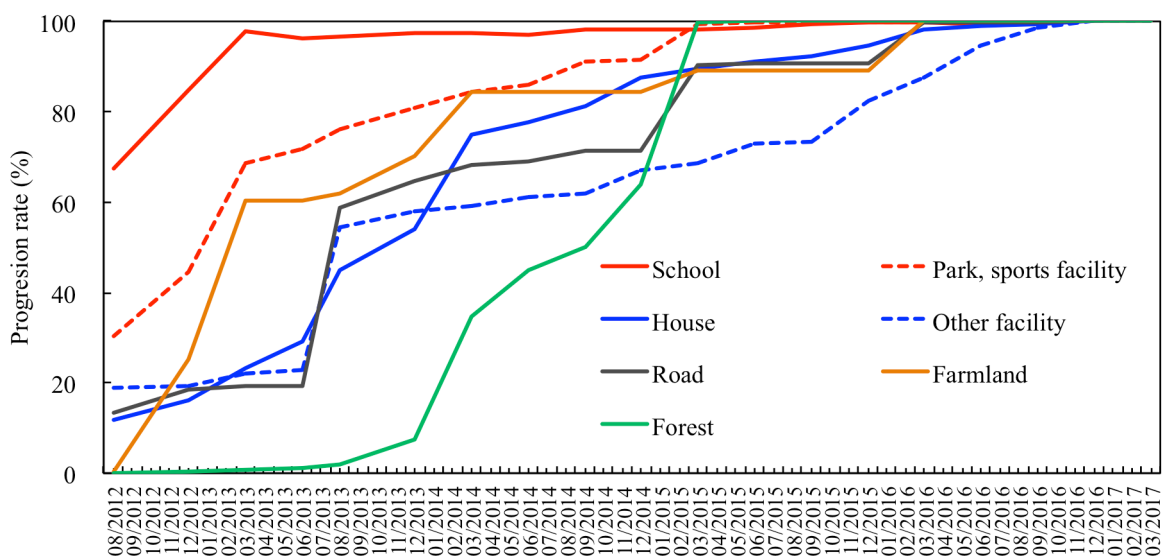


Fig. 2-12 Progression rate of decontamination activities (ICSA out of Fukushima Prefecture)(Aug. 2012 – Mar. 2017). The rate in ICSA out of Fukushima Prefecture was tallied and made open to public by MOE.

In ICSA out of Fukushima prefecture, planned quantity to be decontaminated would be much lower than SDA or ICSA in Fukushima prefecture, because the degree of contamination has been lower than that of areas in Fukushima prefecture.

That is one of the reasons why they were able to be completed before the end of Mar. 2017.

When focusing on the decontamination progress of forests, the timing for publication was different between categories: SDA from Oct. 2013, ICSA (in Fukushima prefecture) from Sep. 2012, ICSA (out of Fukushima prefecture) from Aug. 2012, respectively.

As we can see in Fig. 2-13, the decontaminated dimension steeply rose in Oct. 2013, because the publication for the progress in SDA started for the first time since this month.

The outbreak of dimension was, around 5,900 ha in SDA (55 %), around 4,500 ha in ICSA (in Fukushima prefecture) (42 %) and around 300 ha in ICSA (out of Fukushima prefecture) (3 %).

The number of municipalities containing each area was different between areas, that is, 11 in SDA, 36 in ICSA in Fukushima prefecture, 56 in ICSA out of Fukushima prefecture as of Mar. 2017. Given the fact that the number of municipalities in SDA was much smaller than that of ICSA, it could be guessed that SDA was heavily contaminated and major-scale activities has been conducted compared with ICSA.

MOE has aimed to finish full-scale decontamination until the end of Mar. 2017, but measures for radioactive substances in forest would be continued in so-called Satoyama or forest people enter in their daily life, because large field in forest could have been remained untouched due to its vast area or prevention of second disaster.

In addition to that, the timeline of the number of temporal storage site and the number of preserved containers were shown in Fig. 2-14 - Fig. 2-18.

The number of temporal storage site in SDA has coherently increased from 175 (Jul. 2014), published number for the first time to 279 (Sep. 2016) at maximum. The number peaked out at the same month and has gradually decreased to 242 (Dec. 2017), as the amount of containers brought to the makeshift incinerators or interim storage site located near the Fukushima Dai-ichi Nuclear Power Plant has increased. The number of

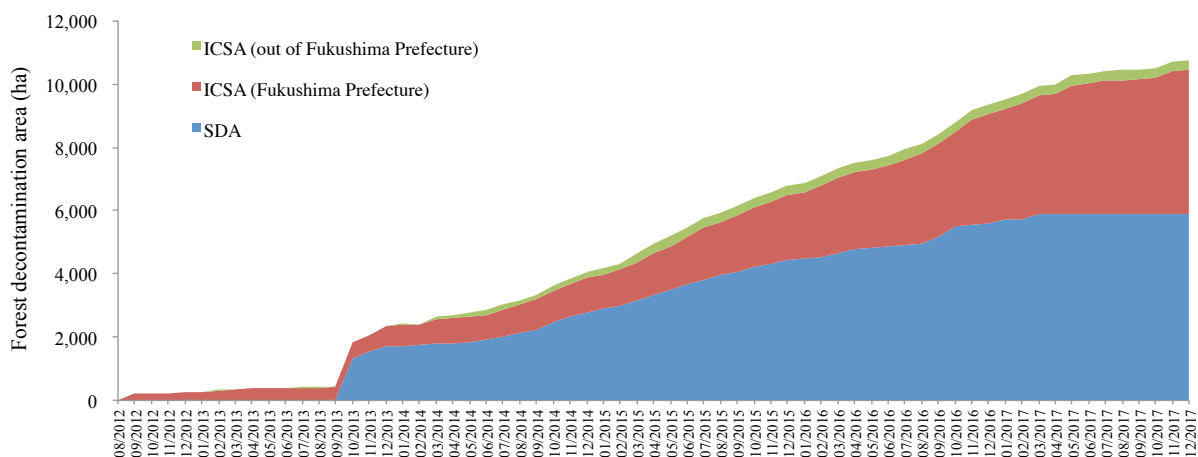


Fig. 2-13 Forest decontamination area (Aug. 2012 - Dec. 2017). Area in SDA, ICSA in Fukushima Prefecture, and ICSA out of Fukushima Prefecture were tallied and made open to public by different authorities and data sources. Therefore, the starting months for publishing are different; ICSA (Out of Fukushima Prefecture), ICSA (Fukushima Prefecture), and SDA were initially made open to public in Aug. 2012, Sep. 2012, and Oct. 2013, respectively.

discharged containers has risen to around 1.5 million, while the number of preserved containers has also peaked to around 7.6 million in Mar. 2017.

The temporary storage site where all containers have been brought out would be returned to the landowners by restoring to original state.

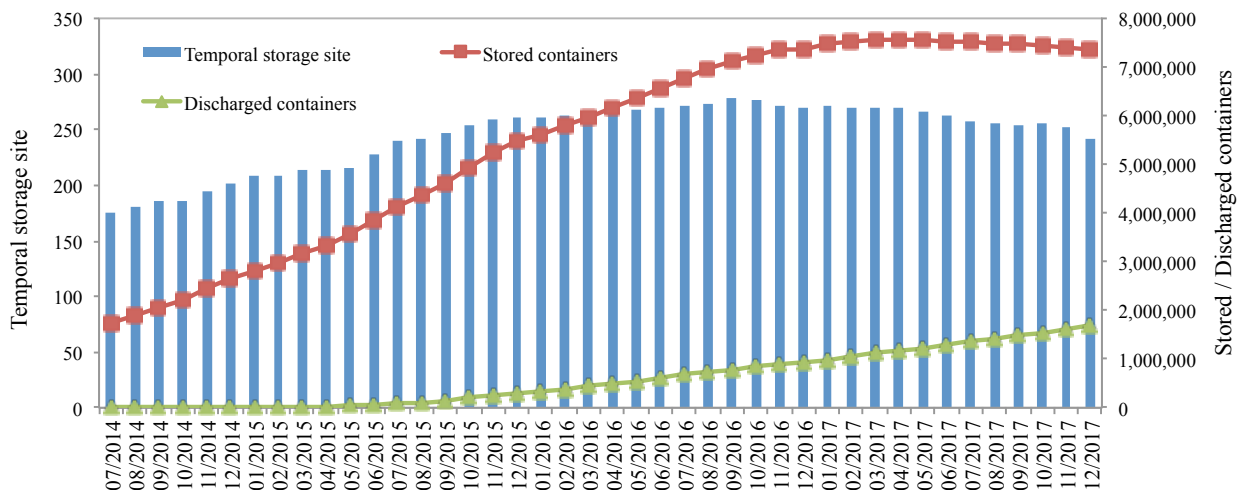


Fig. 2-14 The number of temporal storage site and stored/ discharged containers in SDA. (Jul. 2014 – Dec. 2017). The number of discharged containers is sum of the one brought to the Intermediate Storage Site and the one brought to temporal incineration sites.

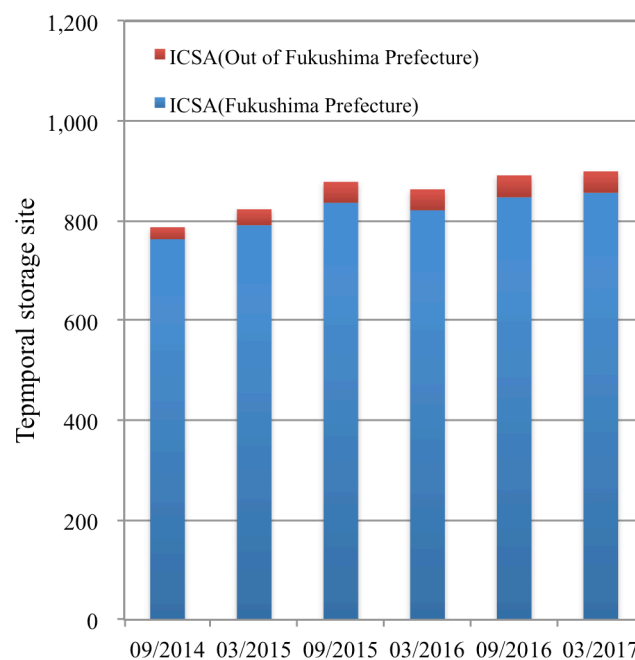


Fig. 2-15 The number of temporal storage site in ICSA (Sep. 2014, Mar. 2015, Sep. 2015, Mar. 2016, Sep. 2016 and Mar. 2017). The number of temporal storage site in ICSA in and out of Fukushima Prefecture were tallied and made open to public by Fukushima Prefectural government and MOE, respectively.

The number of temporal storage site in ICSA has increased to 856 in Fukushima prefecture and 43 out of Fukushima prefecture as of Mar. 2017. These numbers will decrease, according to the transportation to the interim storage site or incineration plants in the days to come.

The number of containers has been also steeply increased to around 4.1 million in Fukushima prefecture and around 1.8 thousand out of Fukushima prefecture at the same month.

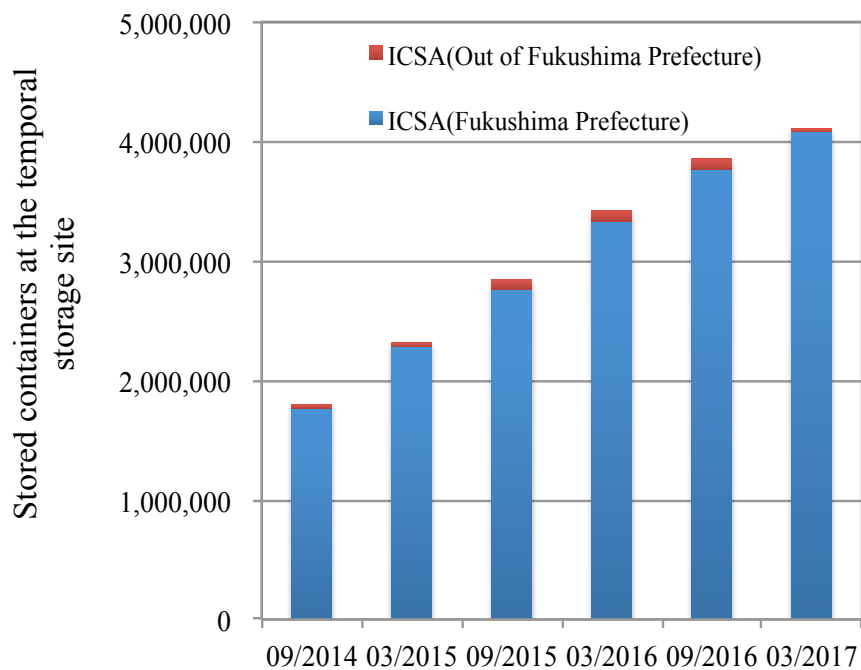


Fig. 2-16 The number of stored containers at the temporal storage site in ICSA (Sep. 2014, Mar. 2015, Sep. 2015, Mar. 2016, Sep. 2016 and Mar. 2017). The number of stored containers in ICSA in and out of Fukushima Prefecture were tallied and made open to public by Fukushima Prefectural government and MOE, respectively.

The number of containers was around half of that of SDA, while the number of temporal storage sites was three times as many as that of SDA, though the survey was conducted in different month.

These facts imply that the size of temporal storage site in SDA is much larger than that of ICSA.

In addition to the preservation at temporary storage site, there is an unique way in ICSA to store at the site where decontamination activities have been conducted. In some urban cities, it was forced for each municipality to secure the containers to preserve on site, because there were not enough space to be secured in each administrative district.

The number of the site was around 150 thousand and 28 thousand in and out of Fukushima prefecture as of Mar. 2017, respectively. The number of preserved containers was around 2.0 million and 310 thousand in and out of Fukushima prefecture as of Mar. 2017, respectively. The number of sites and containers has peaked out in Sep. 2016, and the number will be consecutively dropping, because these containers have been gathered in temporal storage sites.

As mentioned above, the stored containers have been discharged to the interim storage site or makeshift incineration facilities in Fukushima prefecture. It would be significant issue for the containers out of Fukushima prefecture, to determine the concrete ways for their treatment.

Finally, the timeline of number of decontamination workers in SDA was tallied in Fig. 2-19, based on the data weekly published (MOE, 2017b). The number in each month has been estimated from the published average number of workers in one previous week, while the number of workers in ICSA has not been released.

The number was first reported in Jan. 2014 that around 190 thousand workers were involved with the activities per month. The number has been gradually increased later to around 520 thousand in Oct. 2015 at

maximum. Cyclic pattern would be observed that the number has reached a peak in summer and hit least in winter, as the amount of needed construction has declined due to heavy snow or other factors. Generally, the number of workers would be dropping, because full-scale decontamination activities have ended in Mar. 2017 according to the government plan.

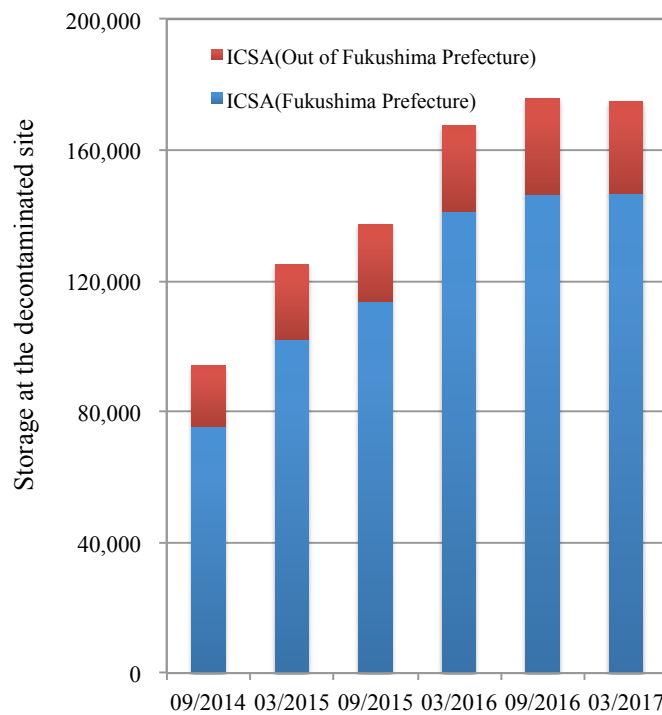


Fig. 2-17 The number of storage at the decontaminated site in ICSA (Sep. 2014, Mar. 2015, Sep. 2015, Mar. 2016, Sep. 2016 and Mar. 2017). The number of storage at the decontamination site in ICSA in and out of Fukushima Prefecture were tallied and made open to public by Fukushima Prefectural government and MOE, respectively.

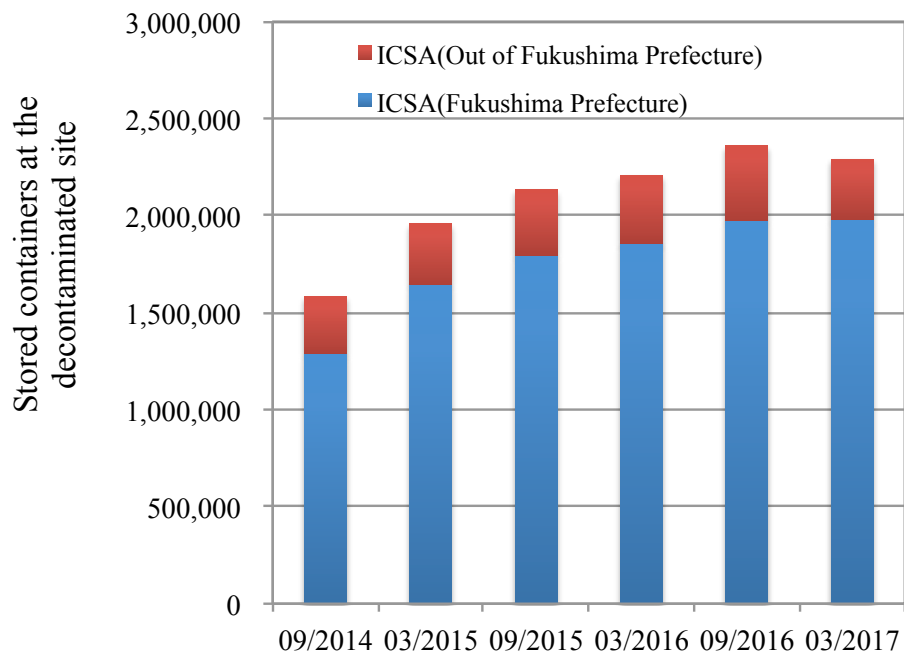


Fig. 2-18 The number of stored containers at the decontaminated site in ICSA (Sep. 2014, Mar. 2015, Sep. 2015, Mar. 2016, Sep. 2016 and Mar. 2017). The number of stored containers in ICSA in and out of Fukushima Prefecture were tallied and made open to public by Fukushima Prefectural government and MOE, respectively.

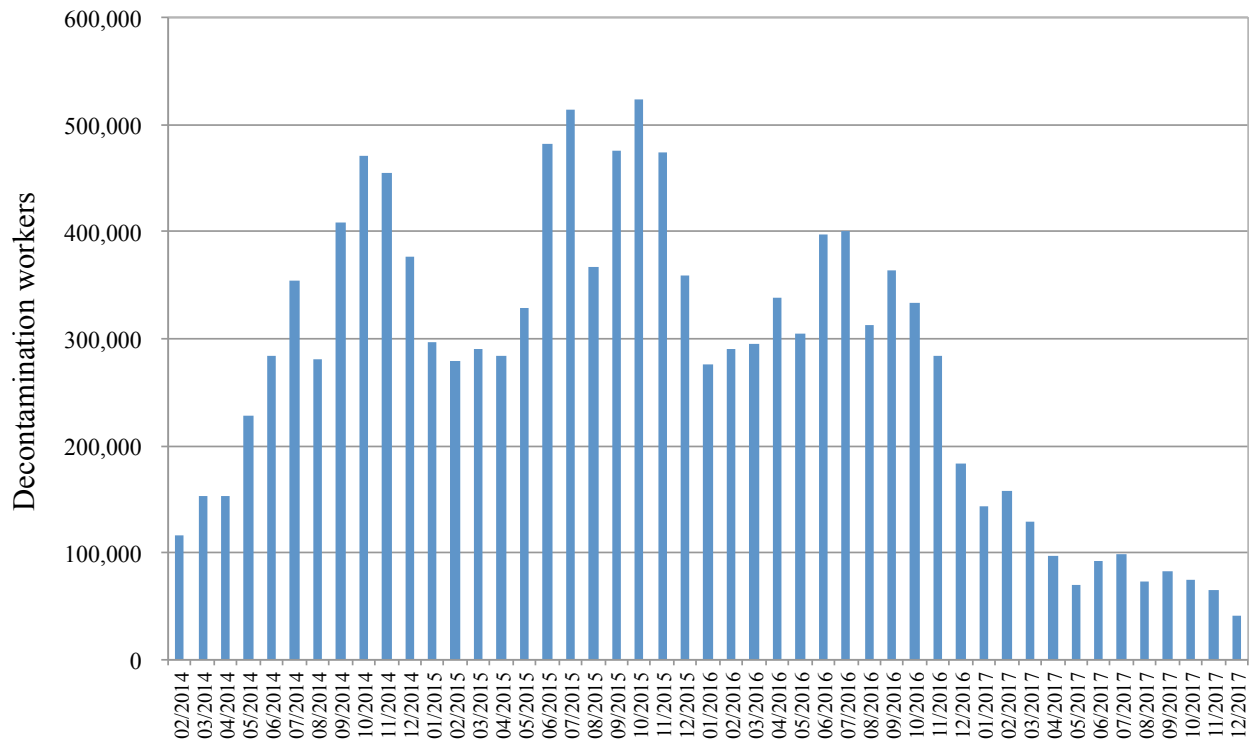


Fig. 2-19 The number of decontamination workers (Feb. 2014 – Dec. 2017). Based on the data published every week, the monthly number of workers has been estimated.

2.3 Implementation of decontamination activities in foreign countries

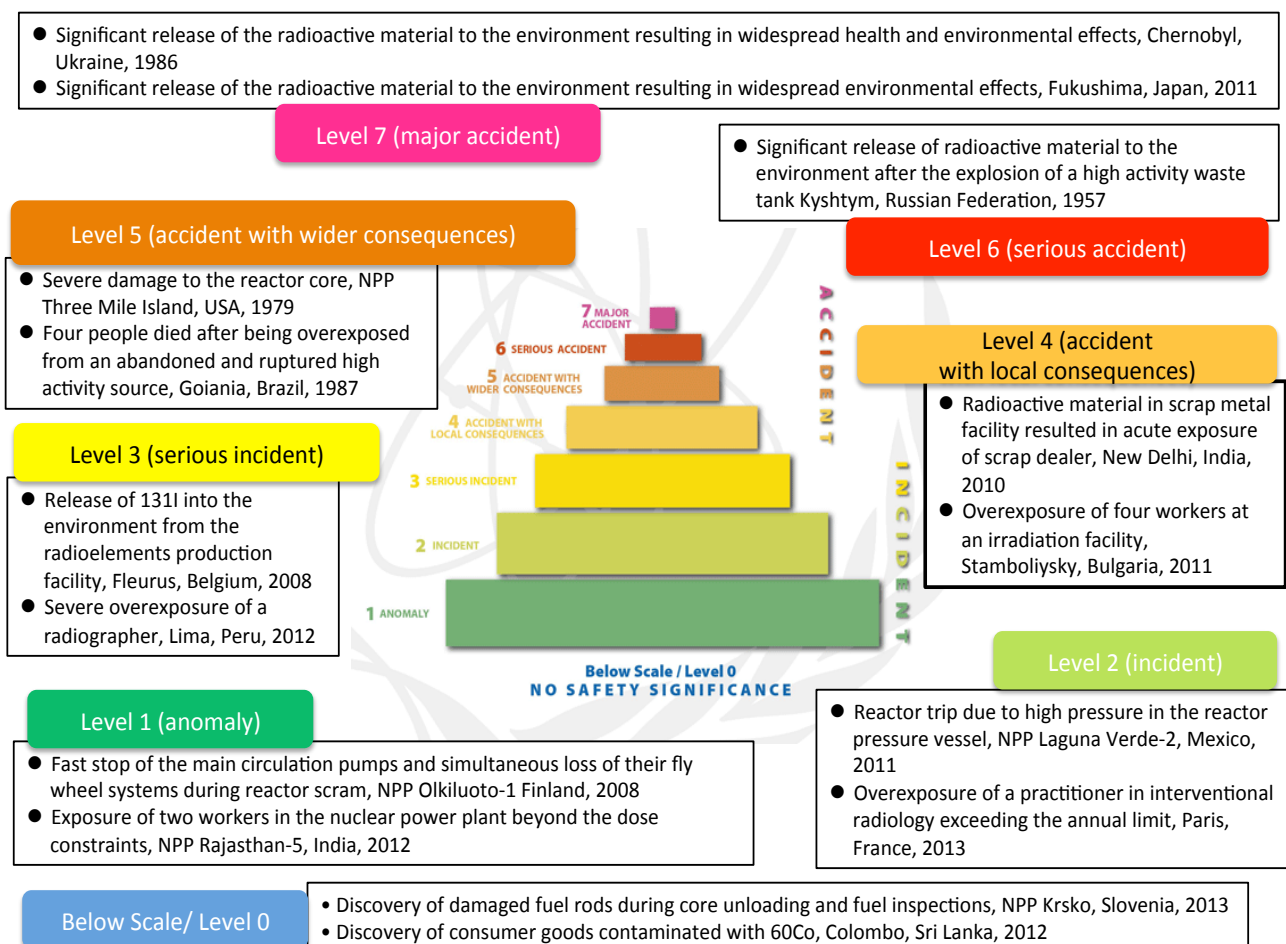
The examples of accident in nuclear facilities in foreign countries and INES (International Nuclear and Radiological Event Scale) were shown in Fig. 2-20 (IAEA, 2016).

From level 1-3 are called incident while 4-6 are called accident, describing more serious situation. Three mile island accident in USA notorious for the severe damage to the reactor was categorize in level 5 (U.S. NRC, 2016), as well as Goiania accident in which people were overexposed from an abandoned high radiation sources in Brazil (IAEA, 1987).

In Russian Federation, there happened severe accident in military-related facility or explosion of high activity waste tank, being ranked level 6.

Level 7, the most severe accidents containing only 2 incidents: Chernobyl nuclear power plant accident (IAEA, 2006) and Fukushima dai-ichi nuclear power plant accident.

There are some reports on the accident and countermeasures for release of radioactive substances to the environment. Among these reports, the measures are summarized based on the one for Chernobyl accident and material of the 15th Panel for the Environment Recovery (MOE, 2015b) which provides more detailed information as follows:



Reference: Made based on INES Flyer: The International Nuclear and Radiological Event Scale (IAEA)

Fig. 2-20 Incident/accident and corresponding category based on the INES.

- The behavior of radioactive substances in forest ecosystem

Around 60 - 90 % of dry deposited radioactive Cs existed in forest canopy right after the Chernobyl accident in Apr. 1986 (Tikhomirov F.A. et al., 1994).

The proportion of radioactive Cs in canopy became around 15 % in the end of summer in 1986 and around 5 % in the end of summer in 1987, through the transition to soil in early stage after the accident by precipitation and leaves falling.

The radioactive Cs in forest soil was absorbed through root and moved to tree or understory plant, followed by partial transition to animals and circulation to soil by way of animal carcass. Several years after the fallout, the distribution of radioactive Cs almost became to equilibrium and seemed to stay unchanged (Shcheglov A.I. et al., 2001). The proportion of radioactive Cs contained in upper part of ground would be around 5 % of all radioactive Cs in whole ecosystem in the Temperate Zone but depends on vegetation.

- The runoff and diffusion of radioactive Cs to out of forest

The radioactivity in forest hardly decreased except for radioactive decay after the Chernobyl accident. Only around 1 % of ^{137}Cs had gone out of forest ecosystem 1 year after the accident.

Several kinds of factors to influence the small-scale alteration of distribution could be considered including wind hoisting (Ould-dada Z. et al., 1996), forest fire (Amiro B.D. et al., 1999), erosion or runoff by wind and rainfall. However, there were little possibility for the radioactive Cs to travel a long distance.

- The necessity of long-term monitoring

Long-term, detailed and scientific monitoring should be continued at specific points in forests in order to grasp the pollution condition, including transition or seasonal variation of radioactive Cs.

- The countermeasures for radioactive pollution in forests

The measures for radioactive pollution were roughly separated into 2 categories: “management (regulation of the various kinds of usual activities in forests)” and “technology (mechanical or chemical ways to transfer or change the distribution of radioactive Cs)”.

In former Soviet Union and surrounding 3 countries, regulation for entry and consumption of forest products were adopted as main measures in Chernobyl accident, which were realistic and effective to minimize the total damage in terms of cost-effectiveness as follows: (Fesenko S., 2000).

(a) Entry regulation for ordinary people or forestry workers

This regulation was disseminated through provision of information obtained through regional monitoring and public relations through cooking of forest products

(b) Harvest regulation of wild foods for ordinary people

Main foods were wild species, strawberries and mushrooms, whose importance differs between counties. In former Soviet Union, the mushroom was important food, but possibly highly contaminated.

(c) Harvest regulation of firewood for ordinary people

There was a risk not only for external exposure but additional exposure in house or garden during

burning firewood, ash treatment or being used as fertilizer.

(d) Change of targeted wild animals

The concentration of radioactive Cs in body of animals, including roe deer eating mushrooms, varied from seasons to seasons. Therefore, the excessive internal exposure could be evitable by taking meat of animals not feeding mushrooms seasonally.

(e) Prevention of forest fire

The prevention of forest fire was one of the most prioritized measures in usual forest management, as well as the measures for re-diffusion of radioactive substances under the circumstances with widespread radioactive pollution. This second pollution was caused mainly by the fire of trees and organic matter, which contains a large amount of proportion of whole radioactive Cs in forest ecosystem. This policy was highly related with the measure (a), because one of the major means to avoid forest fire was preventing the people from entering as possible as they could.

The measures based on the technology should be focused on the limited area, because they could lead to the loss of ecosystem function as well as the enormous cost.

The amount of soil or radioactive Cs, however, could possibly become large, because Japan had steep terrain compared with Chernobyl (Hashimoto S., 2012).

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3.1 Introduction

Decontamination works have been performed to remove radioactive substances scattered by the Fukushima Dai-ichi nuclear accidents from houses, roads, farmlands, schools, parks, forests, and so forth. The decontamination works have been performed in two areas separately designated based on the authorities conducting the works: Special Decontamination Area (“SDA”), where the works have been conducted mainly by the Ministry of the Environment, and Intensive Contamination Survey Area (“ICSA”), where the works have been conducted mainly by each municipality. The decontamination works performed in forest areas have mainly focused around living areas within 20 m from the edges of the forests, with the priority of reducing the influence of radiation on the daily living of people (MOE, 2013b). As a consequence of the heavier contamination in SDA, which includes 11 municipalities, the forest decontamination works there have spanned a vast area. As of Dec. 2017, around 5,900 ha of forests were decontaminated in SDA, versus roughly 4,800 ha of forest in ICSA (4,500 ha and 300 ha in and out of Fukushima Prefecture, respectively). Less area has been decontaminated in ICSA than in SDA, even though ICSA had many more of municipalities in the past (41 and 63 at maximum, in and out of Fukushima prefecture, respectively). Ongoing comprehensive countermeasures for the environmental recovery of the vast remaining forest area have also been examined (MOE, 2016a).

^{134}Cs , ^{137}Cs , and other radioactive isotopes released into the environment are thought to have been effectively captured by trees due to the large surface dimension of their leaves. These radioactive Cs isotopes dropped to ground, either immediately, or gradually together with falling leaves or rainfall, and were finally adsorbed via the negative charge in the soil layer (Yamaguchi, 2011).

Around 70 % of the land in Japan is occupied by forest. The grade is generally steep, and abundant precipitation is delivered from rainy seasons or typhoons. Hence, soil and attached radioactive Cs on the surface ground are likely to flow out faster than expected. Recent research has revealed that forest retains radioactive substances for long periods: the radioactive Cs cannot easily depart because it is partly taken up by the nutrient circulation process of the forest ecosystem (Yamaguchi et al., 2012). For this reason, coupled with the long half-time of ^{137}Cs , it will be crucial to monitor and predict the behavior of radioactive Cs and closely investigate the decontamination effects.

This research analyzed factors that have influenced the effects of forest decontamination works based on the radiation dose before and after the decontamination works, GIS data on vegetation, and field studies on the depth profiles of radioactive Cs.

3.2 Materials and Methods

3.2.1 Factor analyses of forest decontamination works

Factor analyses were performed using dose rate data (Jun. 2012 - Dec. 2015; data obtained under snowy

conditions were eliminated) recorded in SDA before and after the decontamination works to evaluate their effect in accordance with The Act on Special Measures Concerning the Handling of Radioactive Pollution. The surface dose rate (ambient dose equivalent $H^*(10)$, monitoring point: 1 cm from the ground) and air dose rate (100 cm from the ground) were recorded with a NaI scintillation survey meter. The surface contamination concentration was recorded with a GM survey meter. The effect of the decontamination work was defined by equation (1):

$$E = 1 - (D_a / D_b) \quad (1)$$

where D_a is the radiation dose after the decontamination works and D_b is that of before the works. If D_a and D_b were determined to have been recorded at the same point based on collated geological data or points of latitude and longitude, they were counted as one data point. As a result of the collation, 70,608 data points were analyzed for the surface dose rate, 70,272 data points were analyzed for the air dose rate (100 cm from the ground), and 68,035 data points were analyzed for the surface contamination concentration.

First, the relation between the radiation dose of pre-decontamination works and effect of the decontamination works were analyzed. The numbers of data points are shown in Table 3-1- Table 3-3 and Fig. 3-1 – Fig. 3-3.

Table 3-1 The number of data in each surface dose rate range

(unit: $\mu\text{Sv h}^{-1}$)

Range	<0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1.0	1.0-1.1
N	1,159	1,108	1,788	2,466	3,187	3,466	3,925
Range	1.1-1.2	1.2-1.3	1.3-1.4	1.4-1.5	1.5-1.6	1.6-1.7	1.7-1.8
N	3,824	3,707	3,394	2,958	2,783	2,442	2,315
Range	1.8-1.9	1.9-2.0	2.0-2.5	2.5-3.0	3.0-4.0	4.0-5.0	≥ 5.0
N	2,075	1,909	7,978	5,893	7,334	3,482	3,408

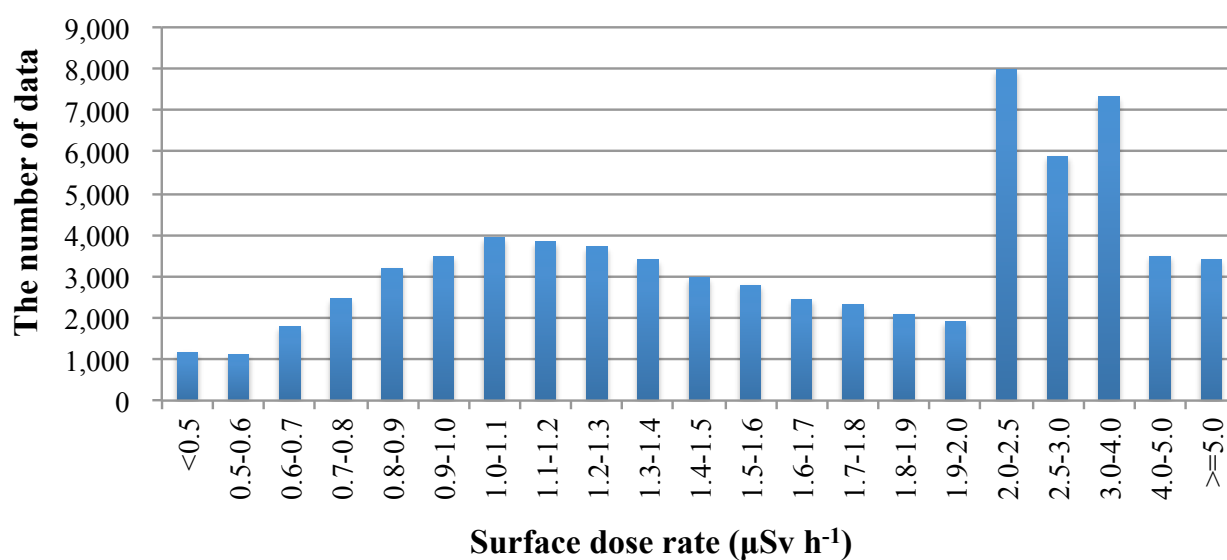


Fig. 3-1 The number of data in each surface dose rate range.

Table 3-2 The number of data in each air dose rate (100 cm from the ground) range

(unit: $\mu\text{Sv h}^{-1}$)							
Range	<0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1.0	1.0-1.1
N	1,969	2,344	3,542	4,995	5,541	5,175	4,691
Range	1.1-1.2	1.2-1.3	1.3-1.4	1.4-1.5	1.5-1.6	1.6-1.7	1.7-1.8
N	4,030	3,521	2,966	2,634	2,280	2,072	1,979
Range	1.8-1.9	1.9-2.0	2.0-2.5	2.5-3.0	3.0-4.0	4.0-5.0	≥ 5.0
N	1,920	1,748	7,217	4,499	4,480	1,567	1,059

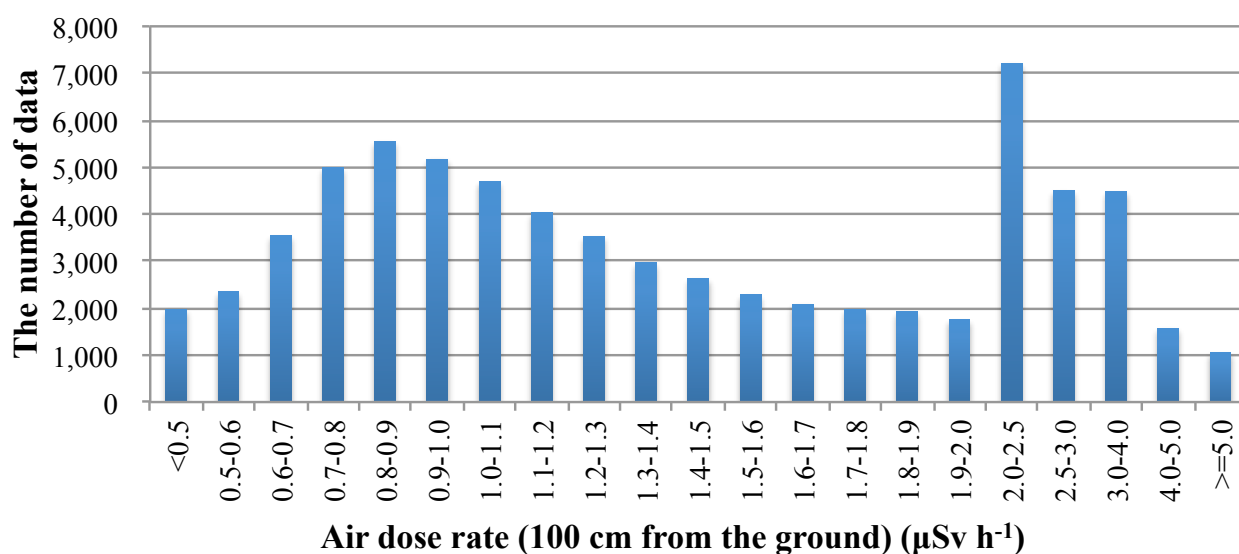


Fig. 3-2 The number of data in each air dose rate (100 cm from the ground) range.

Table 3-3 The number of data in each surface contamination concentration range

(unit: cpm)							
Range	<300	300-350	350-400	400-450	450-500	500-550	550-600
N	1,563	1,971	2,404	3,111	3,113	3,600	3,037
Range	600-650	650-700	700-750	750-800	800-850	850-900	900-1000
N	3,198	2,822	2,864	2,414	2,509	2,163	3,910
Range	1000-1100	1100-1200	1200-1400	1400-1600	1600-2000	2000-3000	>=3000
N	3,707	3,311	5,604	4,149	5,374	5,172	2,007

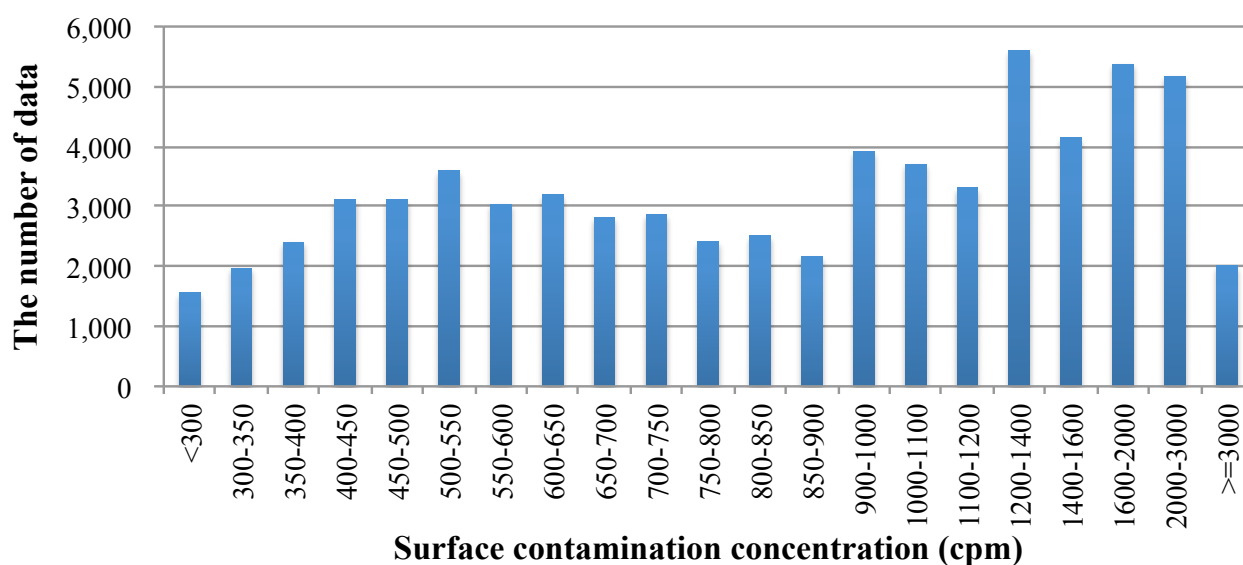


Fig. 3-3 The number of data in each surface contamination concentration range.

The relationship between the months of pre-decontamination monitoring and the decontamination effect were also analyzed. Analyses of the circumstances under which the above decontamination works were conducted revealed that the radiation doses were distributed in widely variable ranges. In very low dose ranges, background radiation attributable to natural substances such as soil particles could not be ignored. For this reason, we eliminated data points lower than $0.6 \mu\text{Sv h}^{-1}$ for the surface dose rate (2,267 data points), $0.6 \mu\text{Sv h}^{-1}$ for the air dose rate (100 cm from the ground) (4,313 data points), and 300 cpm for the surface contamination concentration (1,563 data points), ranging from several times to tens of times greater than the background level. Table 3-4 and Fig. 3-4 – Fig. 3-6 show the number of data points per month. The breakouts of the pre-contamination radiation doses were analyzed to view the radioactive conditions where forest decontamination works were conducted.

Table 3-4 The number of data per month

	06/2012	07/2012	08/2012	09/2012	10/2012	11/2012	12/2012
Surface dose rate	1	4	2	558	3,271	1,731	488
Air dose rate (100 cm from the ground)	1	4	2	442	2,963	1,568	465
Surface contamination concentration	0	5	2	585	3,187	1,558	408
	01/2013	02/2013	03/2013	04/2013	05/2013	06/2013	
Surface dose rate	356	372	558	1,127	2,721	3,262	
Air dose rate (100 cm from the ground)	398	371	541	1,098	2,674	3,214	
Surface contamination concentration	274	367	517	832	2,630	2,874	
	07/2013	08/2013	09/2013	10/2013	11/2013	12/2013	
Surface dose rate	2,751	3,499	4,171	4,209	3,246	1,446	
Air dose rate (100 cm from the ground)	2,688	3,432	4,087	4,136	3,182	1,387	
Surface contamination concentration	2,452	3,255	3,902	3,962	3,223	1,454	
	01/2014	02/2014	03/2014	04/2014	05/2014	06/2014	
Surface dose rate	2,632	542	333	1,306	2,791	3,174	
Air dose rate (100 cm from the ground)	2,573	513	303	1,284	2,728	3,039	
Surface contamination concentration	2,608	535	337	1,275	2,715	3,228	
	07/2014	08/2014	09/2014	10/2014	11/2014	12/2014	
Surface dose rate	3,170	1,238	1,596	2,501	2,122	1,489	
Air dose rate (100 cm from the ground)	3,112	1,222	1,531	2,300	2,068	1,404	
Surface contamination concentration	3,162	1,231	1,592	2,630	2,141	1,538	
	01/2015	02/2015	03/2015	04/2015	05/2015	06/2015	
Surface dose rate	1,431	1,403	1,584	2,643	1,736	1,107	
Air dose rate (100 cm from the ground)	1,367	1,368	1,518	2,542	1,675	1,069	
Surface contamination concentration	1,475	1,409	1,628	2,735	1,784	1,123	
	07/2015	08/2015	09/2015	10/2015	11/2015	12/2015	
Surface dose rate	716	308	433	205	96	4	
Air dose rate (100 cm from the ground)	659	280	416	198	89	4	
Surface contamination concentration	769	309	421	207	96	4	

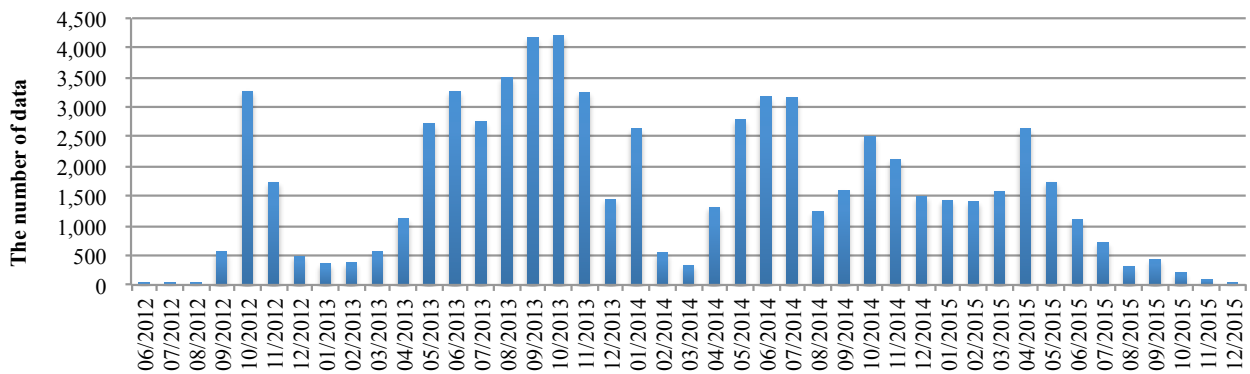


Fig. 3-4 The number of data per month (surface dose rate).

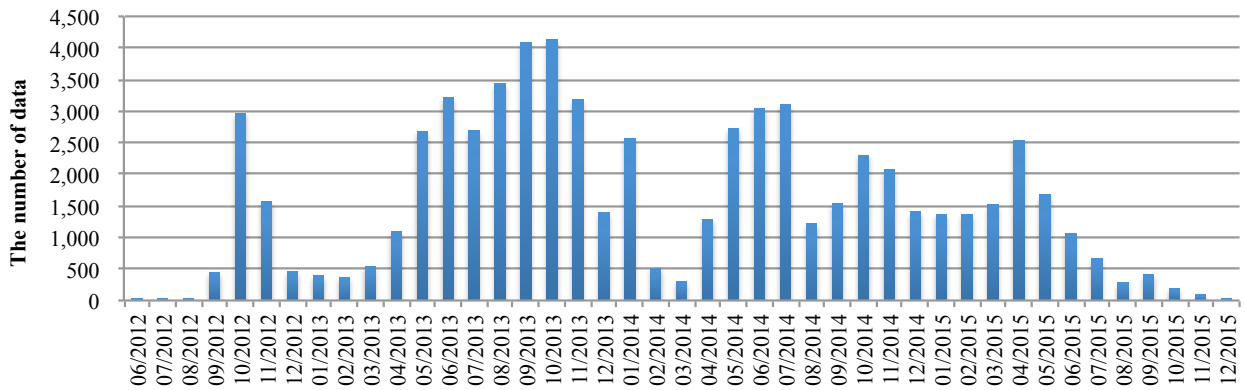


Fig. 3-5 The number of data per month (air dose rate (100 cm from the ground)).

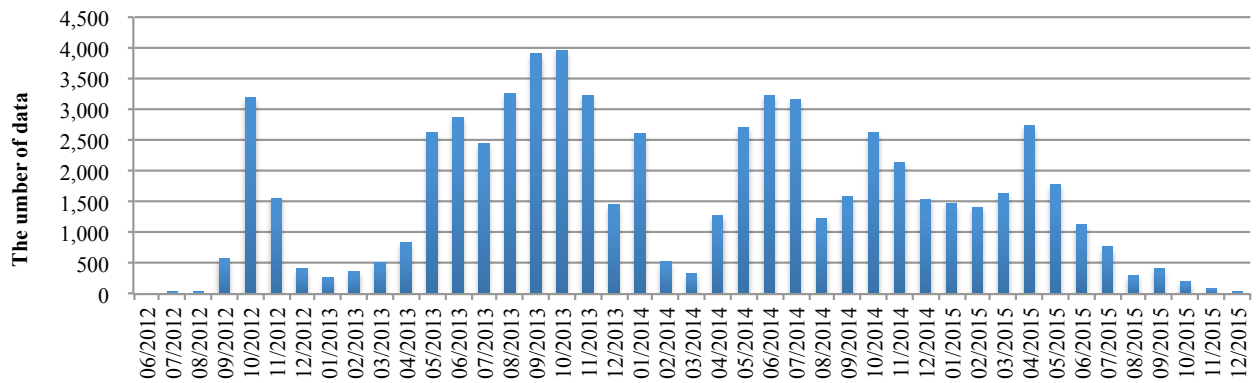


Fig. 3-6 The number of data per month (surface contamination concentration).

Finally, publicly available GIS data on vegetation information from the website of the Biodiversity Center, Ministry of the Environment, Japan (Biodiversity Center of Japan, 2016a) was incorporated and superimposed with geological data obtained during decontamination works by QGIS (2,6,1-Brighton) (QGIS, 2016). Around 20 - 40 years have passed since the vegetation data used in this research was collected. The alteration rate of the green cover space seems to be approximately 0.24 % per year (Biodiversity Center of Japan, 1997). If this rate has been constant from the collection term up to the present, we can assume an accuracy of around 90 %. Some of the data points were probably positioned on or around boundary lines between different types of vegetation, but the calculation using 60,000 - 70,000 data points was assumed to yield results appropriately representative of the general characteristics of the relation between the vegetation and rate of radioactivity reduction.

3.2.2 Depth profile analyses of radioactive Cs in different types of vegetation

Five kinds of vegetation in Fukushima prefecture were selected based on the GIS analyses (Fig. 3-7). Concretely speaking, the depth profiles of ^{134}Cs and ^{137}Cs were analyzed by obtaining and scraping organic matter and soil layers in forest areas dominated by *Larix kaempferi*, *Pinus densiflora*, Deciduous broadleaf trees, *Cryptomeria japonica*, and *Chamaecyparis obtusa*. Litter layers, fermented layers, and humus layers were separately obtained as organic matter. The soil samples were obtained at 0.5 cm intervals in the depth range of 0-5 cm from the soil surface and at 1.0 cm intervals in the depth range of 5-10 cm.

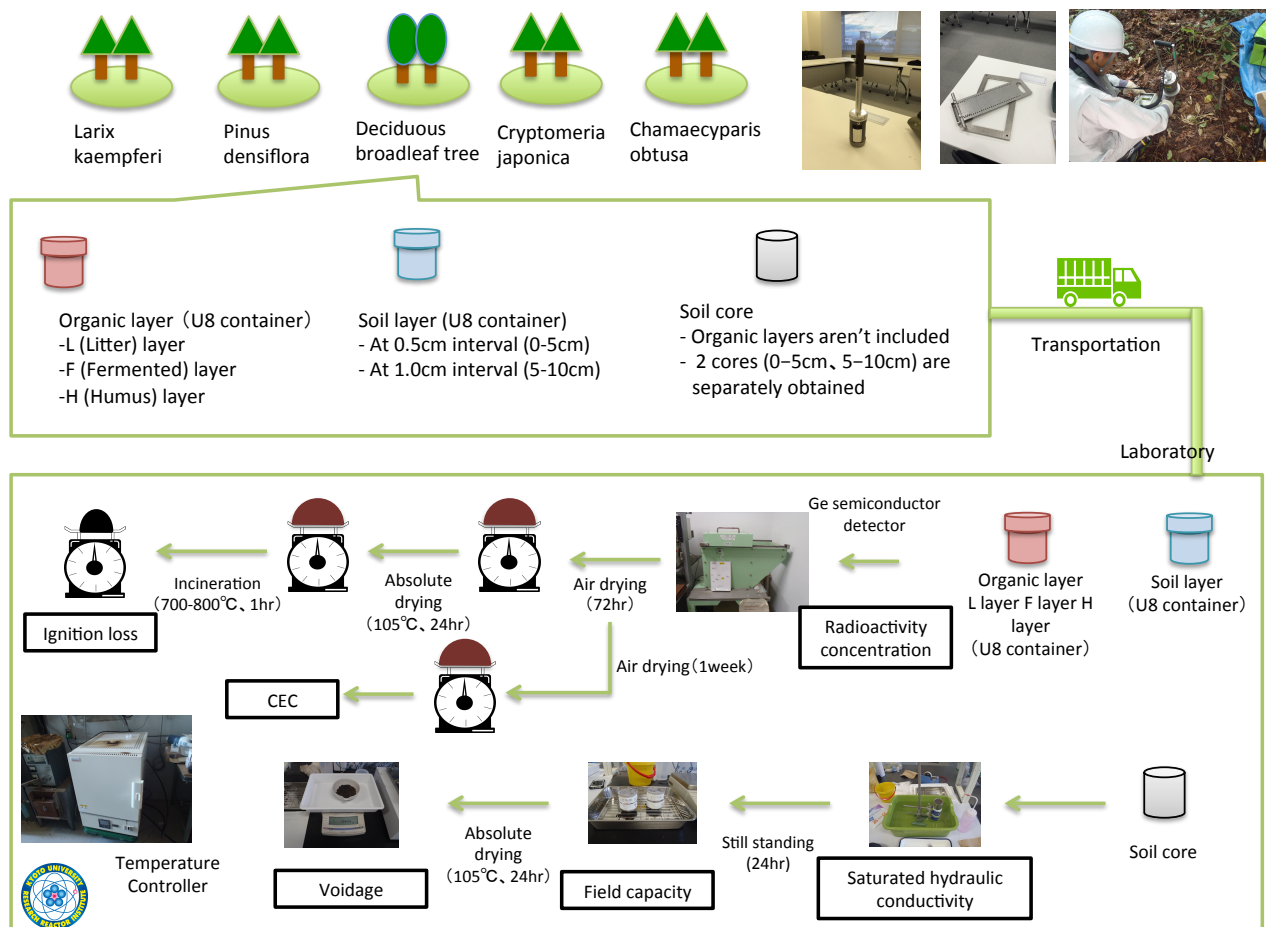


Fig. 3-7 The procedure of experiments.

Field studies were conducted on Sep. 2nd, Nov. 5th, Oct. 7th, Nov. 5th, Sep. 3rd in 2015 for *Larix kaempferi*, *Pinus densiflora*, Deciduous broadleaf tree, *Cryptomeria japonica*, and *Chamaecyparis obtusa*, respectively. The L (Litter) layers, the group of layers located on the top of the ground, consist of fallen leaves and branches remaining in an almost undegraded state. The F (Fermented) layers, the second group of layers from the top, consist of organic matter broken up by small animals or microorganisms. While the forms of the original plants cannot be identified, the tissues of the original plants can be confirmed by the naked eye. The H (Humus) layers are more degraded, rendering the original plant forms unidentifiable. The soil of the humus layer becomes powdery when dry, and fatty when wet (Japan Forest Technology Association, 2001). The samples obtained were stuffed into U8 containers to measure the radioactive concentration of the ¹³⁴Cs and ¹³⁷Cs with a Ge semiconductor detector (ORTEC GMX-30190). All radioactive concentrations were re-calculated through attenuated correction to Oct. 1st, 2015.

Of the samples taken from the forests, organic layer samples of around 7 g (whole samples if sufficient quantities could not be obtained) and soil layer samples of around 12 g were dried for 72 hr in a desiccator. The relation between the concentration of radioactive Cs and mass depth (dry) was analyzed and the relaxation mass depth was calculated through hyperbolic secant (sech) and hyperbolic cosine (cosh) functions, or equation (2) (Matsuda et al., 2015). The monitoring points during forest decontamination were supposed to be positioned at 20 -50 m intervals (MOE, 2013a).

$$A_m(\zeta) = A_{m,0} \cosh(\zeta_0/\beta_d) \operatorname{sech}(-(\zeta - \zeta_0)/\beta_d) \quad (2)$$

where ζ is the mass depth (g cm^{-2}), A_m is the concentration at the mass depth ζ (Bq kg^{-1}), $A_{m,0}$ is the concentration at the ground surface (Bq kg^{-1}), ζ_0 is the mass depth from the ground surface at the point with a maximum concentration (g cm^{-2}), and β_d is the relaxation mass depth (dry) (g cm^{-2}).

$A_{m,0}$, β_d , and ζ_0 are determined by an iterative approach using the solver function in Excel (Microsoft Office).

3.3 Results and considerations

3.3.1 Dose rate reduction in each pre-decontamination level

The rates of reduction of each dose rate from the pre-decontamination levels are shown in Fig. 3-8 - Fig. 3-10.

The rates of reduction of both the surface dose rate and air dose rate (100 cm from the ground) increased according to the radiation dose in areas where decontamination activities were conducted. The reduction rate for the surface dose rate and air dose rate (100 cm from the ground) increased to 33 % and 28 % at $1.1 \mu\text{Sv h}^{-1}$, respectively, and saturated at higher radiation levels.

The surface contamination concentration showed the same tendency: the rate of reduction increased in step with the radiation level, reaching 35 % at 500 cpm and saturating at higher radiation. The rate of reduction of the air dose rate (100 cm from the ground) was slightly lower than the rates for the surface dose rate and surface contamination concentration, indicating low values at low dose rates. Bartlett-test was conducted and homoscedasticity was not confirmed ($p < 0.05$). In the wake of Bartlett-test, Kruskal-Wallis test was

subsequently conducted and at least the reduction rate in one of the ranges of radiation dose stochastically different from that of the other ranges ($p < 0.05$).

The influence of radiation weakened as the distance from the radiation source increased. The beta rays and gamma rays emitted from nearby radiation sources, radiation types closely related to the decontamination works, accounted for large proportions of the radiation making up the surface dose rate and surface contamination concentration, as the detector was located only a short distance from the sources. On the other hand, a large decontamination effect cannot be expected at monitoring points further from the ground level, such as the 100 cm point, in the forest area, because the background radiation from trees, leaves, trenches, and the like contributes to the detected value.

3.3.2 Dose rate reduction in each month of pre-decontamination monitoring

Fig. 3-11 - Fig. 3-13 show the time-trend of the reduction rate in each month of pre-decontamination monitoring.

As shown in Table 3-4, the number of data points is presumed to vary from month to month. The reduction rate of the surface dose rate increased from around 20 % to 40 % in late 2012, and to around 50 % in early 2013. Afterwards it decreased to around 40 % in late 2013 and to 20 % in early 2014. It stayed at around 20 % from late 2014 to early 2015 and then gradually fell, reaching around 10 % by the end of the year. While the reduction rate of the air dose rate (100 cm from the ground) was less than that of surface dose rate throughout the monitoring term, a similar pattern was observed. The reduction rate increased from 20 % to 30 % by the end of 2012 and rose to 40 % in early 2013. It then stayed stable at around 40 % in late 2013, gradually decreased to 30 % in 2014 and early 2015, and dropped to 10 % in late 2015. The reduction rate of the surface contamination concentration was the highest of all three categories, but it conformed with a similar pattern. The reduction rate sharply increased from 20 % to 40 % in late 2012 and reached a peak of around 60 % in early 2013. It stayed above 40 % in late 2013 and then declined stepwise to around 20 % by early 2014. Over the next one and a half years from late 2014 to late 2015, it remained at around 20 %. The reduction rate fluctuated widely in some months due to the small number of monitoring data. Bartlett-test was conducted and homoscedasticity was not confirmed ($p < 0.05$). In the wake of Bartlett-test, Kruskal-Wallis test was subsequently conducted and at least the reduction rate in one of the months stochastically different from that of other months ($p < 0.05$).

The rate of reduction of the air dose rate (100 cm from the ground) followed the same tendency shown in Fig. 3-8 - Fig. 3-10 and was lower than the rates for the surface dose rate and surface contamination concentration. This finding implied that the decontamination effect was influenced by surrounding circumstances in positions apart from the ground.

The reduction rate showed an explicit tendency to decrease over time, as shown in Fig. 3-11 - Fig. 3-13. We investigated the reasons for this phenomenon by analyzing the breakdown of the dose rates per month (Fig. 3-14 - Fig. 3-16).

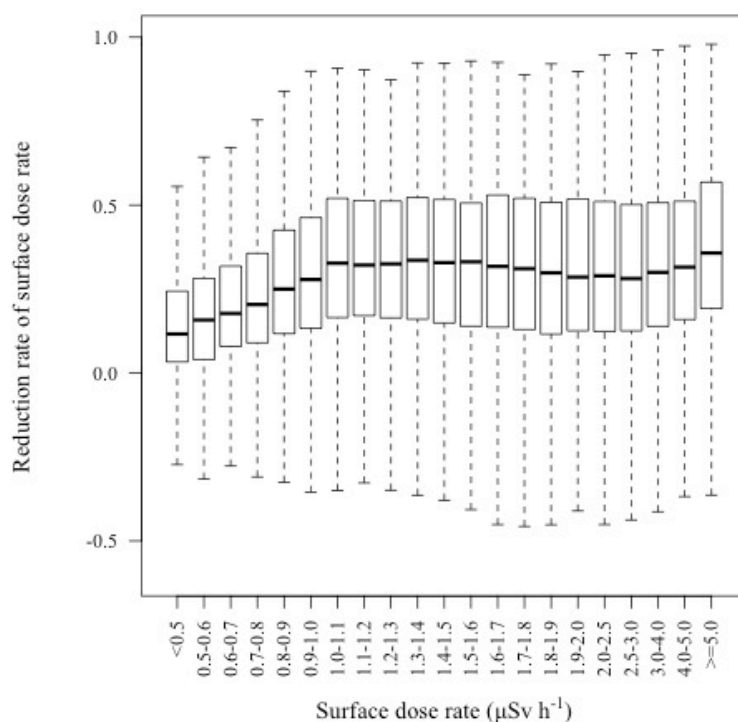


Fig. 3-8 Relation between the surface dose rate and rate at which it was reduced. The top edge in each box refers to the 75th percentile; the bottom edge, the 25th percentile; the middle line, the median. The upper whisker was calculated by adding the 75th percentile to 1.5 IQR, the interquartile range. If, however, the maximum is smaller than the 75th percentile plus 1.5 IQR value, it is represented by the maximum value. The bottom whisker is calculated by subtracting the 1.5 IQR from the 25th percentile. If, however, the minimum value is larger than the 1.5 IQR minus the 25th percentile value, it is represented by the minimum value. The boxplots in this research are plotted in the same way.

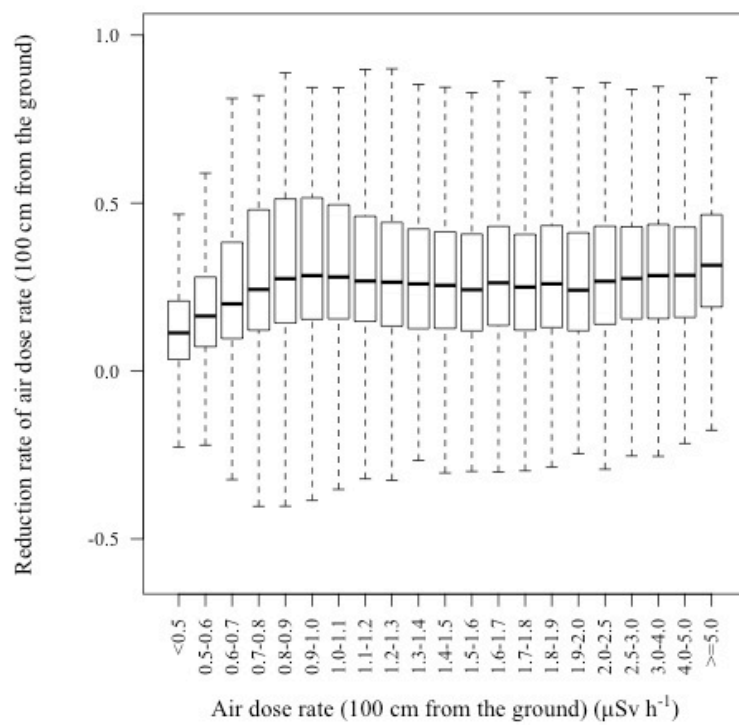


Fig. 3-9 Relation between the air dose rate (100 cm from the ground) and the rate at which it was reduced.

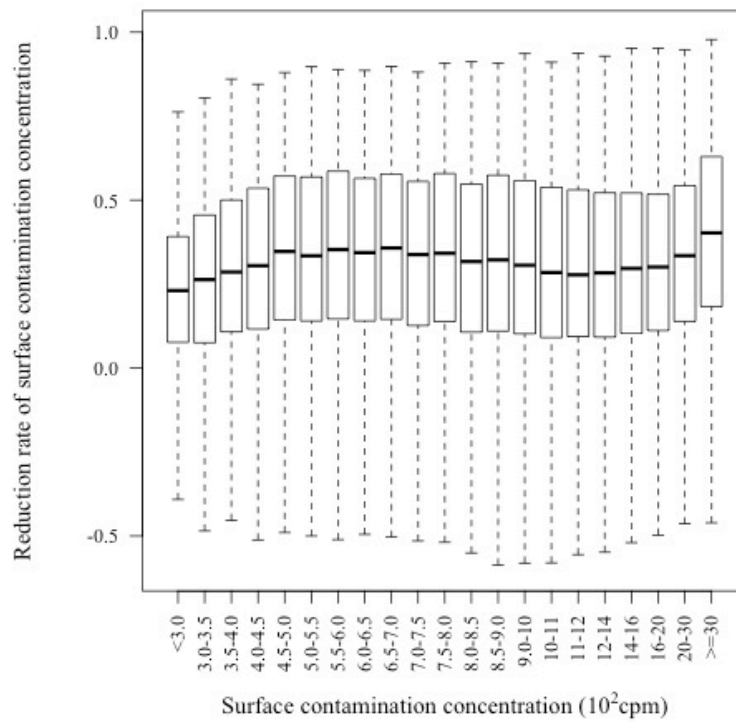


Fig. 3-10 Relation between the surface contamination concentration and the rate at which it was reduced.

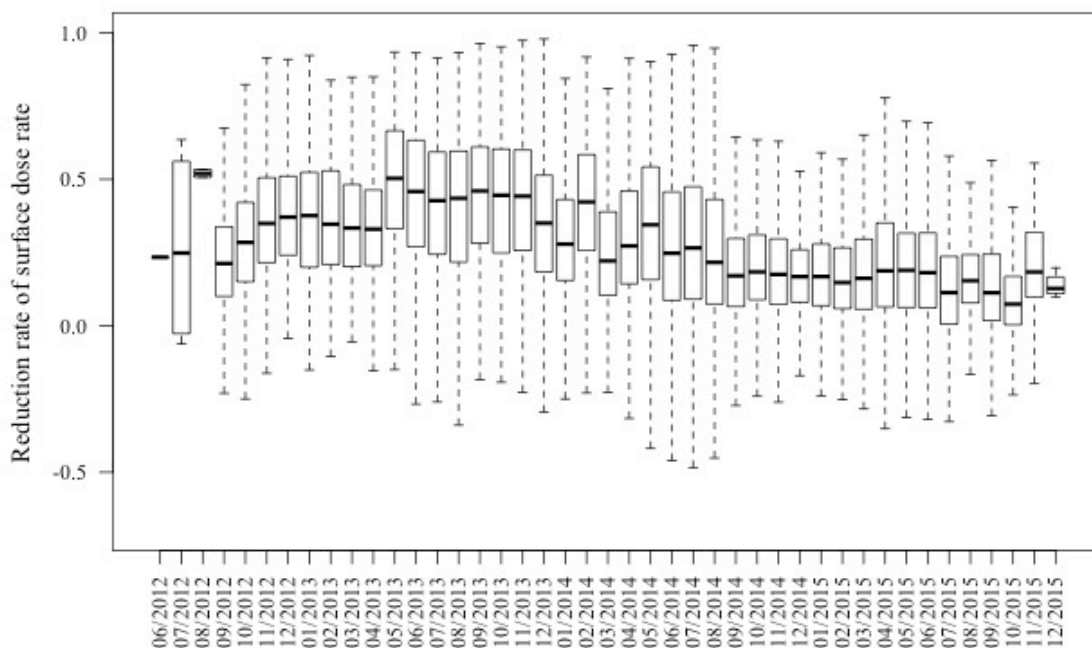


Fig. 3-11 Temporal change of the rate of reduction of the surface dose rate (06/2012 – 12/2015). The categories in the horizontal axis are months of pre-decontamination monitoring. Decontamination works were conducted just after the monitoring or some months later.

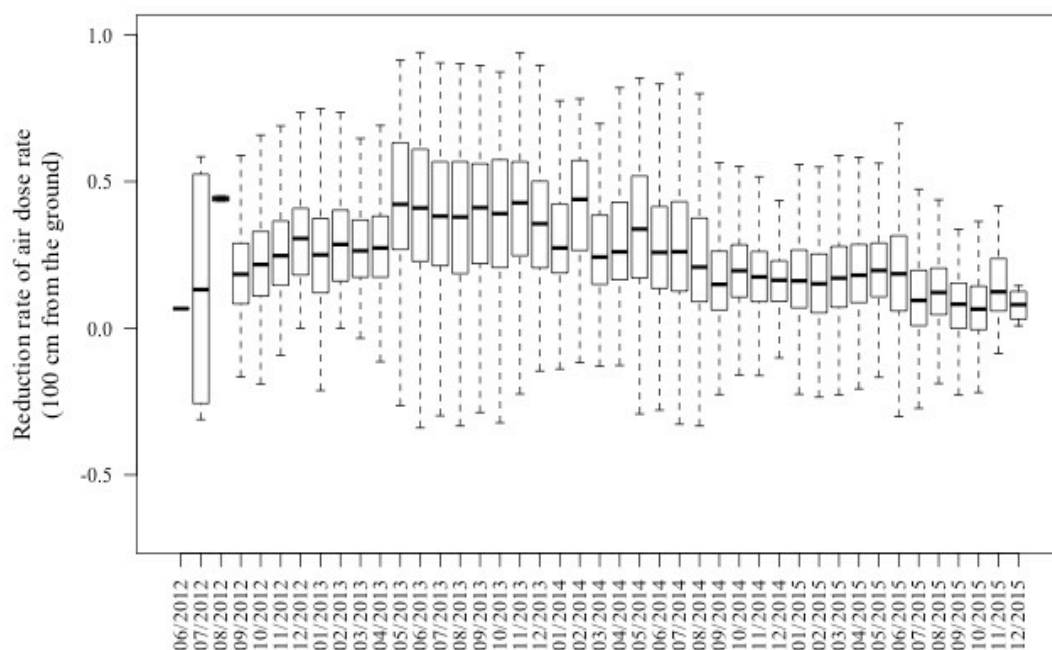


Fig. 3-12 Temporal change of the rate of reduction of the air dose rate (100 cm from the ground) (06/2012 – 12/2015). The categories in the horizontal axis are months of pre-decontamination monitoring. Decontamination works were conducted just after the monitoring or some months later.

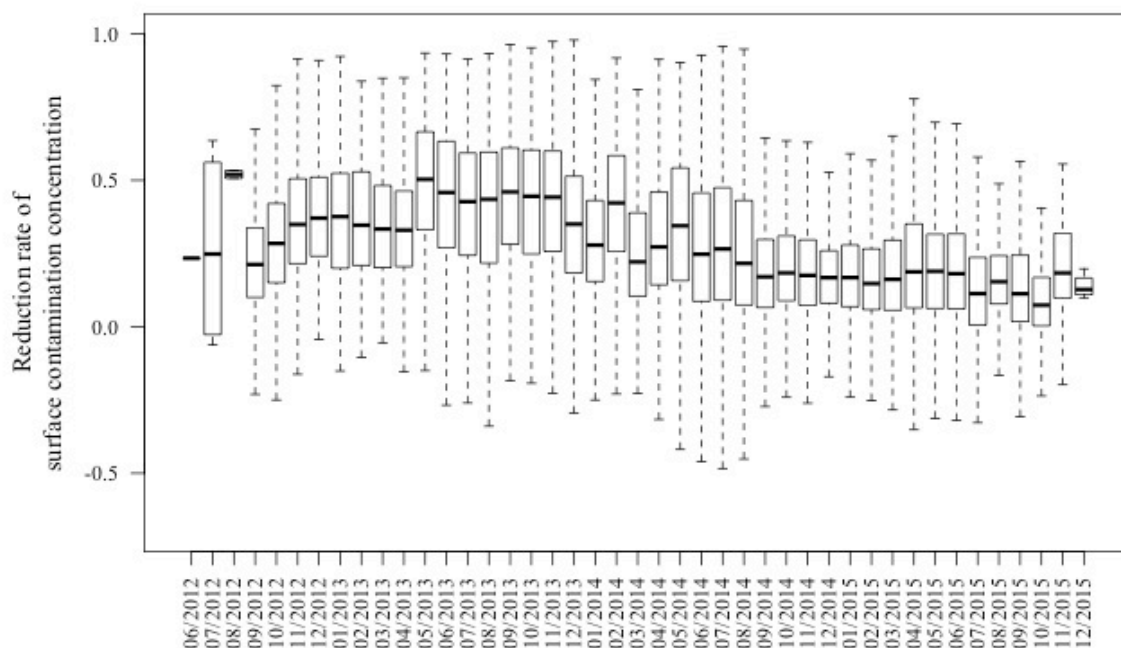


Fig. 3-13 Temporal change of the rate of reduction of the surface contamination concentration (06/2012 – 12/2015). The categories in the horizontal axis are months of pre-decontamination monitoring. Decontamination works were conducted just after the monitoring or some months later.

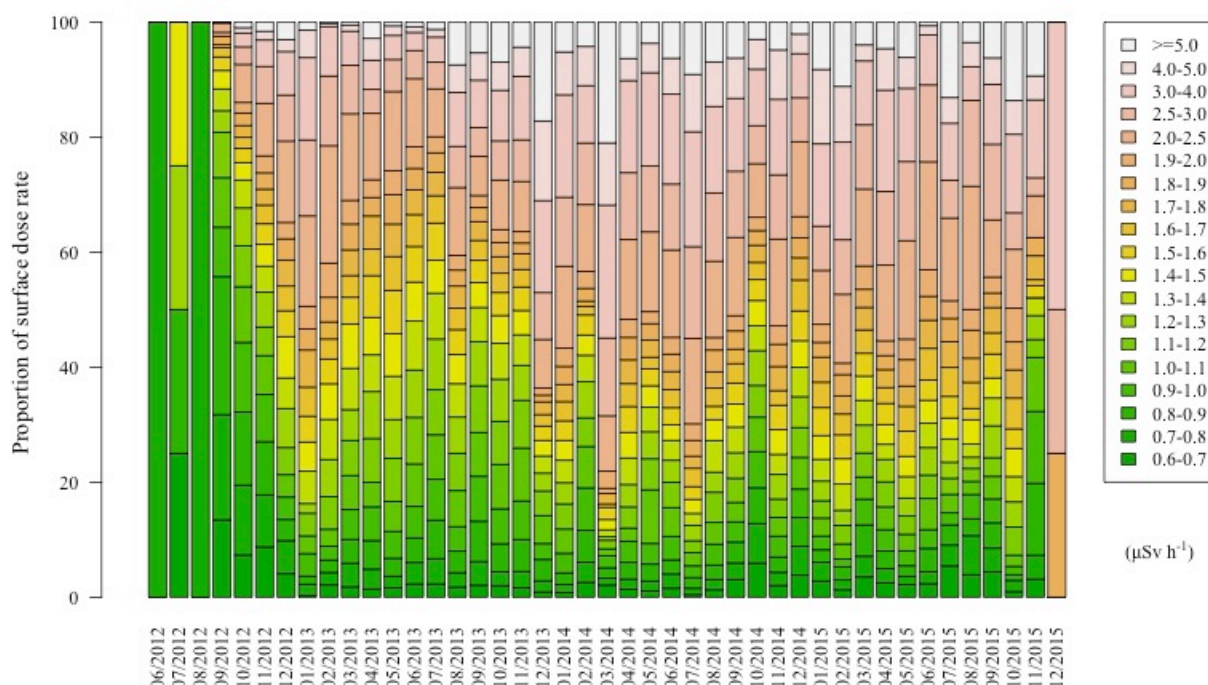


Fig. 3-14 Temporal change in the outbreak of the surface dose rate (06/2012 – 12/2015). The categories in the horizontal axis are months of pre-decontamination monitoring. The colors represent the surface dose rates determined in the pre-decontamination monitoring, from low (green) to high (red).

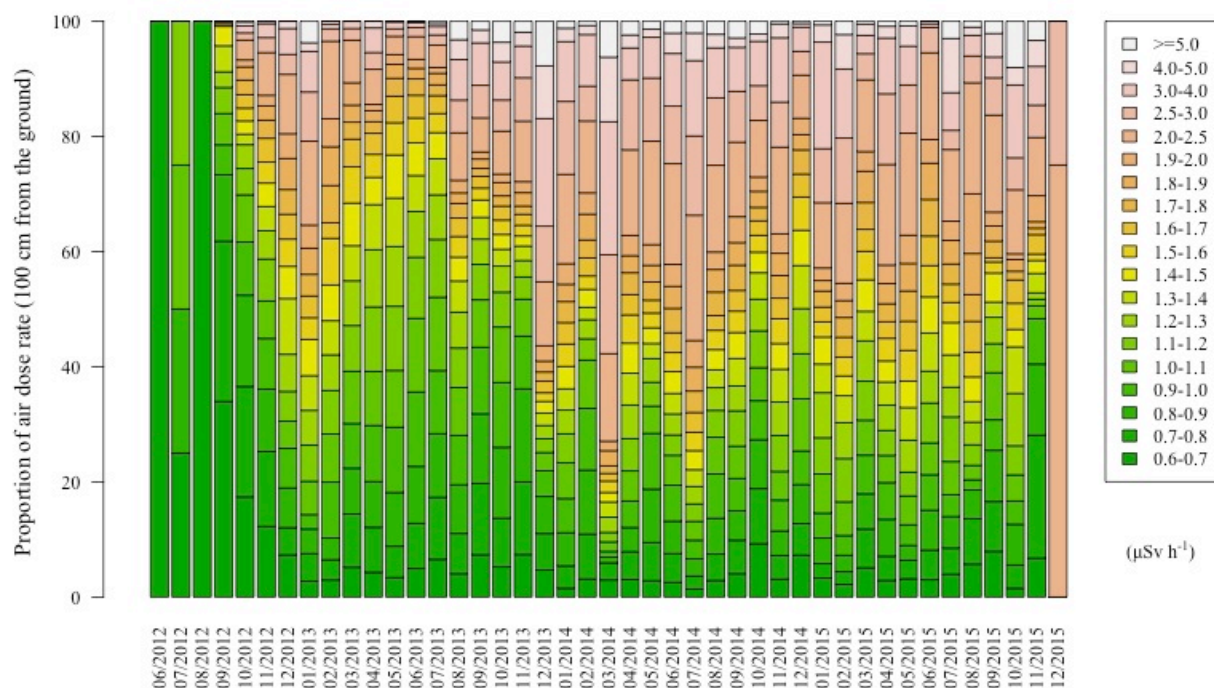


Fig. 3-15 Temporal change in the outbreak of the air dose rate (100 cm from the ground) (06/2012 – 12/2015). The categories in the horizontal axis are months of pre-decontamination monitoring. The colors represent the air dose rates (100 cm from the ground) determined in the pre-decontamination monitoring, from low (green) to high (red).

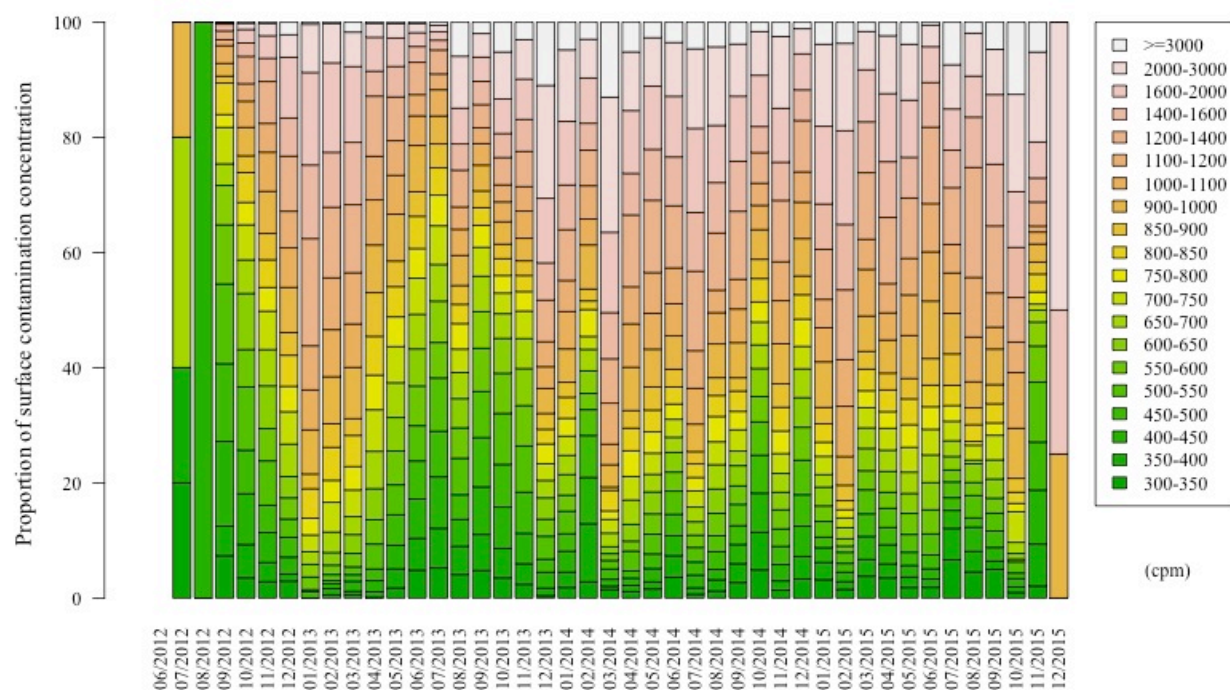


Fig. 3-16 Temporal change in the outbreak of the surface contamination concentration (06/2012 – 12/2015). The categories in the horizontal axis are months of pre-decontamination monitoring. The colors represent the surface contamination concentrations determined in the pre-decontamination monitoring, from low (green) to high (red).

In all three categories, the proportion of the high dose rate gradually increased in late 2012 and inversely decreased in early 2013. It went up again toward early 2014 and down in late 2014. The rate of reduction varied in accordance with the changing dose rate up to late 2013, but thereafter it remained low, even for the high dose rate. This pattern contradicts the results of Fig. 3-8 - Fig. 3-10, where the reduction rate rises to a particular level in accordance with the dose rate. These results imply that the reduction rate may have been influenced by factors other than the radiation dose in the areas where decontamination works were conducted. Some of the radioactive isotopes fallen in the forest area were captured in the tree canopy, trenches, leaves, or upper parts of the ground. The isotopes captured in the canopy dropped to the ground together with falling leaves or precipitation (FA, 2015; FA, 2016). The isotopes thus delivered to the negative charges accumulated in the organic layer or topsoil layer and infiltrated the deeper layers at varying speeds of migration in different types of soil (IAEA, 2006). This process might have contributed to the gradual decline of the reduction rate.

3.3.3 Dose rate reduction in each type of vegetation

Based on the results of analyses performed by combining vegetation maps with geological data on decontamination works, we extracted 4 of 10 categories that had more than data 100 points (Fig. 3-17 - Fig. 3-19). We used data on the Deciduous conifer plantation in the periods of Jun. - Dec. 2013, May - Jul. 2014, Mar. - May, Jul., and Sep. 2015, which had the least number of data points. The rate of reduction of the surface dose rate was much higher for the Deciduous conifer plantation than for the other types of vegetation, reaching 54 %. This was followed, in descending order, by the rates in the *Quercus serrata* community (36 %), *Pinus densiflora* community (32 %), and evergreen conifer plantation (26 %). The reduction rates for the air dose rate (100 cm from the ground) and surface concentration contamination lined up in the same

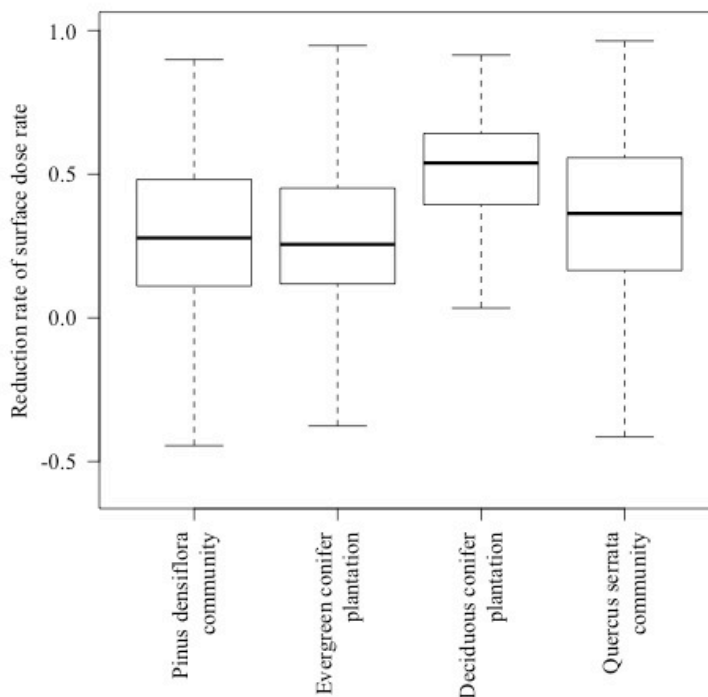


Fig. 3-17 Rates of reduction of the surface dose rates of the four types of vegetation.

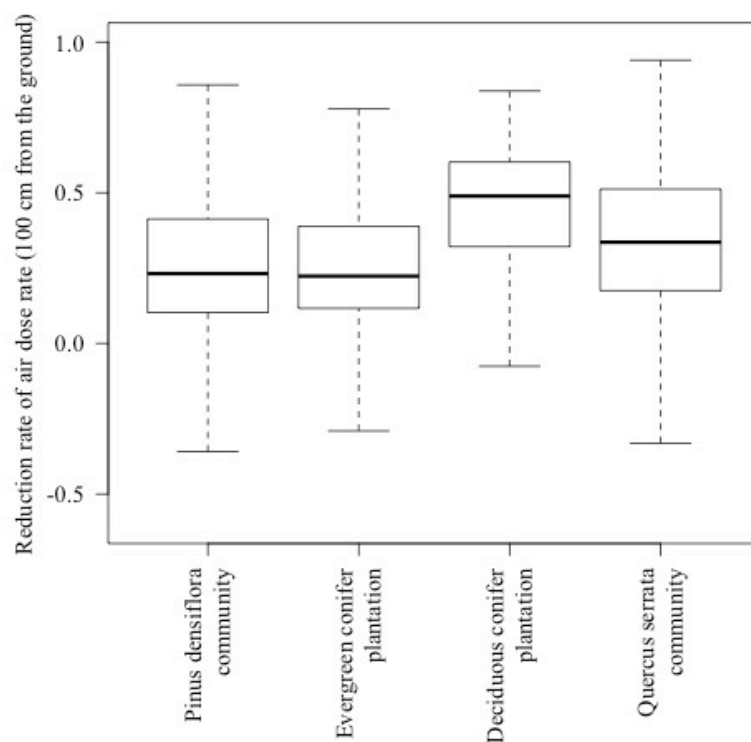


Fig. 3-18 Rates of reduction of the air dose rates (100 cm from the ground) of the four types of vegetation.

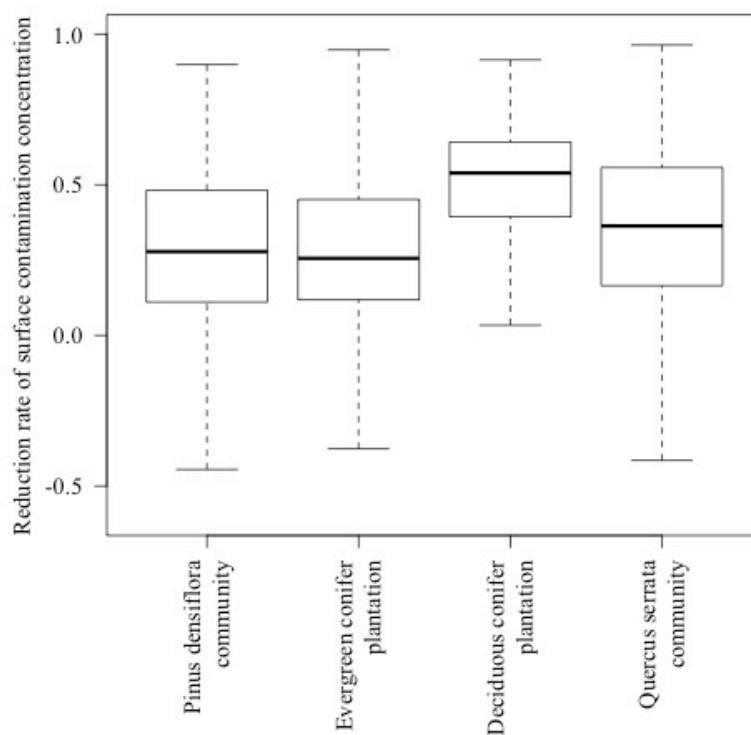


Fig. 3-19 Rates of reduction of the surface contamination concentrations of the four types of vegetation.

order: 49 %, 34 %, 23 %, 22 % and 59 %, 37 %, 33 %, and 27 %, respectively. Bartlett-test was conducted and homoscedasticity was not confirmed ($p < 0.05$). In the wake of Bartlett-test, Kruskal-Wallis test was subsequently conducted and at least the reduction rate in one of the vegetation stochastically different from that of the other vegetation ($p < 0.05$). Several classifications of vegetation appear on the vegetation map, from larger to smaller types. To ensure consistency between the types we adopted the medium-sized vegetation, the type determined to best reflect not only the dominancy, but also physiognomy, and geographical condition. (Biodiversity Center of Japan, 2016b).

In March, when the accident struck, the leaves of the deciduous forests were estimated to have been less abundant than the leaves of the evergreen forests. According to a 2011 annual report on the findings of ongoing research focused on the alignment of radioactive substances, the leaves and branches of *Cryptomeria japonica*, an evergreen conifer plant, contained a higher proportion of radioactive Cs than the leaves and branches of *Quercus serrata*. This was because the latter had fewer leaves, apparently allowing more radioactive Cs to directly reach the ground. *Pinus densiflora* had fewer leaves than *Cryptomeria japonica* in spite of its shared classification as an evergreen conifer, and its leaves similarly contained a lower proportion of radioactive Cs. Parts of this research relied largely on data from 2013, when the concentration of radioactive Cs in evergreen conifer plants was still higher than that in deciduous trees not only in the trench portions, but also the above-ground portions consisting of mainly leaves and branches. The GIS analytical results indicating the highest reduction rates in the deciduous forest, followed by the *Pinus densiflora* and evergreen conifer forest, were coherent with the values determined through continuous monitoring, given that the decontamination works were mainly conducted by removing the organic layers. Yet the monitoring clearly shows that leaves come out and drop even in evergreen forests, albeit over a longer cycle time compared with deciduous trees. Hence, the above-ground radioactive Cs and underground radioactive Cs reach an equilibrium in each type of vegetation (FA, 2011; FA, 2015; FA, 2016).

Organic matter in the *Larix kaempferi* vegetation may be slow or difficult to degrade, and water-shedding hypha nets may be well developed in or under the organic layer (Murai and Iwasaki, 1975). Detailed research will be necessary to clarify why the reduction rate was so much higher in *Larix kaempferi* than in the other types of vegetation. The research should focus closely on the infiltration of radioactive Cs in the organic and soil layers, a process that could influence the decontamination effect.

3.3.4 Infiltration of radioactive Cs and relation with the reduction rate in each type of vegetation

Fig. 3-20, 3-21 - Fig. 3-28, 3-29 show the depth profiles of radioactive Cs in five forests with five different vegetation types according to the GIS analyses.

In Fig. 3-20, 3-22, 3-24, 3-26, and 3-28, the horizontal axis plots the concentration of radioactive Cs and the vertical axis plots the dry mass depth of each layer. In Fig. 3-21, 3-23, 3-24, 3-27, and 3-29, the horizontal axis plots the cumulative proportion of radioactive Cs and the vertical axis plots the kinds of organic layers or depths of the soil layers. No H layer could be identified in the *Chamaecyparis obtusa* forest because its organic layer was comparatively immature. The larger the β_d values become, the radioactive Cs infiltrates the organic and soil layers at progressively greater depths. The analyses indicated β_d values of 1.98 g cm^{-2} in *Cryptomeria japonica* and revealed the deepest penetration of radioactive Cs in the *Cryptomeria japonica* forest, followed by Deciduous broadleaf, *Pinus densiflora*, *Larix kaempferi*, and *Chamaecyparis obtusa*, with β_d values of 1.60 g cm^{-2} , 1.44 g cm^{-2} , 1.21 g cm^{-2} , 1.15 g cm^{-2} , respectively.

Radioactive Cs changes to Cs^+ once it dissolves in water. The quantity of negative charges at the adsorption sites in soil therefore becomes one of the crucial factors in clarifying the process of Cs^+ adsorption. There are three kinds of negative charges in soil: a) negative charges that have strong affinity for Ca^{2+} or other cations besides Cs^+ , where the Cs^+ is easily replaced with other cations even if the negative charges retain Cs^+ at any point; b) negative charges that selectively retain Cs^+ , where the Cs^+ is released after competition with other cations; c) negative charges that retain Cs^+ , where the Cs^+ is not easily released (Yamaguchi, 2011). According to a report issued just after the nuclear accident, radioactive Cs existed mainly in soluble form in water, as well as insoluble large particles such as Fe, Zn, Cs (Adachi et al., 2013), or as sulfuric aerosol (Kaneyasu et al., 2012). Given the fact that the decontamination effect has decreased even under the condition with relatively high dose rate, it would be necessary to consider the infiltration mechanisms for different types of vegetation through research on the conditions of the organic and soil layers including cation exchange capacities, saturated hydraulic conductivity as well as voidage.

We conducted a series of scatter plot analyses of the relaxation mass depth (β_d value) and reduction rate to investigate the relation between the infiltration of radioactive Cs and reduction rate (Fig. 3-30 - Fig. 3-32). The boxplots have the same vertical axes as Fig. 3-17 - Fig. 3-19. The reduction rates for *Larix kaempferi*, *Pinus densiflora*, Deciduous broadleaf tree, *Cryptomeria japonica* and *Chamaecyparis obtusa* were applied to those of the Deciduous conifer plantation, *Pinus densiflora* community, *Quercus serrata* community, evergreen conifer plantation, and evergreen conifer plantation, respectively. Negative correlations were observed between the beta values and rate of radiation dose reduction, though they were not so strong. We had no choice but to adopt the same reduction rate for *Cryptomeria japonica* and *Chamaecyparis obtusa*, as there were no sub-categories in the vegetation map more detailed than “evergreen conifer plantation.” As a consequence of these analyses, *Chamaecyparis obtusa* represented a lower value relative to the tendency of the other types of vegetation. Additional research might provide additional measurements to clarify the mechanism of the relation. The conditions of the organic layers are shown in Table 3-5. Regarding the distribution of *Cryptomeria japonica* and *Chamaecyparis obtusa*, the former had a larger thickness and mass depth than the latter, as previously mentioned. The difference could be attributed to the H layer, which was too immature to observe in *Chamaecyparis obtusa*. As shown in Fig. 3-21, 3-23, 3-25, 3-27, and 3-29, the ratios of radioactive Cs contained in the organic layer were 20 % and 26 % for *Cryptomeria japonica* and *Chamaecyparis obtusa*, respectively. The organic layer in the Deciduous broadleaf, which had nearly the same thickness as that in *Cryptomeria japonica*, contained 49 % of the radioactive Cs. The organic layer in *Larix kaempferi*, which had nearly as same mass depth as that in *Cryptomeria japonica*, contained 65 % of the radioactive Cs.

In light of these consequences, we see that even in apparently well-developed organic layers, the ratios of retained radioactive Cs widely differed among the different types of vegetation. As mentioned, radioactive Cs was adsorbed in a negative charge in the soil layer through a step-by-step approach. Radioactive Cs was therefore accumulated in the upper portion of the soil layers in the *Chamaecyparis obtusa*, a vegetation type lacking a well-developed organic layer. Approximately 82 % of the radioactive Cs remained in a 2.0 cm soil layer from the top in *Chamaecyparis obtusa*, while 48 % of the radioactive Cs remained at the same depth from the top in *Cryptomeria japonica*. These results implied that the condition of the soil might influence the infiltration pattern. Yet as we observed above, the infiltration pattern differed among the different types of vegetation. Whether this phenomenon influences the decontamination effect has to be additionally investigated through further analyses on properties such as the cation exchange capacity, saturated hydraulic

conductivity, and ignition loss in both the organic matter and soil layers.

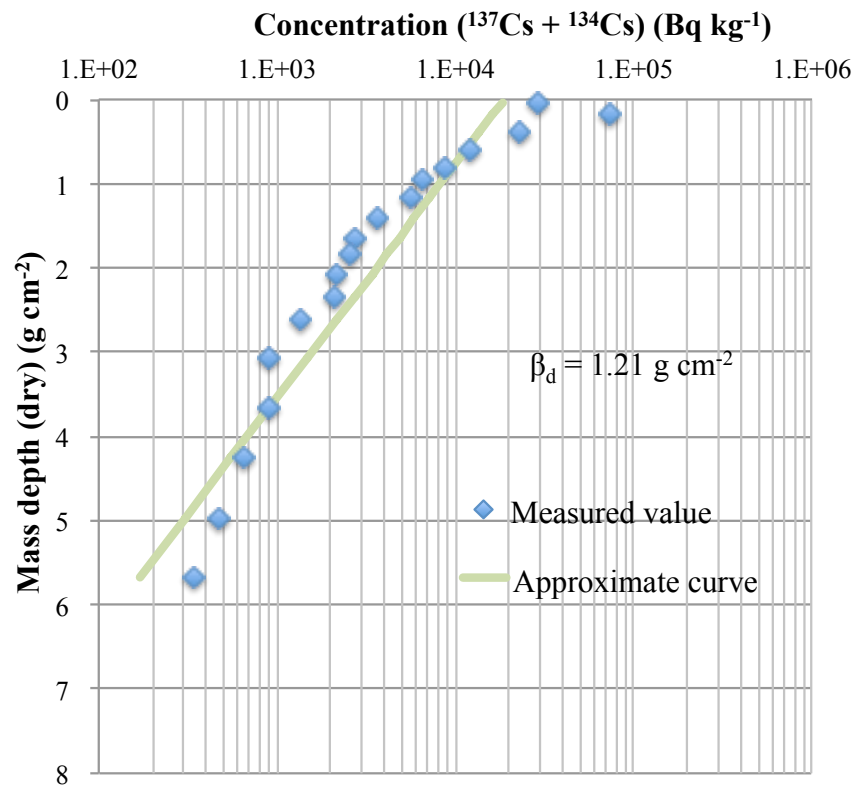


Fig. 3-20 Depth profile of radioactive Cs with mass depth (dry) in Larix kaempferi.

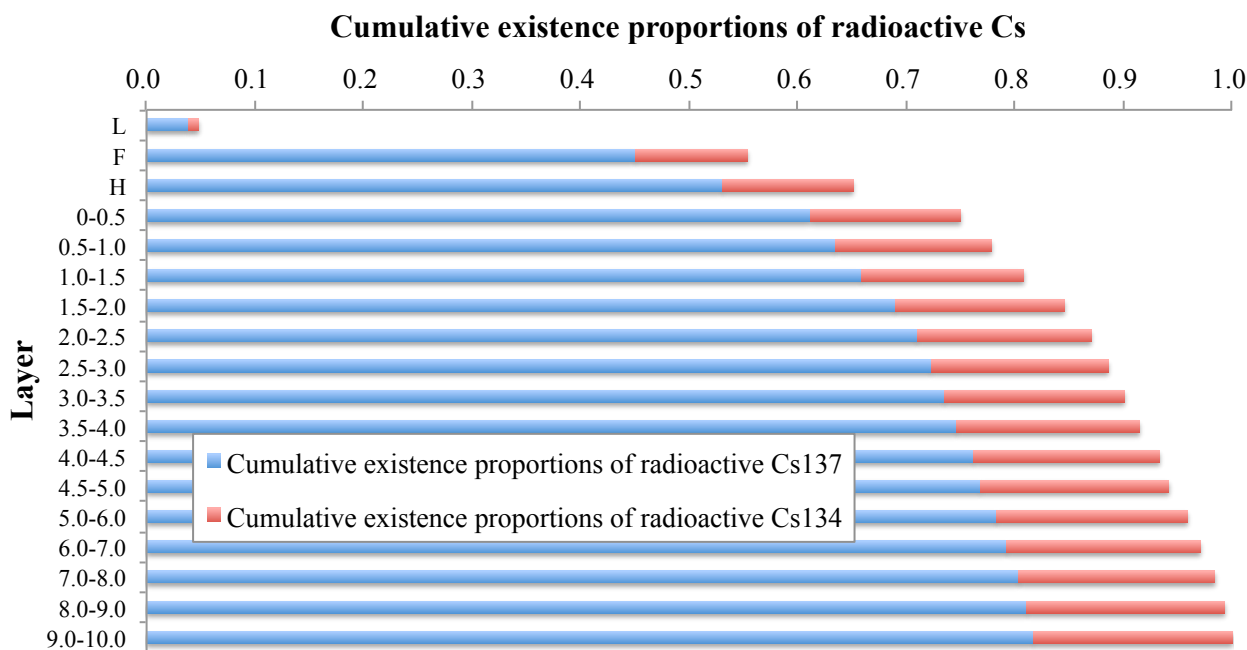


Fig. 3-21 Cumulative existence proportion of radioactive Cs with depth in Larix kaempferi.

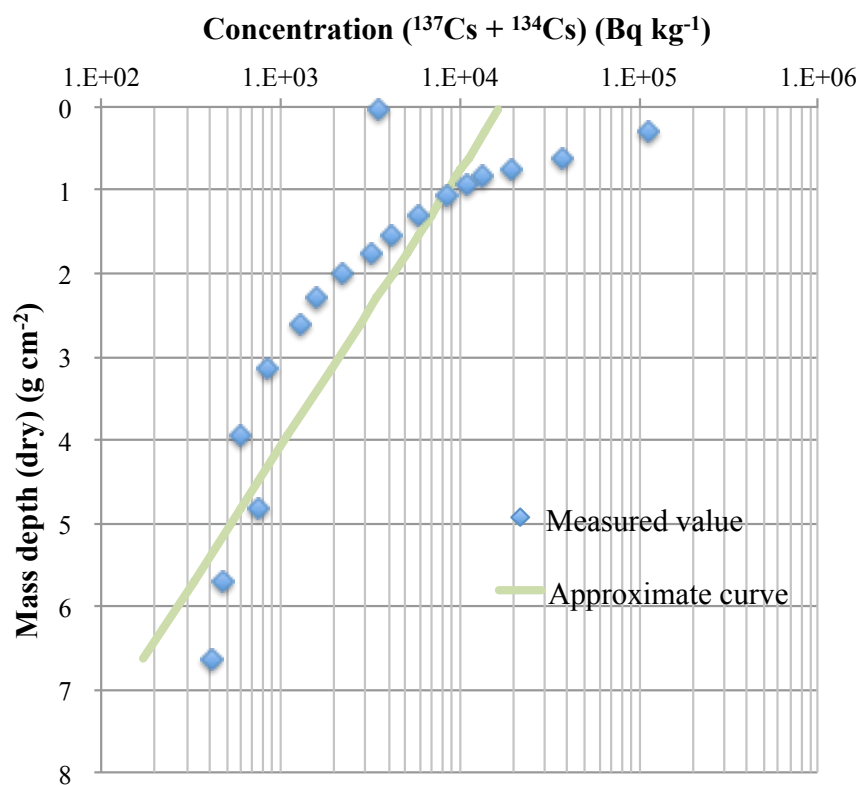


Fig. 3-22 Depth profile of radioactive Cs with mass depth (dry) in *Pinus densiflora*.

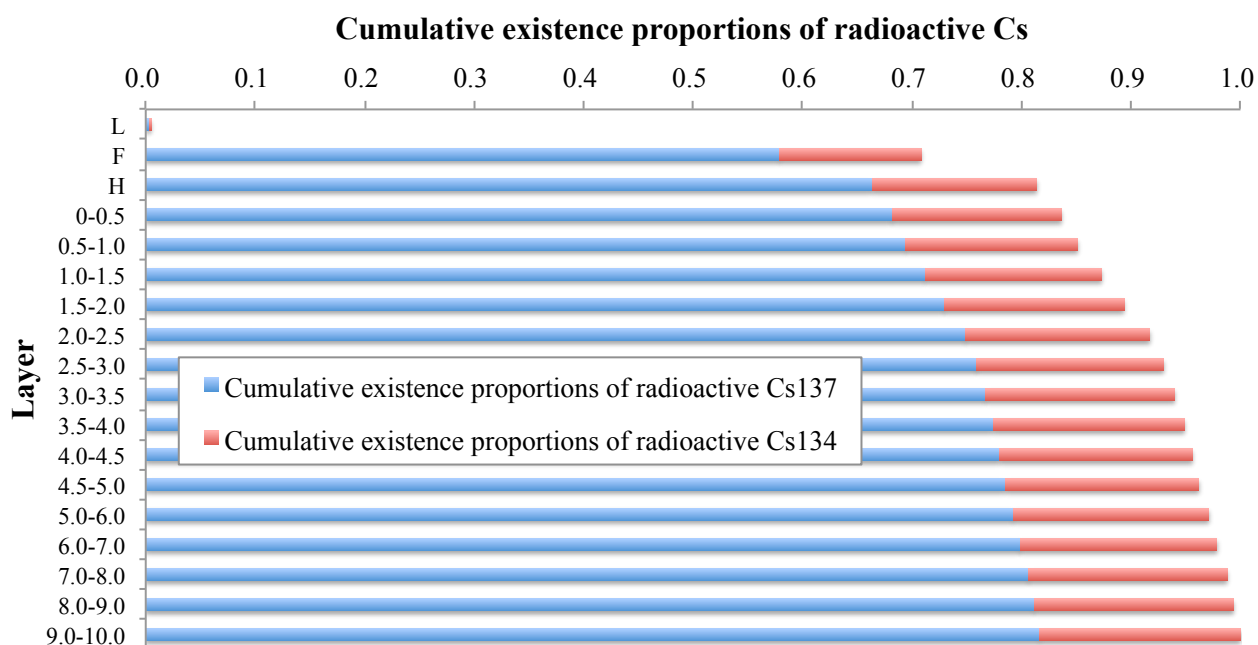


Fig. 3-23 Cumulative existence proportion of radioactive Cs with depth in *Pinus densiflora*.

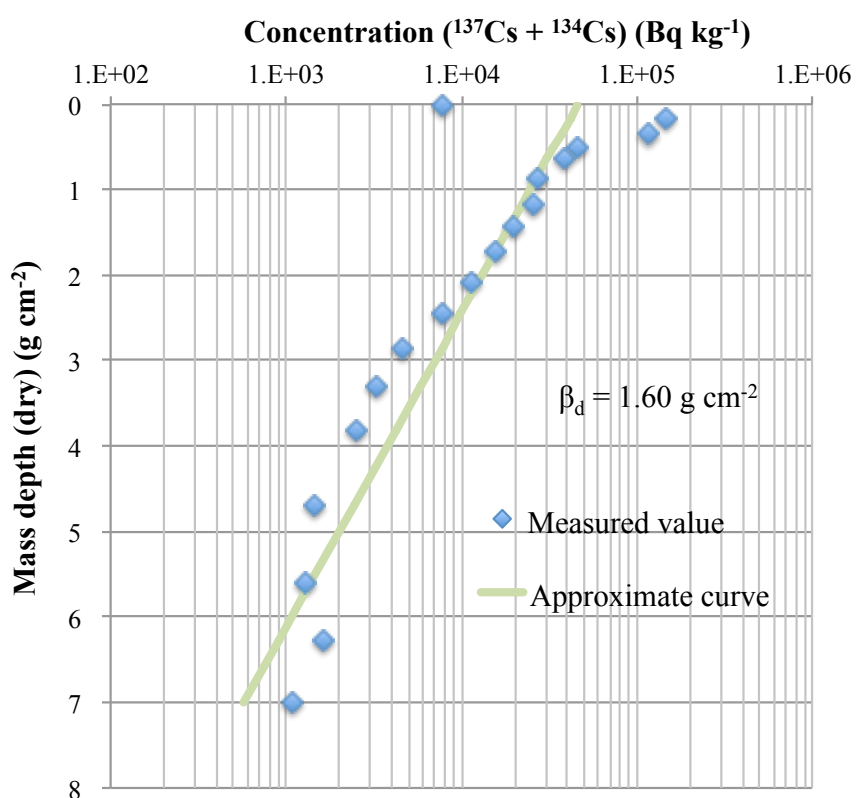


Fig. 3-24 Depth profile of radioactive Cs with mass depth (dry) in Deciduous broadleaf trees.

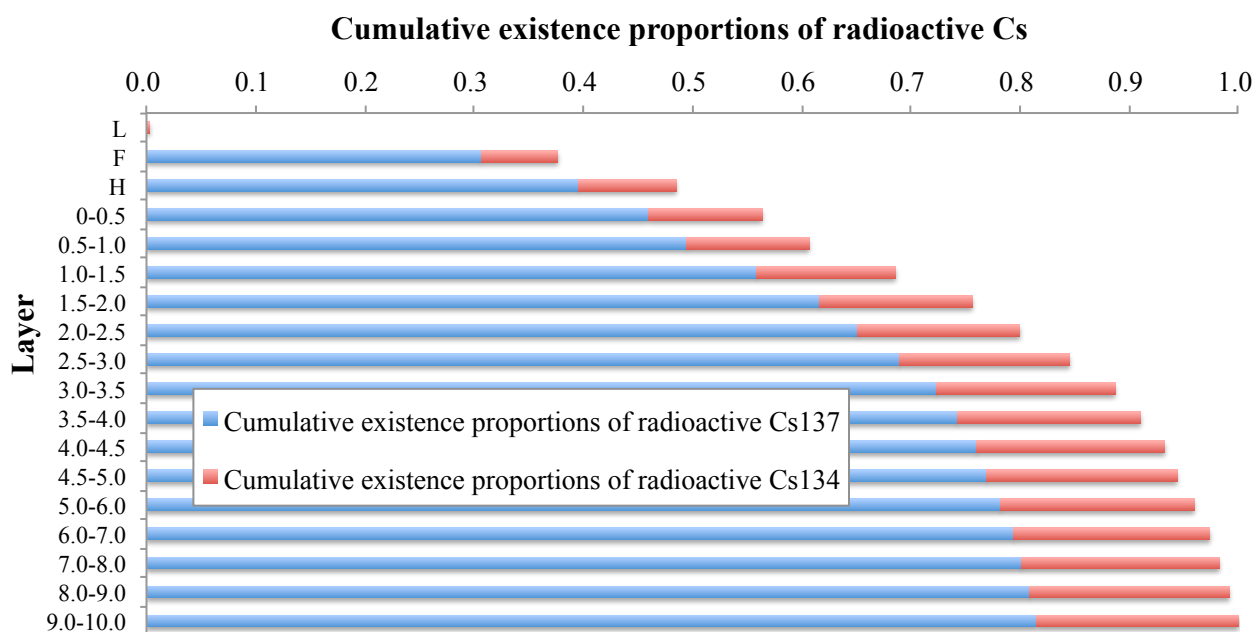


Fig. 3-25 Cumulative existence proportion of radioactive Cs with depth in Deciduous broadleaf trees.

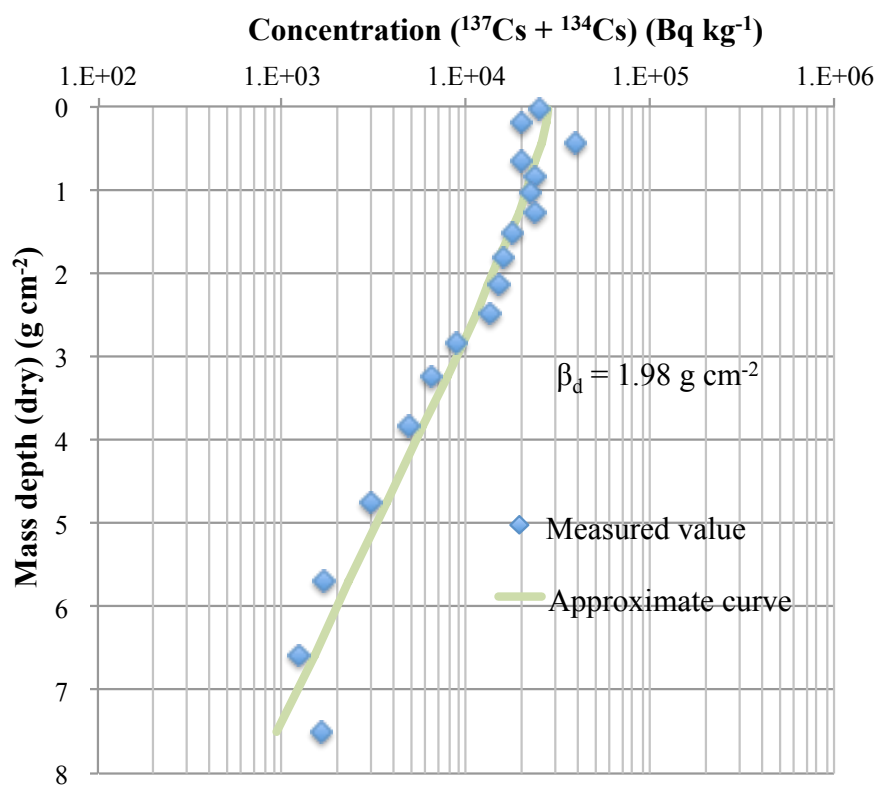


Fig. 3-26 Depth profile of radioactive Cs with mass depth (dry) in *Cryptomeria japonica*.

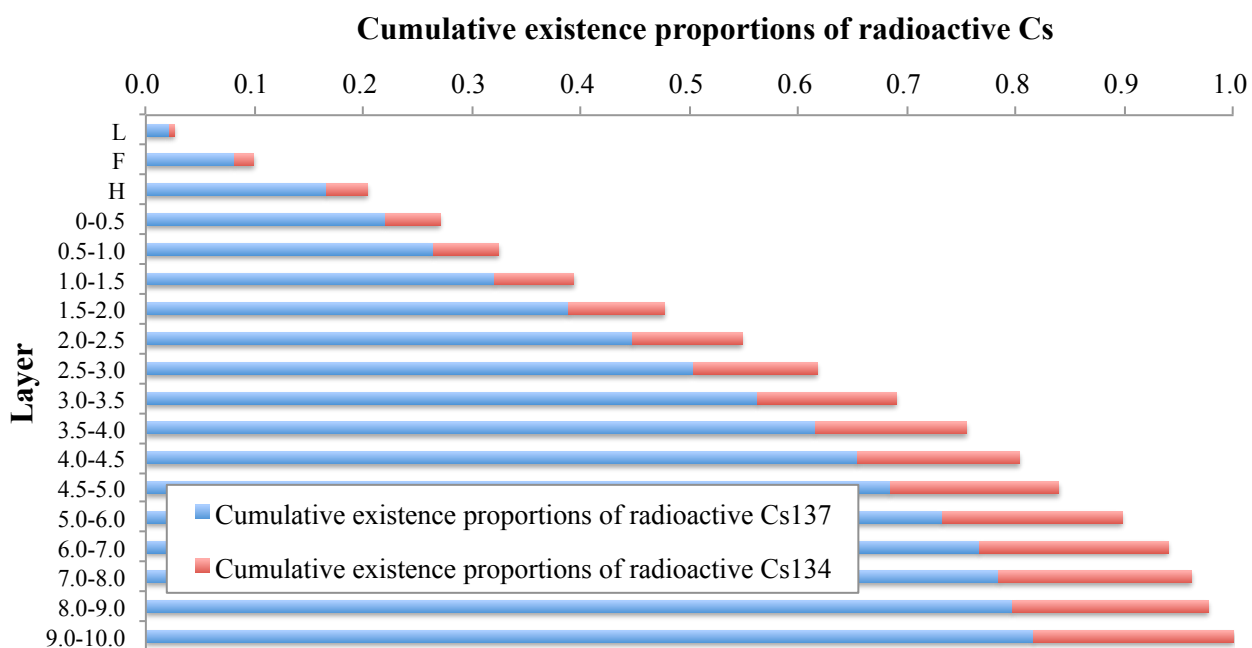


Fig. 3-27 Cumulative existence proportion of radioactive Cs with depth in *Cryptomeria japonica*.

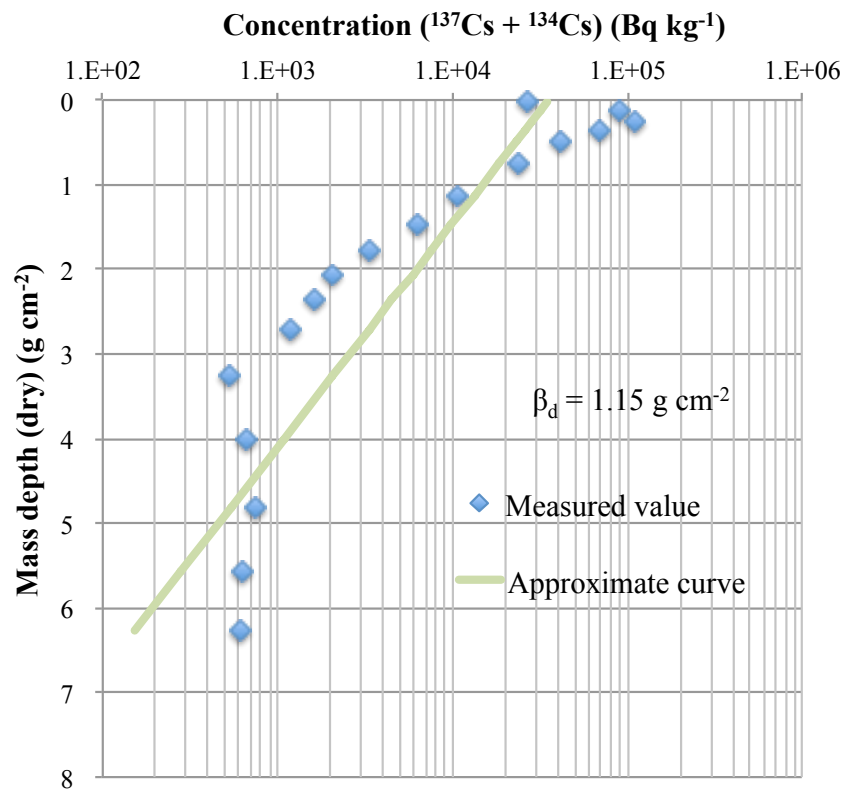


Fig. 3-28 Depth profile of radioactive Cs with mass depth (dry) in *Chamaecyparis obtusa*.

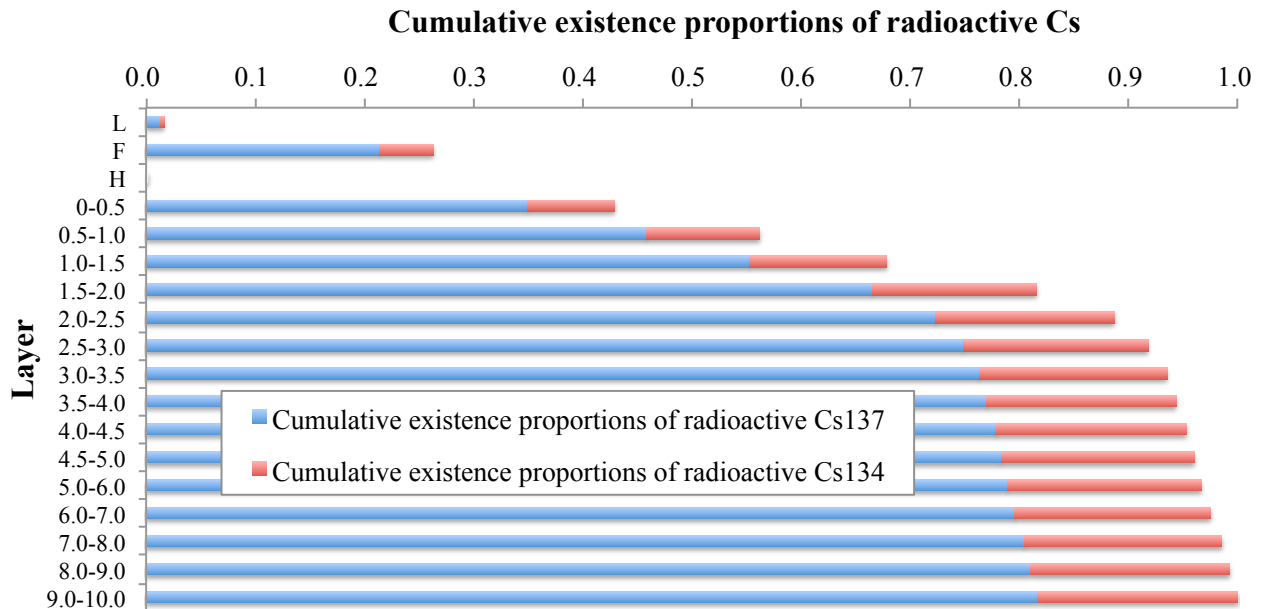


Fig. 3-29 Cumulative existence proportion of radioactive Cs with depth in *Chamaecyparis obtusa*.

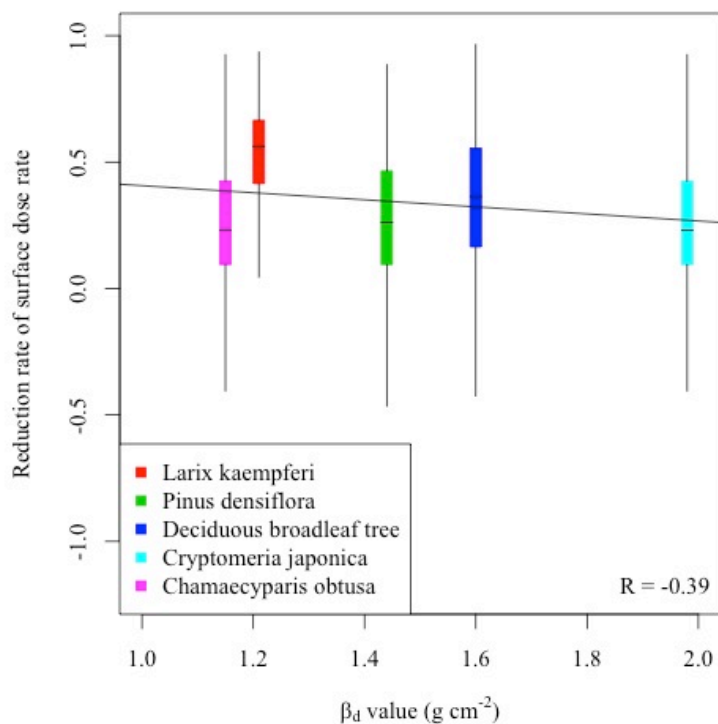


Fig. 3-30 Relation between the rate of reduction of the surface dose rate and the relaxation mass depth (β_d value (g cm^{-2})).

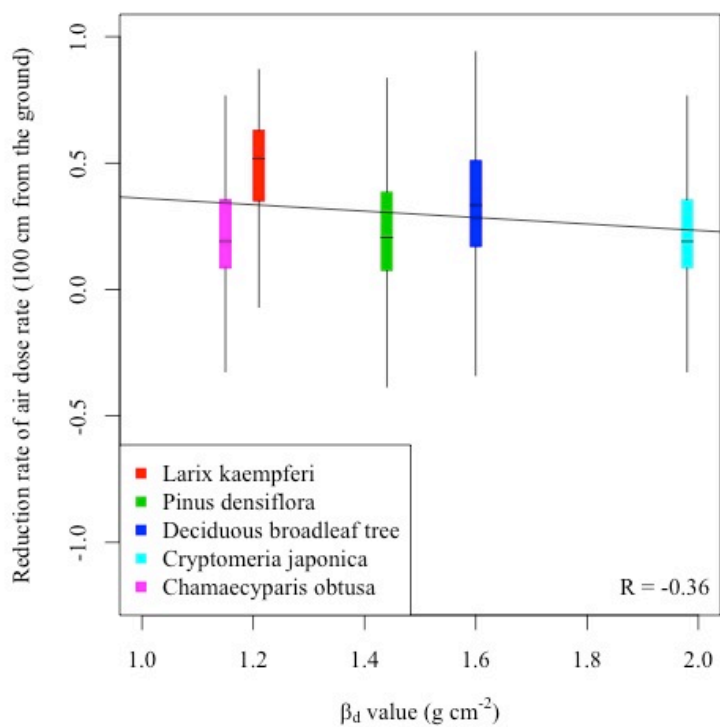


Fig. 3-31 Relation between the rate of reduction of the air dose rate (100 cm from the ground) and the relaxation mass depth (β_d value (g cm^{-2})).

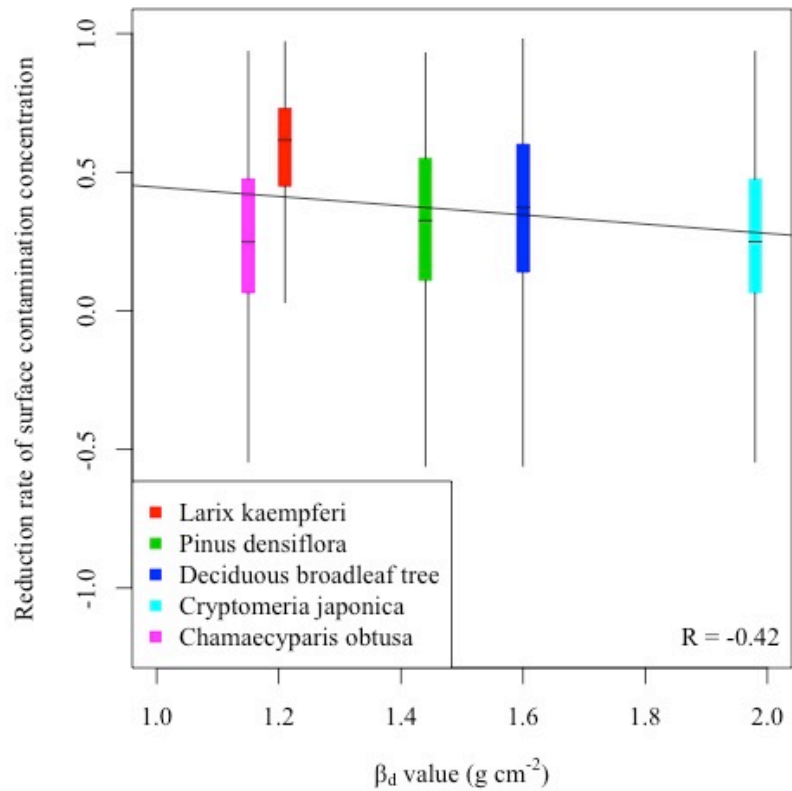


Fig. 3-32 Relation between rate of reduction of the surface contamination concentration and the relaxation mass depth (β_d value (g cm^{-2})).

Table 3-5 Properties of the organic layers

	Thickness (cm)	Mass depth (dry) (g cm^{-2})	Proportion of radioactive Cs contained in organic layer
<i>Larix kaempferi</i>	4.0	0.47	0.65
<i>Pinus densiflora</i>	6.0	0.70	0.81
Deciduous broadleaf tree	5.5	0.40	0.49
<i>Cryptomeria japonica</i>	5.3	0.52	0.20
<i>Chamaecyparis obtusa</i>	2.0	0.20	0.26

3.4 Discussion and conclusions

The reduction rates for the surface dose rate, the air dose rate (100 cm from the ground), and surface contamination concentration basically increased as the dose rate rose but saturated after reaching threshold levels. The air dose rate (100 cm from the ground) was reduced at a lower rate than the surface dose rate and surface contamination concentration. Forest decontamination activities were conducted based on the guidelines, basically by removing the organic matter on the top of the ground. When sufficient effects could not be confirmed in the living environment afterwards, the residue of organic matter within 5 m from the edge of forest was removed when necessary, with care taken not to unduly expose the roots or trigger disasters such as landslides. Taking this workflow into account, the background radiation exerted an especially marked influence on the effects of the reduction rate at low radiation levels. The reduction rate has also declined over time, albeit with some observable fluctuation. During the early stages of the monitoring term the reduction rate rose in step with the dose rate: the higher the dose rate, the larger the effect. Yet late in the term the effect remained low even under a high dose rate condition. This phenomenon partly contradicted the increase we observed in the decontamination effect in step with the surrounding dose rate, up to a certain level. The phenomenon implied that the recovery efficiency of radioactive substances declined in the later part of the monitoring term, possibly as a consequence of factors such as infiltration down to deeper layer or the higher dose rate caused by the removal of the less contaminated organic matter on the top of the ground, with its radiation-shielding effect. When we used the GIS data to analyze the reduction rates for vegetation in order to validate this hypothesis, the results identified possible discrepancies between them. Specifically, the reduction rates for the Deciduous conifer plantation (e.g., *Larix kaempferi*) were much higher than the rates for the other vegetation types. Compared to the green conifer plantation, for example, the rates for the Deciduous conifer plantation were slightly more than double: 56 %, 49 %, and 59 % versus 26 %, 22 % and 27 % for the surface dose rate, air dose rate (100 cm from the ground), and surface contamination concentration, respectively. According to the annual report, the inhabitation of forests in Fukushima on a dimension basis was as follows: Deciduous broadleaf tree, 56 %; *Cryptomeria japonica*, 24 %; *Pinus densiflora* and *Pinus thunbergii*, 14 %; *Chamaecyparis obtusa*, *Chamaecyparis pisifera*, and *Selaginella*, 2 %; *Larix kaempferi*, 2 % (Fukushima Prefectural Government, 2014). All vegetation chosen by the GIS analyses was included in these statistical data. To clarify the relation between the infiltration of radioactive Cs and reduction rate, we conducted field studies in five types of forest in Fukushima using scraper plates to determine the depth profiles of radioactive Cs. According to analyses using approximate hyperbolic secant (sech) and hyperbolic cosine (cosh) functions, the depth profiles differed among the vegetation types. The correlation between the infiltration pattern and reduction rate was not too strong to determine that the penetration of radioactive Cs dominated the rundown of the reduction rate. This was partially due to the vegetation map, which lacked categories more detailed than “evergreen conifer plantation” for the division of different forest types. The vegetation in the GIS reflects not only the dominancy of vegetation, but also the physiognomy and geographical condition. Even if the organic layers appeared to have been equally developed, the variable characteristics of the soil layers also influenced the infiltration of radioactive Cs in different ways. Additional field studies or research will be needed to clarify how the conditions of the organic and soil layers may influence the infiltration of radioactive Cs.

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4.1 Introduction

Radioactive substances scattered from the Fukushima Dai-ichi nuclear accident have been removed from living areas, including forest areas, through decontamination efforts based on the guidelines. In forest areas, decontamination activities were conducted mainly by removing organic matter, such as branches and leaves, within 20 m from the edge of the forest. For the rest of the forest area, comprehensive countermeasures should be considered from a long-term perspective, using a variety of methods, such as the Satoyama reconstruction model project and so forth (RA, 2016).

It is well known that radioactive Cs deposited on the ground is adsorbed by negative charges in clay particles (Yamaguchi et al., 2011; Tsukada et al., 2008); however, in studies published before (Mori et al., 2016), it had been reported that the infiltration of radioactive Cs is different in forests with different types of vegetation. However, neither the cause of such phenomenon nor the mechanism for infiltration in the vertical direction have been explained. In this research, soil characteristics in forests with different vegetation were investigated, and the change upon infiltration was also analysed. In addition, the ignition loss, which is the index to describe the concentration of organic matter was used, as a parameter to replicate the infiltration pattern of radioactive Cs using a compartment model. We expected to obtain beneficial outputs to contribute to comprehensive measures for eliminating radioactive pollution, including more effective decontamination activities, through this research.

4.2 Materials and Methods

4.2.1 Measurement of saturated hydraulic conductivity, field capacity and voidage

In five forests with different types of vegetation, where *Larix kaempferi*, *Pinus densiflora*, Deciduous broadleaf tree, *Cryptomeria japonica*, *Chamaecyparis obtusa* are dominant in Fukushima Prefecture, soil core (0 - 5 cm and 5 - 10 cm) were collected by driving a 100 cc cylinder, 5 cm in diameter and 5 cm in height, into the soil layer, after the organic layer was removed (Fig. 3-7). In the laboratory, two empty columns with gauze on each side were attached with tape to the soil core, and the soil samples and cores were soaked for 1 hr in water. After that, water was filled to the top of the core, and the time (t_1) for the water surface to move down one core length (L) was measured three times (Fig. 4-1).

Afterwards, the empty columns were detached, and the weight of the soil core was measured. Then, the core was kept still for 24 hr to allow the contained water to flow down naturally, followed by another weight measurement of the soil core.

The soil in the core was transferred to a porcelain dish and absolutely dried in a constant temperature bath (105 °C, 24 hr), followed by weight measurement.

The saturated hydraulic conductivity, field capacity and voidage were calculated by Equations (1), (2), and (3).

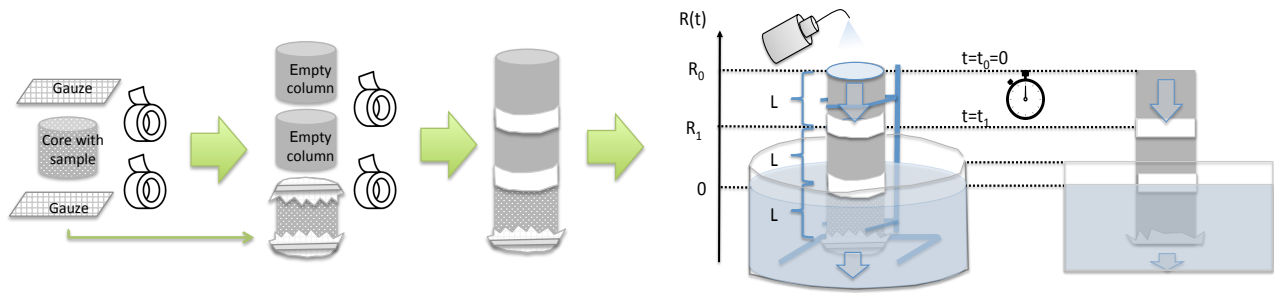


Fig. 4-1 Outline of the saturated hydraulic conductivity experiment.

Saturated hydraulic conductivity is the index describing the water velocity through the core and can possibly evaluate the ease of radioactive Cs infiltration.

$$K_s = L/t_1 \ln (R_1/R_0) \quad (1)$$

where K_s is the saturated hydraulic conductivity (cm s^{-1}), t_1 is the time for the surface to move down one core length (sec), L is the length of the core (cm), and R is the height from the surface of the water bath (R_0 : 10 cm, R_1 : 5 cm).

The field capacity is the amount of water, subtracting the extra water transported by gravity, after the water conditions reach saturation. This index can possibly describe the relation between the water retained against gravity and the infiltration of radioactive Cs.

$$K_w = (W_1 - W_2 - W_3)/(V_s + V_w) \quad (2)$$

where K_w is the field capacity (g cm^{-3}), W_1 is the weight of the soil core after remaining still for 24 hr, W_2 is the weight of the core, gauze and the tape, W_3 is the weight of the soil after drying, W_4 is the weight of the soil core directly after immersion in the water bath, V_s (W_3/D_s) is the volume of the soil (cm^3), V_w ($(W_4 - W_2 - W_3)/D_w$) is the volume of water contained in the core (cm^3), D_s is the density of the soil (2.6 g cm^{-3}), and D_w is the density of water (1.0 g cm^{-3}). We adopted 2.6 g cm^{-3} as the soil density because the density, excluding the organic soil, ranges between approximately $2.5 - 2.7 \text{ g cm}^{-3}$, though the actual value depends on the conditions (JGS, 2009).

Voidage is the proportion of void in a certain amount of soil volume and can possibly describe the relation between the gap quantity and the infiltration of radioactive Cs.

$$K_v = V_w/(V_s + V_w) \quad (3)$$

where K_v is the voidage.

4.2.2 Depth profile analyses of radioactive Cs and measurement of ignition loss in forests with different types of vegetation

In the five forests with different types of vegetation, the depth profile of radioactive Cs was analysed. Concretely speaking, three organic layers (L, F, and H) and fifteen soil layers were obtained at 0.5 cm intervals for depths of 0 - 5 cm and at 1.0 cm intervals depths of 5 - 10 cm. The obtained samples were preserved in U8 containers, and the radioactive concentration was measured using a Ge semiconductor detector (ORTEC GMX-30190). All radioactive concentrations were re-calculated using an attenuated correction to Oct. 1st, 2015.

The L (litter) layers, the group of layers located on the top of the ground, consist of fallen leaves and branches remaining in an almost undegraded state. The F (fermented) layer, the second group of layers from the top, consists of organic matter broken up by small animals or microorganisms. While the forms of the original plants cannot be identified, the tissues of the original plants can be confirmed by the naked eye. The H (humus) layers are more degraded, rendering the original plant forms unidentifiable. The soil of the humus layer becomes powdery when dry and fatty when wet (JFTA, 2001).

Of the samples taken from the forests, organic layer samples of approximately 7 g (whole samples if sufficient quantities could not be obtained) and soil layer samples of approximately 12 g were dried for 72 hr in a desiccator.

Afterwards, the organic layers and soil layers, except for the L and F layers, were passed through a sieve with a 2 mm lattice, and impassable organic matter and soils were finely comminuted in the mortar and passed through a sieve again. Organic matter and soils that were passable were absolutely dried for 24 hr at 105 °C, followed by weight measurement. The water content was calculated by the weight alteration.

The samples under absolute dry conditions were incinerated at 700 – 800 °C in a programmed temperature controller (ISUZU, VTDS-16R), followed by weight measurement to determine the ignition loss.

The ignition loss is the proportion of volatile substances mainly composed of organic matter in a certain amount of soil and was analysed to reveal the relation between the contained organic matter and the infiltration of radioactive Cs.

Considering only the soil layer, the approximate curve was drawn using Equation (4) to derive the relaxation mass depth β_d , because it is well known that the concentration of radioactive Cs decreases exponentially according to the mass depth when the depth profile is expressed using the concentration of radioactive Cs (Bq kg^{-1}) as the horizontal axis and the mass depth (g cm^{-2}) as the vertical axis (ICRU, 1994).

The relation between the concentration of radioactive Cs and the mass depth was analysed, and the relaxation mass depth was calculated using hyperbolic secant (sech) and hyperbolic cosine (cosh) functions, as in Equation (5) (Matsuda et al., 2015), when both the concentration in the organic layer and the soil layer were considered. This was because the relaxation mass depth can be overvalued when the concentration of radioactive Cs peaks not on the surface but at a certain depth due to its infiltration.

$$A_m(\zeta) = A_{m,0} \exp(-\zeta/\beta_d) \quad (4)$$

$$A_m(\zeta) = A_{m,0} \cosh(\zeta_0/\beta_d) \text{sech}(-(\zeta - \zeta_0)/\beta_d) \quad (5)$$

where ζ is the mass depth (dry) (g cm^{-2}), A_m is the concentration of radioactive Cs at the mass depth ζ (Bq kg^{-1}), $A_{m,0}$ is the concentration at the ground surface (Bq kg^{-1}), ζ_0 is the mass depth from the ground surface at the point of maximum concentration (g cm^{-2}), and β_d is the relaxation mass depth (dry) (g cm^{-2}).

$A_{m,0}$, β_d , and ζ_0 are determined by an iterative approach using the solver function in Excel (Microsoft Office).

4.2.3 Measurement of the cation exchange capacity

The cation exchange capacity (CEC) is the amount of positive charges to be exchanged with negative charges in the humic substances in the organic matter or clay particles contained in the soil layer and is typically represented as the number of milliequivalents per 100 g mass.

The CEC was monitored to consider its relation to the depth profile, because the CEC possibly impacts the infiltration of radioactive Cs, which becomes Cs^+ once dissolved in water.

The CEC in the soil layer (0 - 5 cm and 5 - 10 cm) was measured by the proposed shaking extraction method (Muramoto et al., 1992). Concretely speaking, the obtained 15 types of soils were dried for a week in a desiccator and passed through a sieve with a 2 mm lattice. For the passable soil samples from depths of 0 - 5 cm (10 layers) and 5 - 10 cm (5 layers), 1 g and 2 g of the samples were extracted from each layer and mixed into 10 g samples. Then, 2 g of the 10 g sample was extracted and transferred to a centrifuge tube.

Next, 30 ml of ammonium acetate (pH 7, 1 M) was added to the 2 g samples and shaken for 15 min, followed by centrifugal separation and discharge of the supernatant solution.

The series of these processes, that is, shaking, centrifugal separation and discharging of the supernatant solution, was repeated a total of three times, and the second and last shaking were conducted by hand vigorously for 30 sec instead of using a shaking machine.

Then, 20 ml of 80 % methanol solution was added to the centrifuge tube, and the tube was vigorously shaken by hand, followed by centrifugal separation and discharge of the supernatant solution.

The extraction processes of using methanol solution and centrifugal separation were additionally repeated twice.

To extract the ammonium ions from the soil, 30 ml of 10 % potassium chloride solution was added to the centrifuge tube and shaken for 15 min, followed by centrifugal separation, and finally the supernatant solution was filtered through 0.45 μm filter paper.

The series of these processes, that is, shaking, centrifugal separation and filtering, was repeated a total of three times, and the second and last shakings were conducted by hand vigorously for 30 sec instead of using a shaking machine.

The filtrate was collected in a graduated cylinder, and 10 % potassium chloride solution was added to reach 100 ml. The concentration of ammonia nitrogen was measured by the Ammonia Nitrogen Meter (AT - 2000, Central Kagaku Corp.), and the CEC was evaluated.

4.2.4 Simulation of the concentration of radioactive Cs in forests using a compartment model

Generally, the infiltration of substances, including radioactive Cs, is expressed using the convective diffusion equation and a retardation coefficient. However, the dynamics of radioactive Cs in organic matter and the soil layer, as well as factors that influence the infiltration of radioactive Cs, have not been clarified. Therefore, the transportation of radioactive Cs based on the transition coefficient (P) was hypothesized by regarding each layer in the organic matter (L, F, and H) and soil layer (0.5 cm intervals at a depth of 0 - 5 cm and 1.0 cm intervals at a depth of 5 - 10 cm) as one compartment.

The concentration of radioactive Cs in each layer, both the organic layer and soil layer, was simulated, based on the hypothesis that the radioactivity in “layer x” would vary according to the inflow from the upper “layer x-1”, represented by multiplication of the concentration of radioactive Cs and the transition coefficient in the upper “layer x-1”, and outflow into the lower layer is represented by the multiplication of the concentration of radioactive Cs and the transition layer in “layer x” (Equation (6))(Fig. 4-2). The relation between the transition coefficient (P) and the ignition loss (Q) can be expressed by Equation (7) and Equation (8), because a strong positive correlation was observed between the ignition loss and CEC through the experiments.

$$M_x(t+1) = M_x(t) + M_{x-1}(t) * P_{x-1}/L_{x-1} - M_x(t) * P_x/L_x \quad (6)$$

$$P_x = aQ_x^{-1} + b \quad (7)$$

$$P_x = aQ_x^{-b} \quad (8)$$

where M_x , P_x , L_x , and Q_x are the radioactivity of radioactive Cs (Bq), the transition coefficient, the thickness and the ignition loss of “layer x”, respectively.

The VBA program to estimate the concentration of radioactive Cs, the example of program for *Larix kaempferi*, based on the equation (7), is shown in Appendix 1. Depth profile and the soil characteristics differ between types of vegetation.

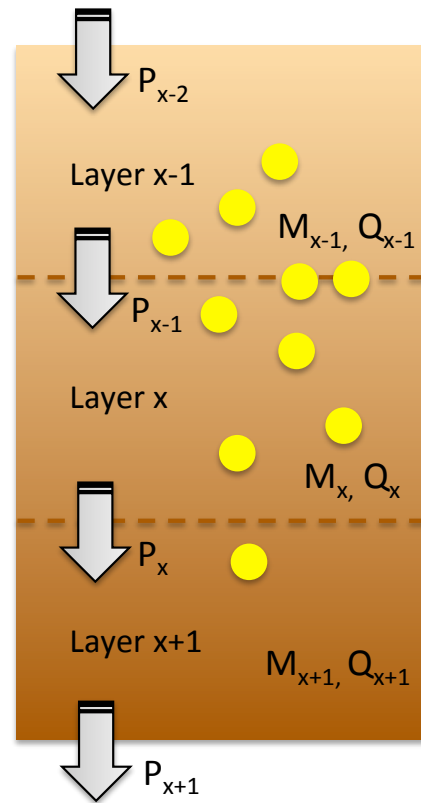


Fig. 4-2 Concept of the compartment model.

The radioactivity in each layer was estimated by a compartment model using Microsoft Excel VBA. Specifically, a and b in Equation (7) and Equation (8) were determined by minimizing the sum of the error, that is, the difference between the logarithmic value of the monitored concentration and the logarithmic value of the estimated concentration.

The concentration of radioactive Cs present in the soil before the accident was adopted as 22 Bq kg^{-1} , obtained from a grass field in Fukushima city (JCAC, 2016).

In addition to the analyses by taking ^{137}Cs into account, analyses concerning ^{134}Cs were conducted, in order to eliminate the influence of fallout from nuclear test in the atmosphere. In this case, the concentration of radioactive Cs in the background wasn't considered, because the half period of ^{134}Cs is short.

4.3 Results and considerations

4.3.1 Measurement of saturated hydraulic conductivity, field capacity and voidage

Saturated hydraulic conductivity, field capacity and voidage in the soil layer from each forest are shown in Fig. 4-3, Fig. 4-4 and Fig. 4-5, respectively. The saturated hydraulic conductivity showed a great deal of difference between the forests. The largest values were 0.96 cm s^{-1} (0 - 5 cm) and 0.98 cm s^{-1} (5 - 10 cm) in *Cryptomeria japonica*, followed by 0.74 cm s^{-1} (0 - 5 cm) and 0.23 cm s^{-1} (5 - 10 cm) in *Pinus densiflora*, 0.37 cm s^{-1} (0 - 5 cm) and 0.16 cm s^{-1} (5 - 10 cm) in Deciduous broadleaf tree, 0.27 cm s^{-1} (0 - 5 cm) and 0.34 cm s^{-1} (5 - 10 cm) in *Chamaecyparis obtusa*, and 0.17 cm s^{-1} (0 - 5 cm) and 0.14 cm s^{-1} (5 - 10 cm) in *Larix kaempferi*.

The field capacity was smaller in the 5 - 10 cm layer than in the 0 - 5 cm layer, except for in *Pinus densiflora*, where the value was slightly smaller in *Pinus densiflora* at 0.41 g cm^{-3} (0 - 5 cm) and 0.47 g cm^{-3} (5 - 10 cm). In forests with other types of vegetation, the field capacity did not show large differences and ranged between $0.50 - 0.60 \text{ g cm}^{-3}$.

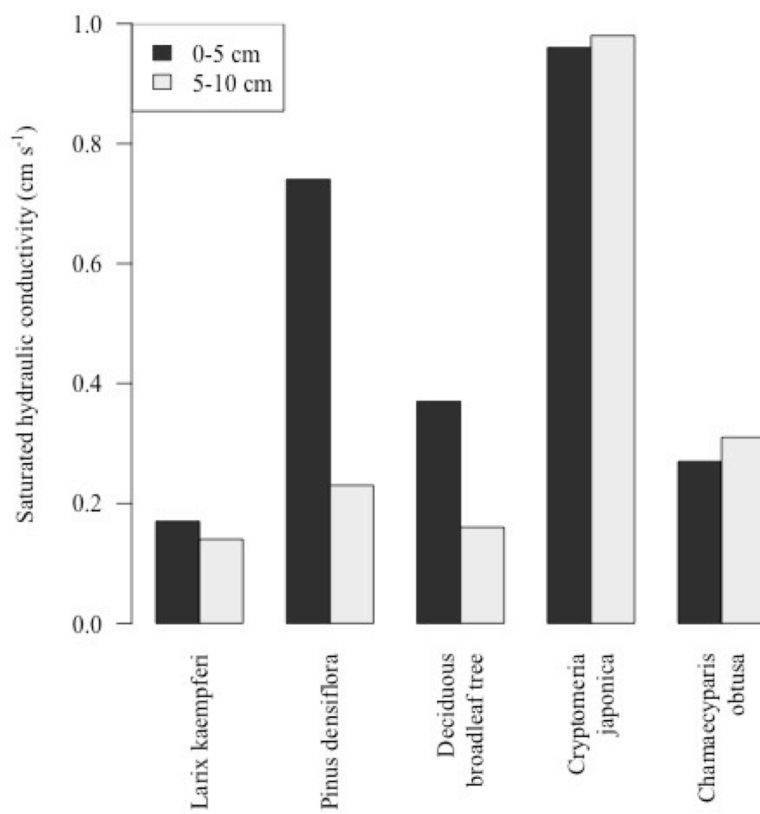


Fig. 4-3 Saturated hydraulic conductivity of each forest soil.

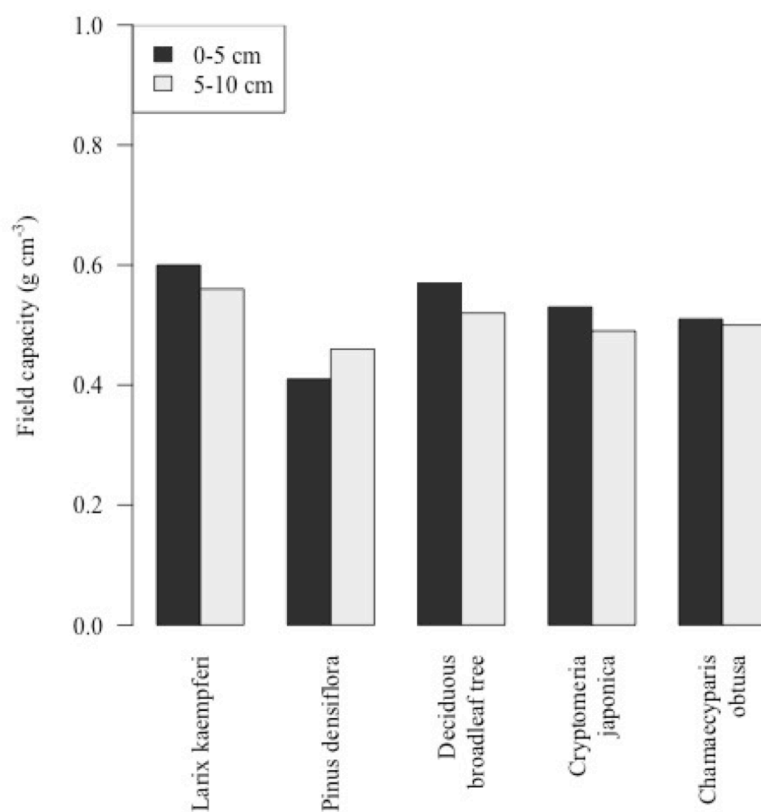


Fig. 4-4 Field capacity of each forest soil.

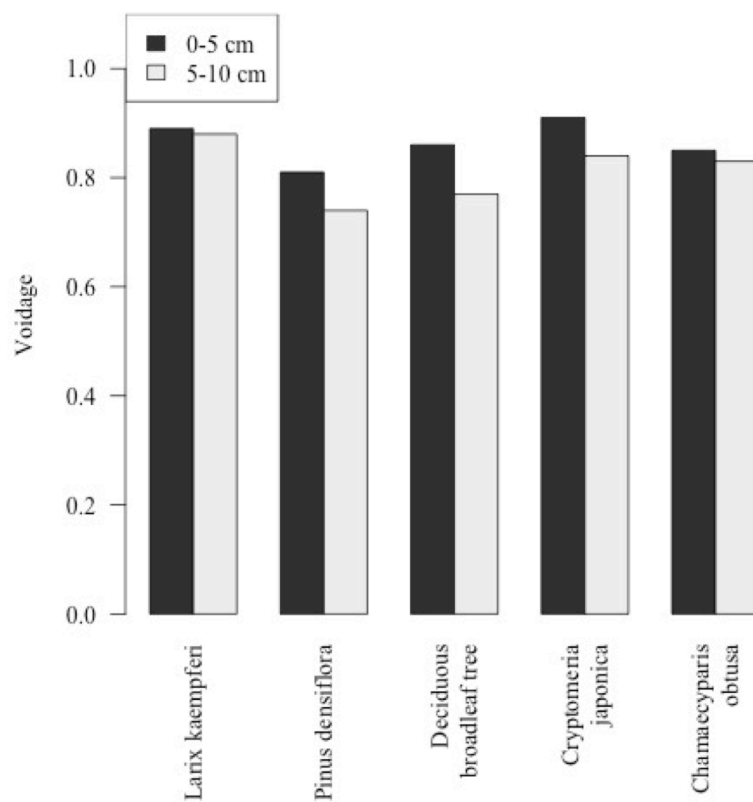


Fig. 4-5 Voidage of each forest soil.

The voidage was smaller in the 5 - 10 cm depth than in the 0 - 5 cm depth, and the values ranged between approximately 80 - 90 % in every forest.

The percolation rates in forests with different types of vegetation were previously reported as follows: 209 cc min⁻¹ (0 - 5 cm) and 128 cc min⁻¹ (20 - 25 cm) in *Cryptomeria japonica*, 149 cc min⁻¹ (0 - 5 cm) and 83 cc min⁻¹ (20 - 25 cm) in *Pinus densiflora*, 128 cc min⁻¹ (0 - 5 cm) and 81 cc min⁻¹ (20 - 25 cm) in broadleaf tree, and 91 cc min⁻¹ (0 - 5 cm) and 48 cc min⁻¹ (20 - 25 cm) in *Larix kaempferi* (Murai et al., 1975). The reported percolation rates show a similar trend as the results in this research, except for *Chamaecyparis obtusa*, which was not studied.

The porosity was also reported to be 70.8 % (0 - 5 cm) and 67.4 % (20 - 25 cm) in *Cryptomeria japonica*, 74.5 % (0 - 5 cm) and 66.9 % (20 - 25 cm) in *Pinus densiflora*, 76.9 % (0 - 5 cm) and 63.2 % (20 - 25 cm) in broadleaf tree, and 68.6 % (0 - 5 cm) and 68.2 % (20 - 25 cm) in *Larix kaempferi*. The reported results are similar to those of this research, that is, no strong difference was observed between the types of vegetation compared with the saturated hydraulic conductivity.

4.3.2 The infiltration of radioactive Cs in forest soil layers and measurement of the ignition loss

The infiltration profile of radioactive Cs in forests with different types of vegetation and β_d are shown in Fig. 4-6 to Fig. 4-10. Additional experiments with more samples are necessary to reach a comprehensive conclusion concerning the relation between the type of vegetation and the soil conditions, because in this research, only one sample was obtained from each forest.

The vertical axes indicate the mass depth (dry) (g cm⁻²) in the soil layer, and the horizontal axes indicate the concentration of radioactive Cs. The approximate curves were produced based on Equation (4) and are shown in Fig. 4-6 to Fig. 4-10. Generally, the concentration of radioactive Cs decreases exponentially according to the mass depth. The approximate curve was consistent with the monitored value in the forests with *Larix kaempferi*, Deciduous broadleaf tree and *Cryptomeria japonica*, while discrepancies were observed in the forests with *Pinus densiflora* and *Chamaecyparis obtusa*. In forests with *Pinus densiflora* and *Chamaecyparis obtusa*, the concentration of radioactive Cs did not decrease in the deep part of the soil layer but remained high compared with the prediction based on Equation (4).

Detailed analyses are necessary to elucidate the relation between the soil conditions and infiltration, though the content of organic matter, represented by the ignition loss, may influence the infiltration of radioactive Cs.

The concentration of radioactive Cs in organic matter was also monitored but is not discussed in this section, and instead, the correlation with the results of the core experiment will be analysed later.

A larger β_d indicates the deeper infiltration of radioactive Cs, and among the five forests, the deepest infiltration was observed in *Cryptomeria japonica* ($\beta_d = 2.09$ g cm⁻²) and the least in *Chamaecyparis obtusa* ($\beta_d = 1.20$ g cm⁻²).

The ignition losses in each layer in the forests with different types of vegetation are shown in Fig. 4-11, and the meaning of L, F, and H on the horizontal axis is same as that mentioned in section 4.2.

In every forest, the ignition loss was commonly more than 0.9 at the L layer and decreased with layer depth. The decreasing profile was, however, different between forests. In the forest with *Larix kaempferi*, the ignition loss tended to be large, even in the deeper layer, and was approximately 0.4 in the soil layer at a depth of 9.0 - 10.0 cm. On the other hand, in the forest with Deciduous broadleaf trees, the ignition loss was

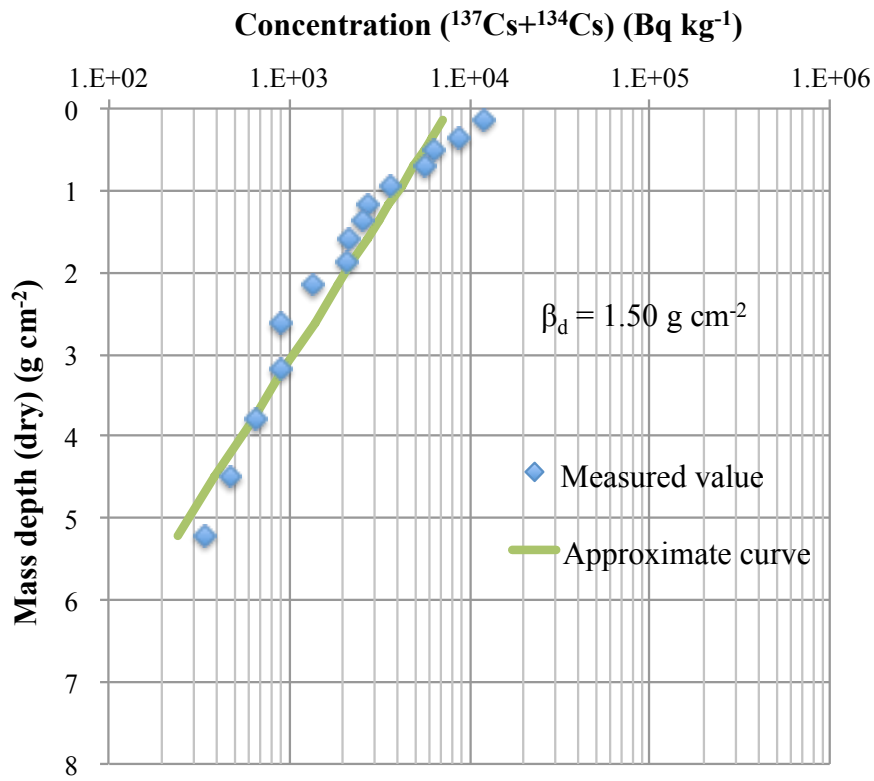


Fig. 4-6 Depth profile of radioactive Cs with mass depth (*Larix kaempferi*).

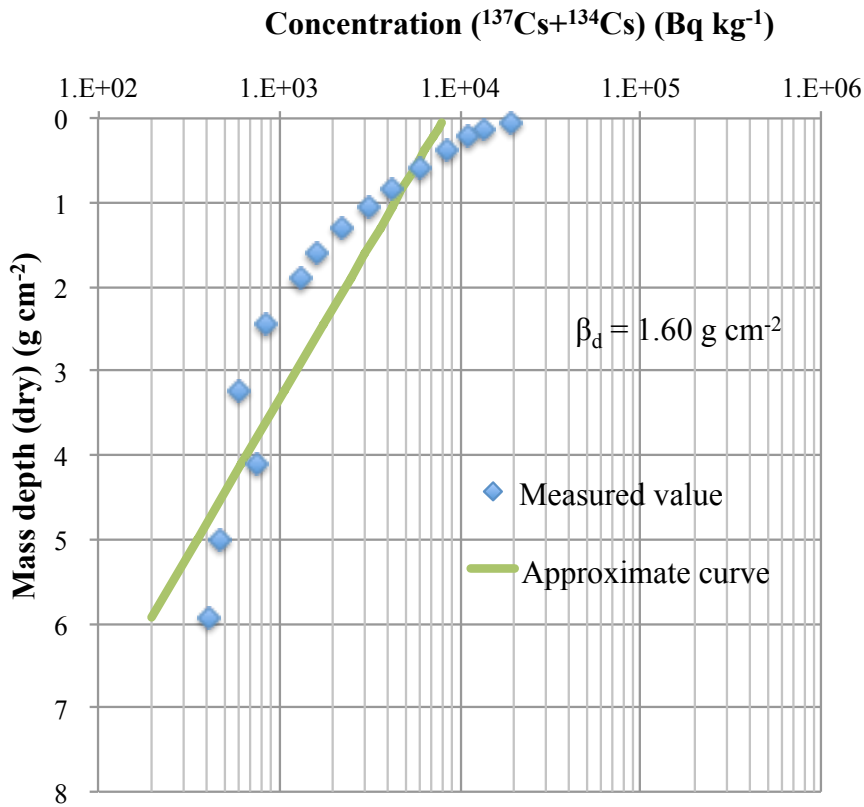


Fig. 4-7 Depth profile of radioactive Cs with mass depth (*Pinus densiflora*).

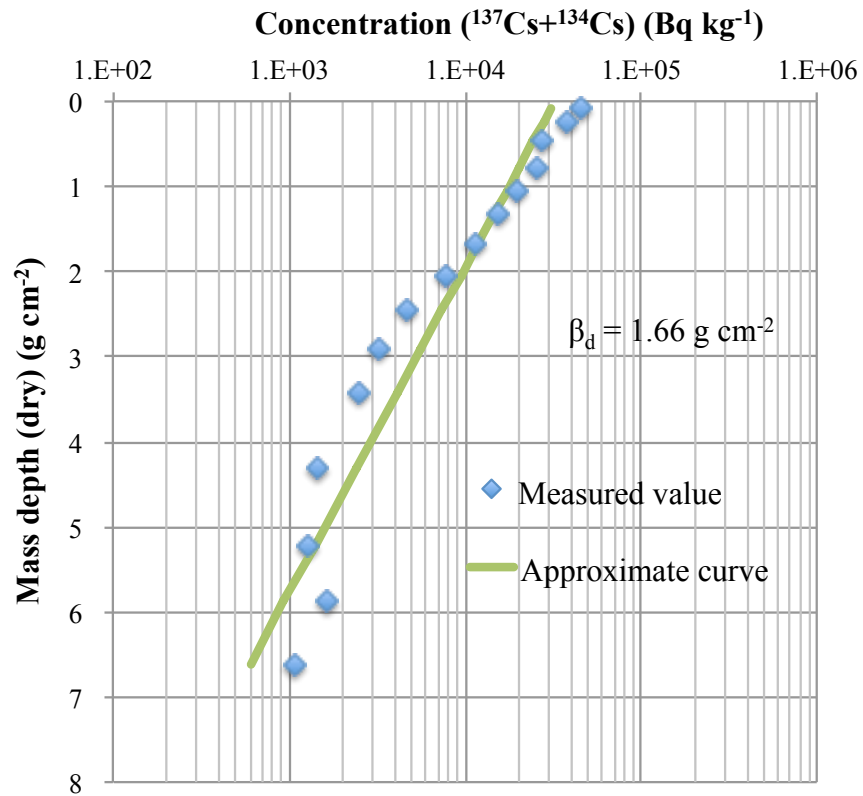


Fig. 4-8 Depth profile of radioactive Cs with mass depth (Deciduous broadleaf tree).

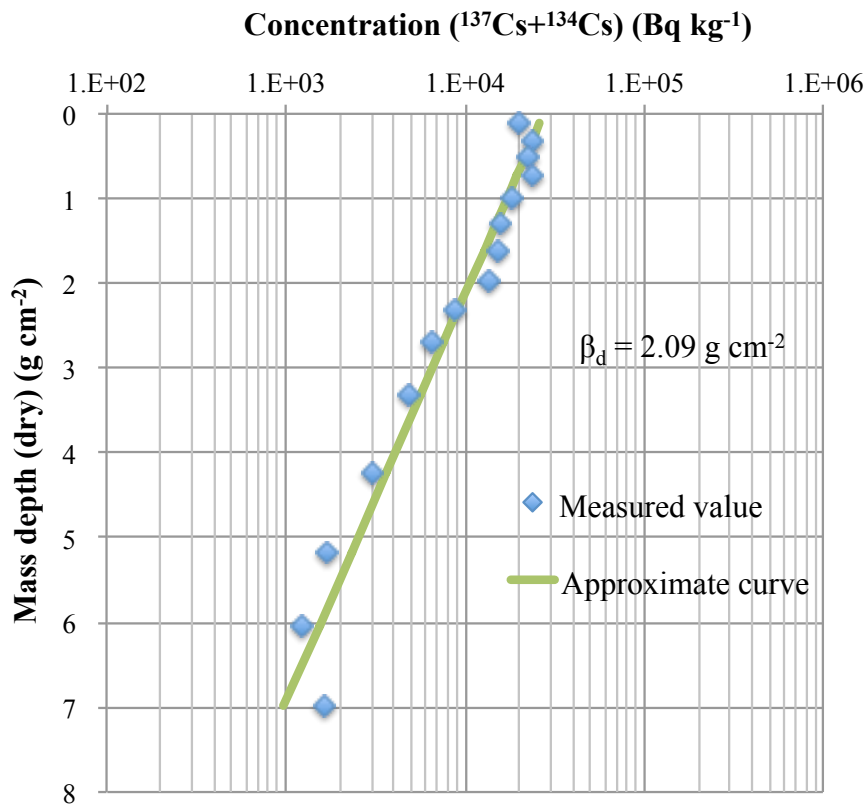


Fig. 4-9 Depth profile of radioactive Cs with mass depth (*Cryptomeria japonica*).

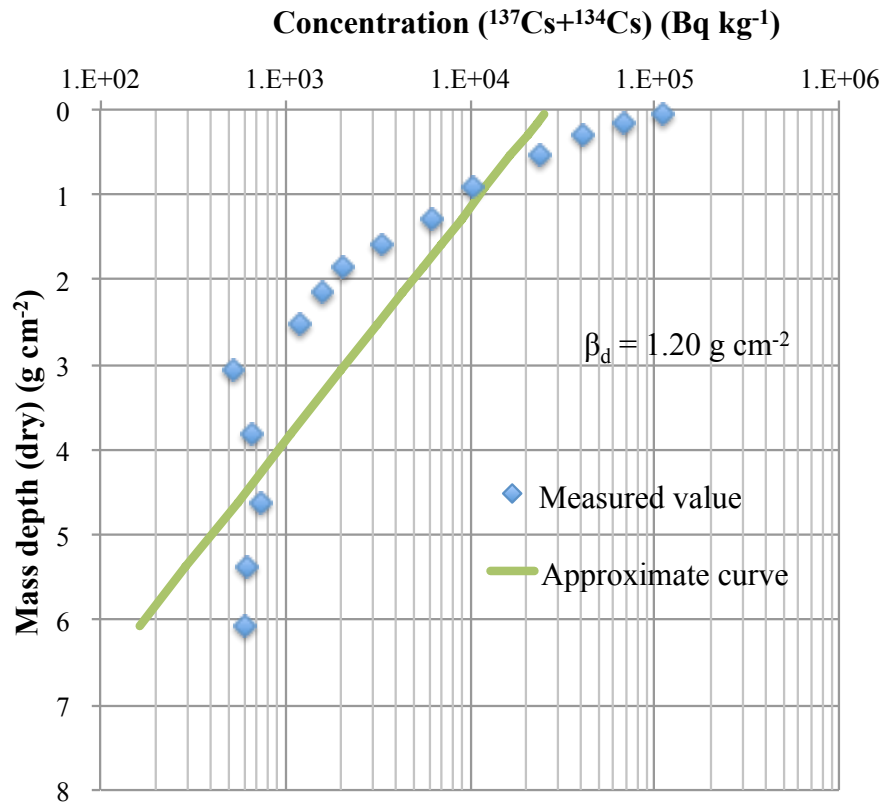


Fig. 4-10 Depth profile of radioactive Cs with mass depth (*Chamaecyparis obtusa*).

small compared to the other forests and was recorded to be approximately 0.1 at the deepest layer. The reason for these differences was thought to be attributed to the difference in water content, that is, the abundant amount of water prevented the organic matter from degrading and the amount of retained organic matter remained high (Miyoshi et al., 2010). The ignition loss measured in this research was relatively high in *Larix kaempferi* and *Chamaecyparis obtusa* and low in Deciduous broadleaf tree and *Pinus densiflora*, which nearly reflected the profile of the water content, except for *Cryptomeria japonica* (Fig. 4-11 and Fig. 4-12). In light of these results, it can be suggested that the water content may influence the ignition loss.

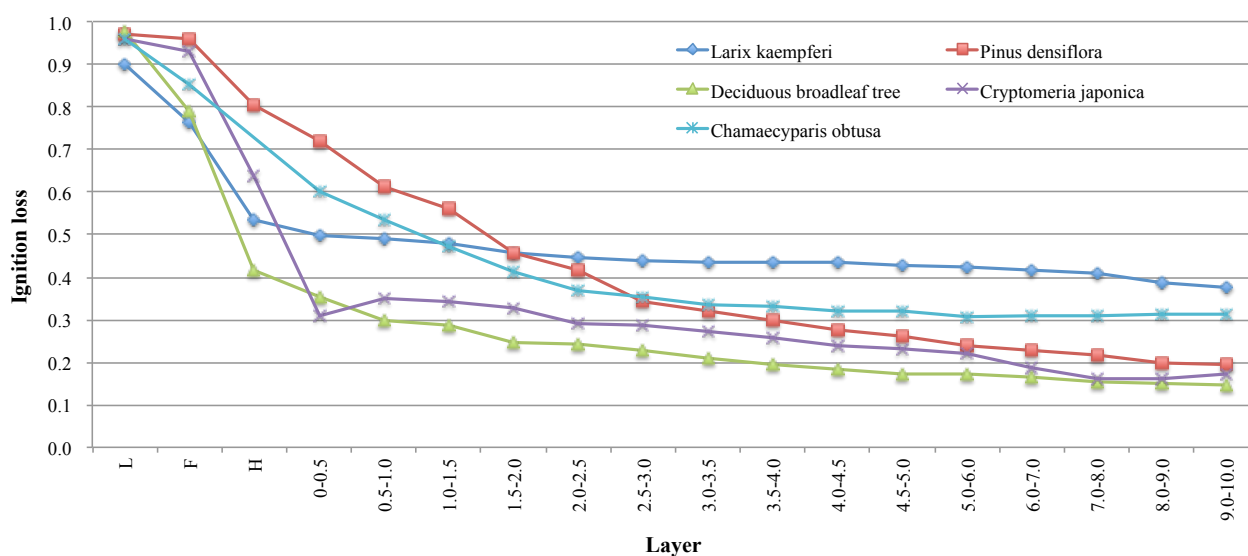


Fig. 4-11 Ignition loss in each forest with different vegetation.

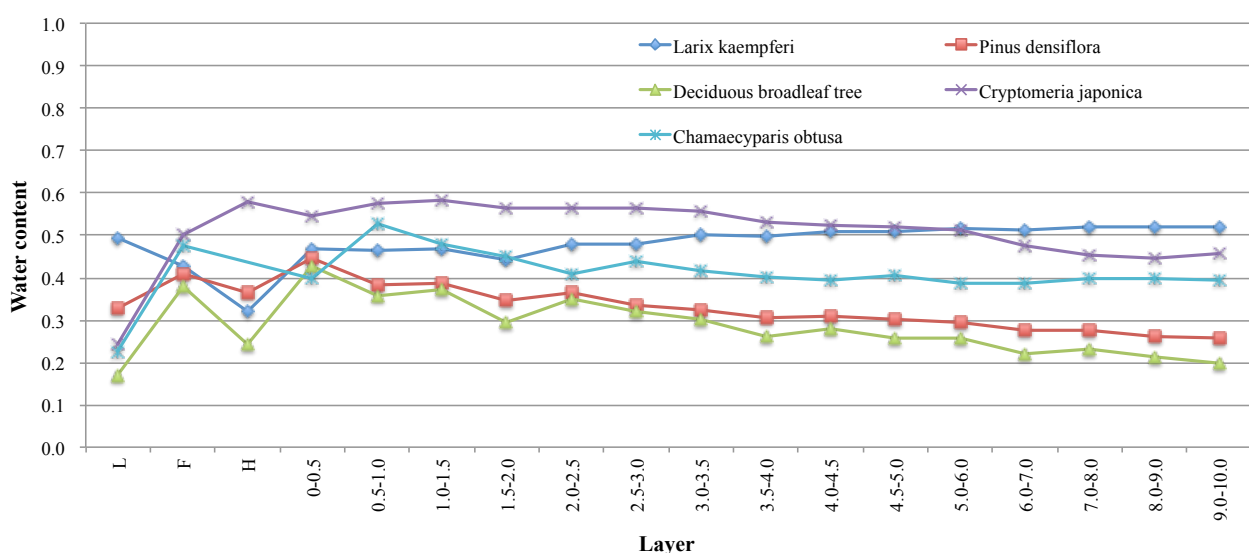


Fig. 4-12 Water content in each forest with different vegetation.

4.3.3 Measurement of the cation exchange capacity

The CEC of the upper soil layer (0 - 5 cm) was larger than that of the bottom soil layer (5 - 10 cm), except for *Larix kaempferi*, where the CEC was $49 \text{ meq (100 g)}^{-1}$ in *Chamaecyparis obtusa* (the average of the 0 - 5 cm and 5 - 10 cm layers), $48 \text{ meq (100 g)}^{-1}$ in *Larix kaempferi*, $36 \text{ meq (100 g)}^{-1}$ in *Pinus densiflora*, $31 \text{ meq (100 g)}^{-1}$ in *Cryptomeria japonica*, and $22 \text{ meq (100 g)}^{-1}$ in *Deciduous broadleaf tree* (Fig. 4-13). CEC is the index of the amount of negative charge in the soil and is also related to the fertilizer holding ability and humus content (Ogawa et al., 2004). The CEC in the soil layer (0 - 5 cm) being larger than that in the 5 - 10 cm layer can be attributed to the supply of organic matter from the upper part, including leaves and branches. It has been reported that CEC has a positive correlation with the ignition loss in river subsoil (Shimokawa et al., 1980; Hosokawa et al., 1957), and the same relation was observed in this research (Fig. 4-14), implying

that abundant organic matter contains a great deal of carboxy groups, which leads to a large CEC value.

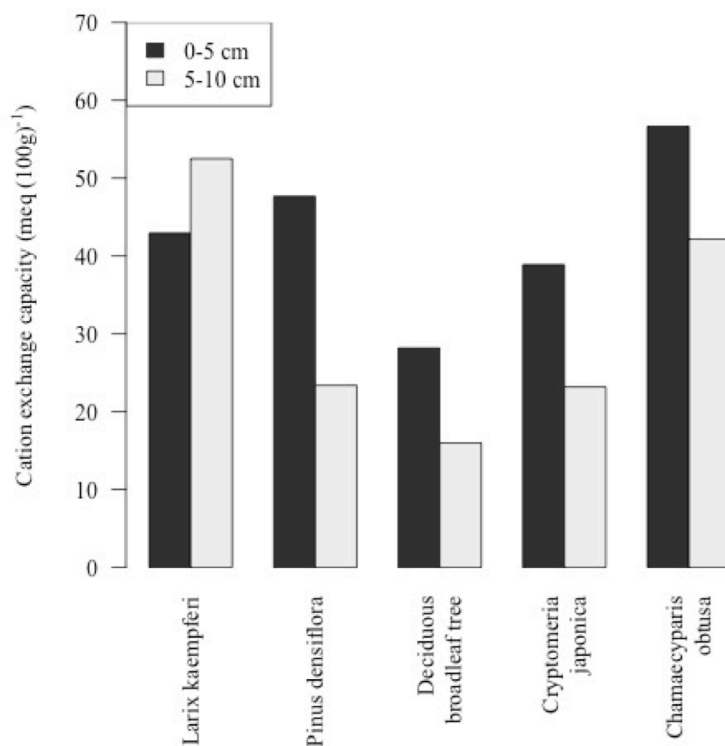


Fig. 4-13 CEC of each vegetation soil.

4.3.4 The relation between the soil condition in forests with different types of vegetation and the infiltration of radioactive Cs

The β_d value, as described in Fig. 4-6 to Fig. 4-10, had a strong correlation with the saturated hydraulic conductivity and weak correlation with the CEC. Meanwhile, specific correlation with the field capacity or voidage wasn't observed (Fig. 4-15 to Fig. 4-18).

The field capacity, which indicates the amount of water remaining after the excess has been removed by gravity, and the voidage, the proportion of porosity in a certain volume, were not related to the β_d value, while the CEC, the amount of positive ions that can be exchanged with negative ions, and the saturated hydraulic conductivity, which indicates how easily substances could penetrate downward, had some relation with the β_d value. This phenomenon implies that the dynamics of radioactive Cs is influenced by electronic adsorption and desorption with negative charges or the behaviour of water flow when radioactive Cs exists in its soluble form.

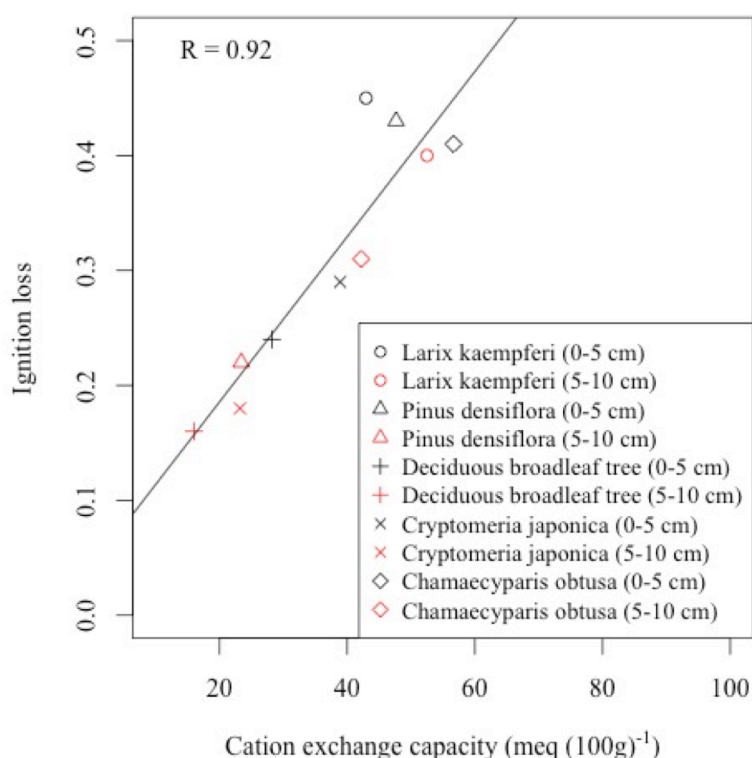


Fig. 4-14 Correlation between the CEC and ignition loss of the vegetation.

Every radioactive Cs atom released by the accident becomes Cs^+ when dissolved in water, though several reports indicate that the radioactive Cs fallout fell to the ground in a water-soluble form or as water-insoluble particles with Fe, Zn, Cs (Adachi et al., 2013), or sulfate aerosol (Kaneyasu et al., 2012).

There are three kinds of negative charges in soil: a) a negative charge with strong affinity for Ca^{2+} or other cations besides Cs^+ , in which Cs^+ , if retained at any point, is easily replaced with other cations; b) a negative charge that selectively retains Cs^+ but releases Cs^+ after competition with other cations; and c) a negative charge that retains Cs^+ , in which Cs^+ is not easily released (Yamaguchi et al., 2012).

For the negative charge c) mentioned above, Cs^+ is firmly adsorbed between the metal layers; the initial release of K^+ from the position creates room for Cs^+ , which slots into the space and recloses the layers (Yamaguchi et al., 2012). This space is called the “frayed edge site” (FES), and it is commonly known to be strongly selective for Cs^+ (Sawhney, 1972). The water-soluble radioactive Cs^+ that fell to the ground was finally adsorbed to negative charges in the soil particles. The proportion of FES occupying the whole CEC is below 2 % (Cremers et al., 1988).

Radioactive Cs has been reported to move towards the organic and soil layers from the upper parts of trees, such as branches, leaves and trenches, where it was captured through wet deposition (e.g., precipitation) or dry deposition (e.g., filter effect of the canopy), approximately 1 year after the accident (FA, 2015). It is implied from studies regarding the Chernobyl accident that radioactive Cs is circulated in the forest ecology through absorption to the root of trees, where it is then transported to other living things, and approximately 5 % of all radioactive Cs exists in above ground in the temperate zone (IAEA, 2006).

It is presumed that the newly provided amount of radioactive Cs is much smaller than that accumulated below ground. Taking into account the issues mentioned above, precipitation in the early stage post-accident

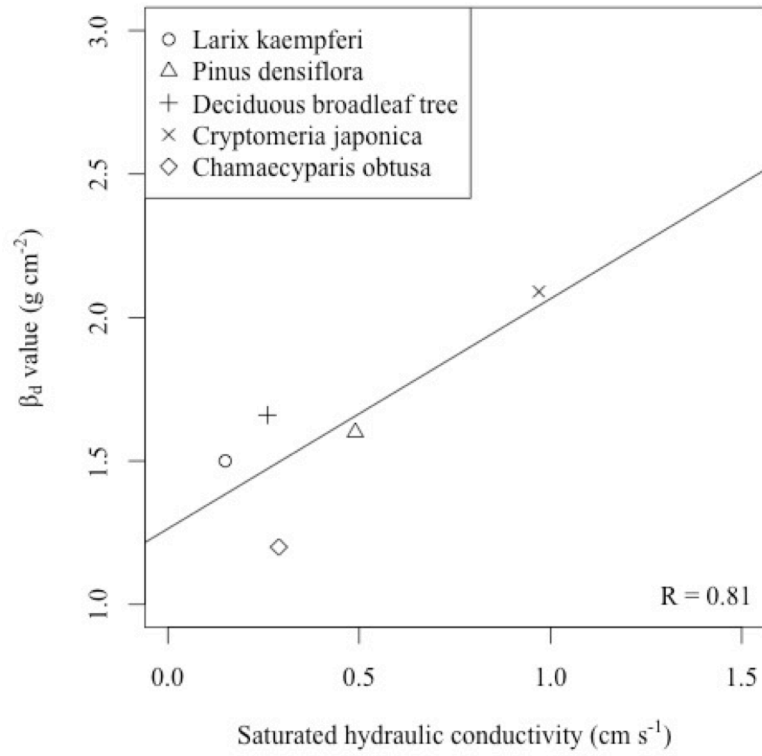


Fig. 4-15 Correlation between saturated hydraulic conductivity of each vegetation soil and the relaxation mass depth (β_d value (g cm⁻²)).

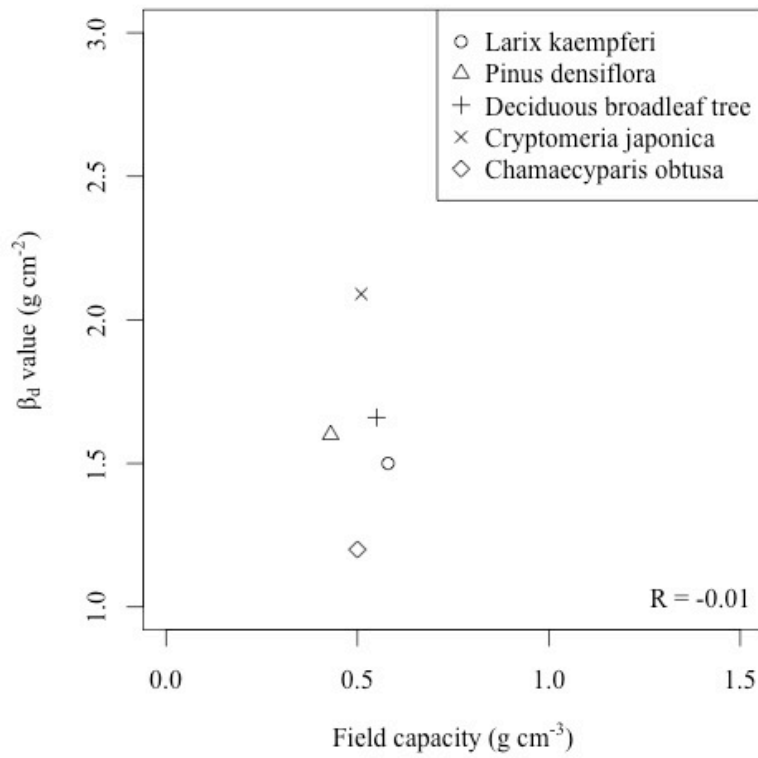


Fig. 4-16 Correlation between field capacity of each vegetation soil and the relaxation mass depth (β_d value (g cm⁻²)).

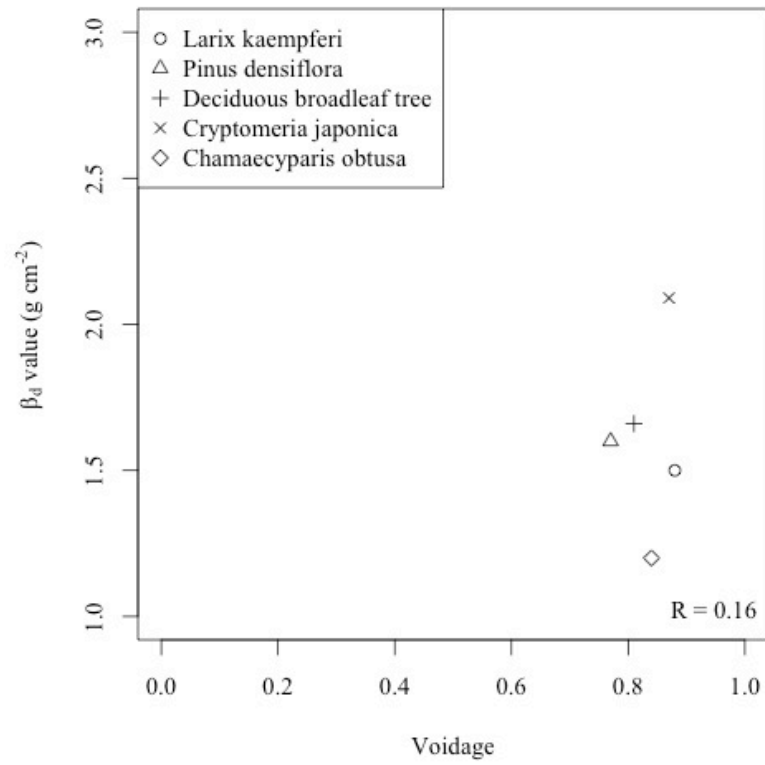


Fig. 4-17 Correlation between voidage of each vegetation soil and the relaxation mass depth (β_d value (g cm^{-2})).

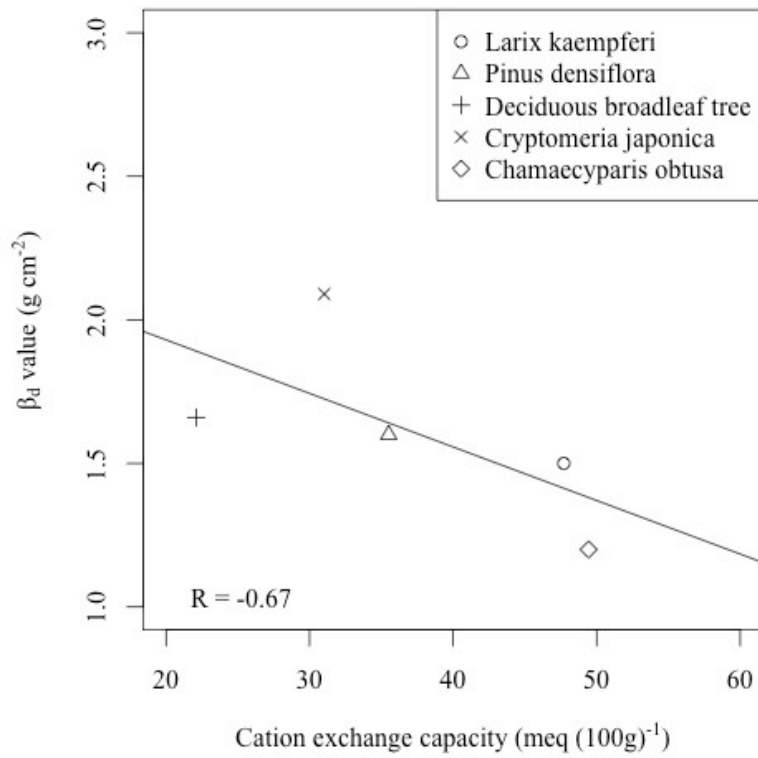


Fig. 4-18 Correlation between CEC of each vegetation soil and the relaxation mass depth (β_d value (g cm^{-2})).

would influence the depth profile of radioactive Cs, which was still in its water-soluble form before adsorption to the FES.

However, in depth analyses concerning the relation with radioactive Cs infiltration, including RIP (Radiocaesium Interception Potential), indicating the degree of adsorption of radioactive Cs to the soil and expressing the multiplication of the selectivity coefficient and the FES concentration, are necessary (Vanderhoek et al., 2012).

4.3.5 Simulation of the concentration of radioactive Cs in forests using a compartment model

For the forests with different types of vegetation, the measured value, and the calculated value derived from a compartment model are represented in Fig. 4-19 to Fig. 4-23 and Table 4-1 to Table 4-5. These diagrams and tables are results when ^{137}Cs are taken into account to eliminate the influence derived from ^{134}Cs . This analysis would be effective when the prolonged simulation is conducted, because the half-time of ^{134}Cs is very short compared with ^{137}Cs . The analyses results when only ^{134}Cs is considered are shown in Fig. 4-24 to Fig. 4-28 and Table 4-6 to Table 4-10. If the concentration of radioactive Cs is so low that the influence of background derived from nuclear test in the atmosphere can't be ignored, this method will be useful.

In every forest, the monitored value and calculated value both in the organic layer and the soil layer were highly consistent, although in the middle of the soil layer (approximately 4 - 7 cm depth in the soil layer and 2 - 5 g cm⁻² when expressed as the mass depth, including both the organic layer and the soil layer), the simulated values tended to be larger than the monitored value.

Some validations for the compartment model have been conducted. First, regarding the standard errors and mean of residuals have been calculated based on the logarithmic values of simulated concentrations and the logarithmic values of monitored concentrations. Deciduous broadleaf tree and *Cryptomeria japonica* tend to have less means of the residual errors and the standard errors compared with other types of vegetation (Table 4-21). Second, normal distributions have been validated by standard normal distribution plot analyses. Standard logarithmic distributions have been confirmed, because almost all of residual errors (logarithmic values) of radioactivity concentrations in all forests are aligned on a straight line. (Fig. 4-29 – Fig. 4-38 and Table 4-11 – Table 4-20). Finally, Bartlett-test has been conducted and homoscedasticity was not confirmed ($p < 0.05$). In the wake of Bartlett-test, Kruskal-Wallis test was subsequently conducted, because the radioactivity concentrations of ^{137}Cs were measured independently at random spatial and time design. According to the Kruskal-Wallis test, at least one of the concentrations in forests is stochastically different from the other places ($p < 0.05$).

Because radioactive Cs is firmly attached to the negative charges in the soil layer and a strong positive correlation was observed between the CEC and the ignition loss (Fig. 4-14), the depth profile of radioactive Cs was simulated by a compartment model based on the ignition loss. As a result of the analyses, it was generally possible to simulate the monitored values in each forest with different types of vegetation. It has been reported that the contribution of abundant humus to the adsorption of radioactive Cs is limited (Loftsa et al., 2002; Wauters et al., 1996). However, according to the results of this research, it is possible that the CEC impacts the infiltration of radioactive Cs when Cs exists in its soluble or ion-exchange form. It is still necessary to develop the parameter and transition coefficient in the compartment model, as well as investigate the correlation between the depth profile and the other indices describing the soil properties, including RIP mentioned above.

In addition, various soil conditions, as well as value a and value b in Equation (7) and Equation (8), shown in Table 4-21, did not show any correlation.

Continued laboratory experiments for assumption of behaviour of radioactive Cs at early stage after the accident would be crucial, as well as the evaluation of residual condition of radioactive Cs on the surface that could contribute to the realization of effect decontamination activities.

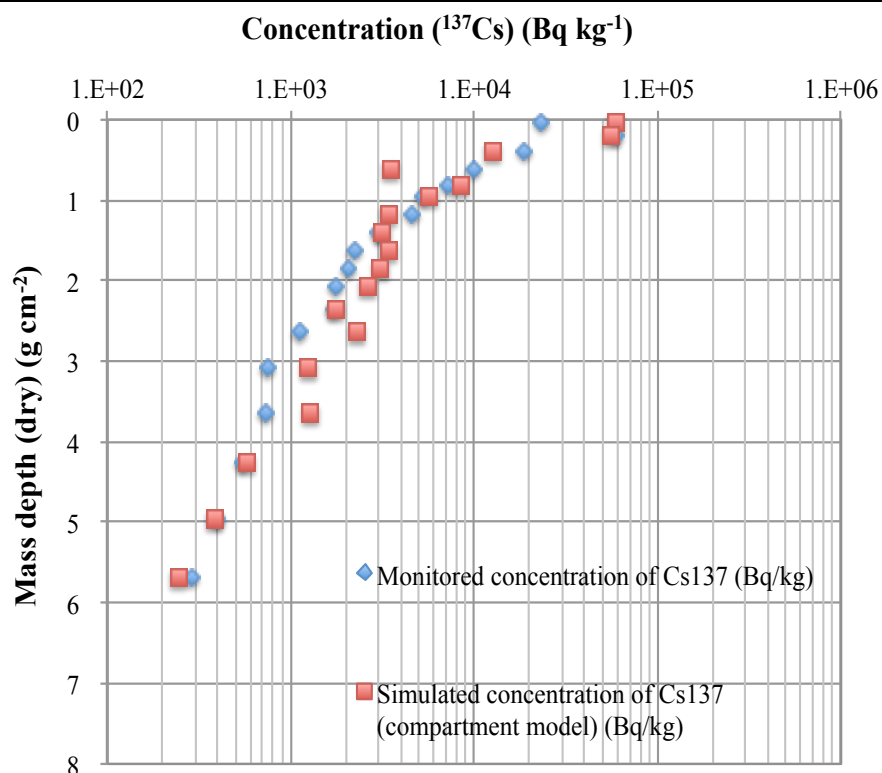
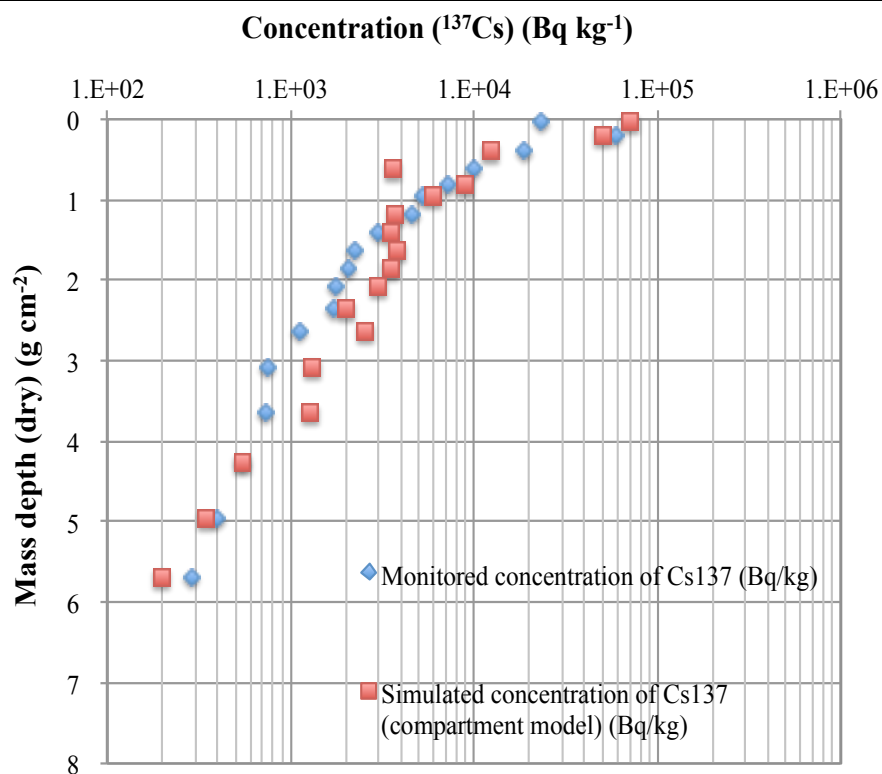


Fig. 4-19 Mass depth profile of radioactive Cs (^{137}Cs) in the forest with *Larix kaempferi*, represented by monitored values and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-1 Mass depth profile of radioactive Cs (^{137}Cs) in the forest with *Larix kaempferi*, represented by monitored values, calculated values by considering physical attenuation, and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Monitored concentration of ^{137}Cs (Oct. 2015) (Bq kg ⁻¹)	Calculated concentration of ^{137}Cs (Mar. 2011) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $P=aQ^{-1}+b$) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $P=aQ^{-b}$) (Bq kg ⁻¹)
L	0.03	0.90	23,218	25,783	70,841	59,598
F	0.19	0.76	59,303	65,856	50,533	55,074
H	0.39	0.54	18,498	20,541	12,280	12,676
0-0.5	0.61	0.50	9,860	10,950	3,586	3,515
0.5-1.0	0.82	0.49	7,214	8,011	8,814	8,492
1.0-1.5	0.96	0.48	5,266	5,848	5,956	5,639
1.5-2.0	1.17	0.46	4,585	5,091	3,703	3,389
2.0-2.5	1.41	0.45	2,976	3,305	3,525	3,170
2.5-3.0	1.64	0.44	2,257	2,506	3,810	3,372
3.0-3.5	1.85	0.43	2,077	2,306	3,477	3,036
3.5-4.0	2.07	0.43	1,752	1,945	2,949	2,599
4.0-4.5	2.35	0.43	1,698	1,886	1,990	1,778
4.5-5.0	2.62	0.43	1,112	1,235	2,531	2,302
5.0-6.0	3.08	0.43	754	837	1,315	1,255
6.0-7.0	3.65	0.42	737	818	1,275	1,271
7.0-8.0	4.26	0.41	542	602	544	576
8.0-9.0	4.97	0.39	393	436	342	383
9.0-10.0	5.68	0.38	289	321	197	242

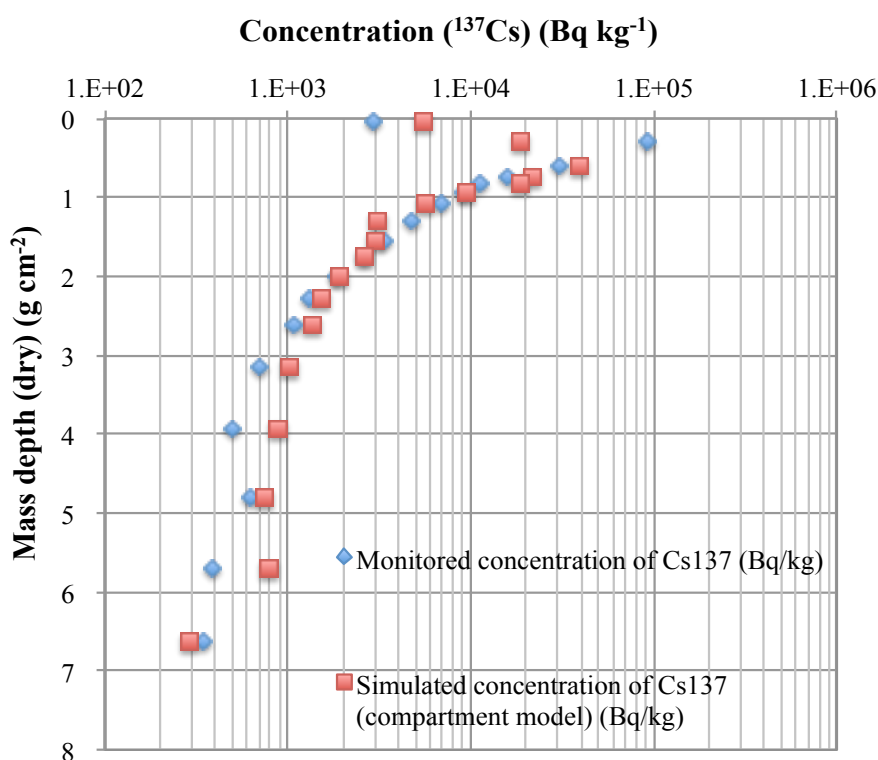
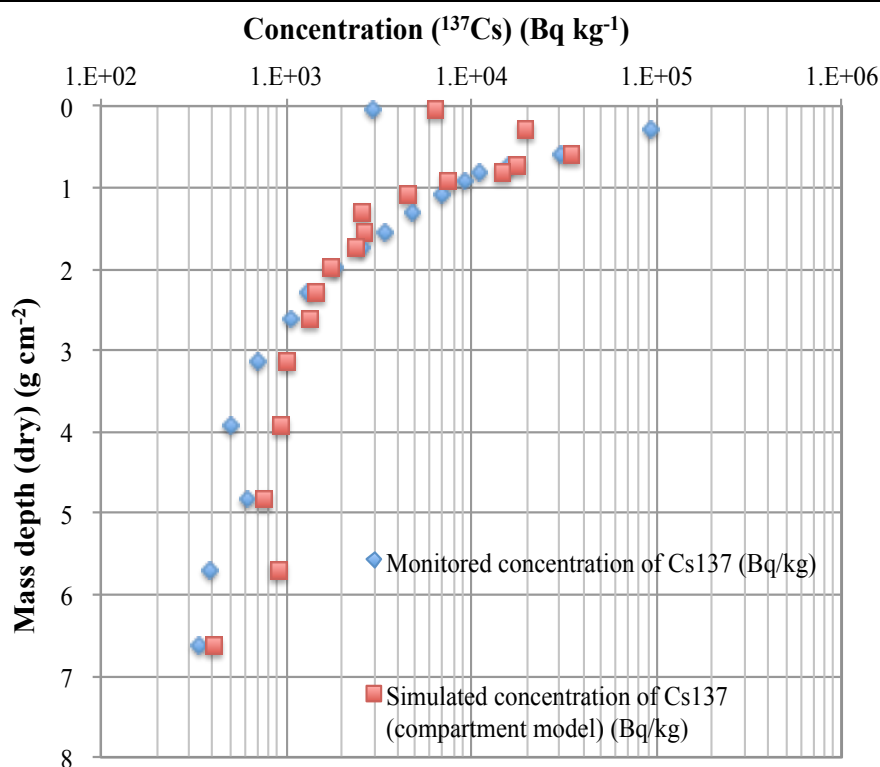


Fig. 4-20 Mass depth profile of radioactive Cs (^{137}Cs) in the forest with *Pinus densiflora*, represented by monitored values and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-2 Mass depth profile of radioactive Cs (^{137}Cs) in the forest with *Pinus densiflora*, represented by monitored values, calculated values by considering physical attenuation, and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Monitored concentration of ^{137}Cs (Oct. 2015) (Bq kg ⁻¹)	Calculated concentration of ^{137}Cs (Mar. 2011) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $P=aQ^{-1}+b$) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $P=aQ^{-b}$) (Bq kg ⁻¹)
L	0.04	0.97	2,903	3,224	6,414	5,519
F	0.29	0.96	92,685	102,926	19,493	18,534
H	0.60	0.81	30,158	33,490	34,434	39,427
0-0.5	0.74	0.72	15,748	17,488	17,743	21,488
0.5-1.0	0.82	0.61	11,092	12,318	14,805	18,548
1.0-1.5	0.92	0.56	9,121	10,129	7,538	9,500
1.5-2.0	1.08	0.46	6,989	7,761	4,604	5,688
2.0-2.5	1.30	0.42	4,834	5,368	2,570	3,118
2.5-3.0	1.54	0.34	3,415	3,792	2,620	2,992
3.0-3.5	1.75	0.32	2,609	2,897	2,370	2,649
3.5-4.0	2.00	0.30	1,842	2,045	1,761	1,921
4.0-4.5	2.29	0.28	1,312	1,456	1,439	1,527
4.5-5.0	2.61	0.26	1,074	1,193	1,352	1,365
5.0-6.0	3.14	0.24	695	772	1,016	1,030
6.0-7.0	3.94	0.23	504	560	929	878
7.0-8.0	4.82	0.22	622	690	762	750
8.0-9.0	5.69	0.20	384	426	907	792
9.0-10.0	6.63	0.19	344	382	408	292

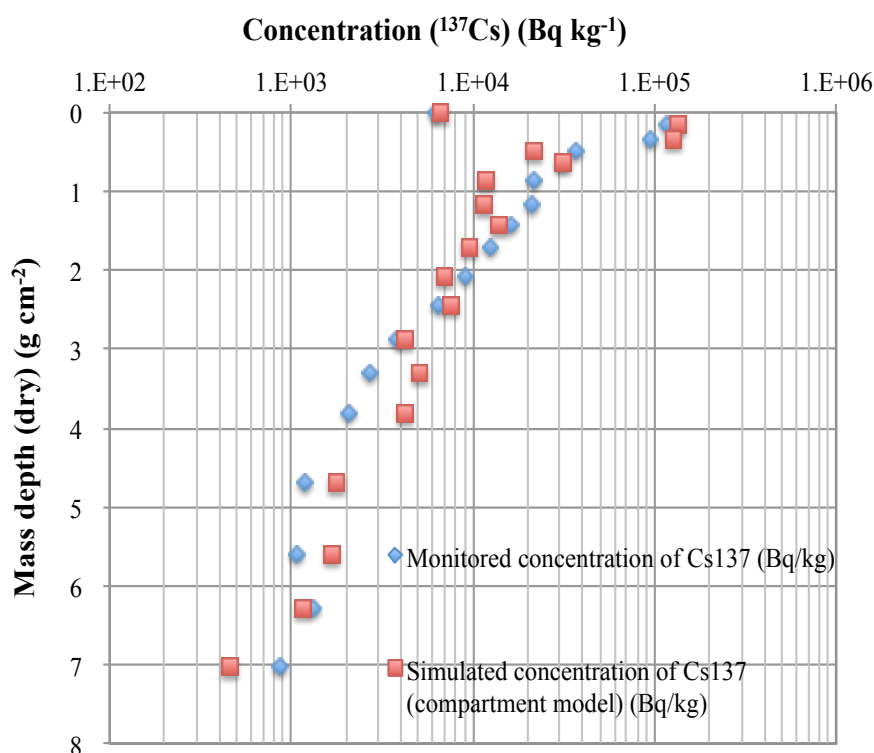
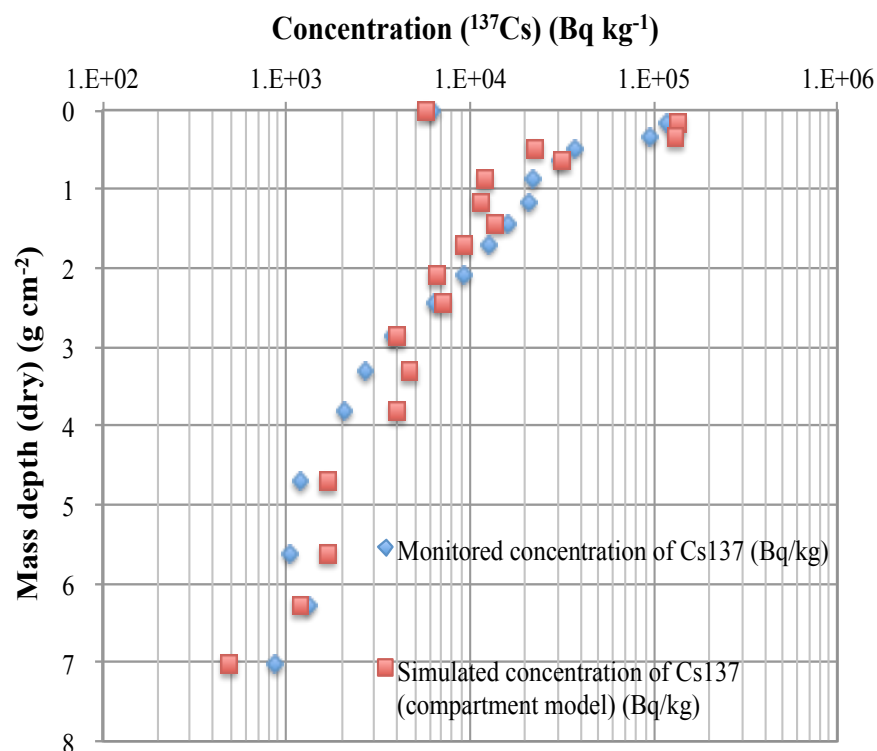


Fig. 4-21 Mass depth profile of radioactive Cs (^{137}Cs) in the forest with Deciduous broadleaf tree, represented by monitored values and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-3 Mass depth profile of radioactive Cs (^{137}Cs) in the forest with Deciduous broadleaf tree, represented by monitored values, calculated values by considering physical attenuation, and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Monitored concentration of ^{137}Cs (Oct. 2015) (Bq kg ⁻¹)	Calculated concentration of ^{137}Cs (Mar. 2011) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $P=aQ^{-1}+b$) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $P=aQ^{-b}$) (Bq kg ⁻¹)
L	0.01	0.98	6,213	6,899	5,755	6,695
F	0.16	0.79	118,386	131,466	133,073	132,102
H	0.35	0.42	95,275	105,802	132,592	127,567
0-0.5	0.49	0.35	37,041	41,134	22,591	21,951
0.5-1.0	0.64	0.30	31,094	34,529	31,565	31,141
1.0-1.5	0.86	0.29	21,903	24,323	11,945	11,870
1.5-2.0	1.17	0.25	20,976	23,294	11,473	11,647
2.0-2.5	1.44	0.24	16,136	17,919	13,591	13,929
2.5-3.0	1.72	0.23	12,584	13,975	9,249	9,572
3.0-3.5	2.08	0.21	9,192	10,208	6,658	7,004
3.5-4.0	2.44	0.19	6,363	7,066	7,025	7,515
4.0-4.5	2.86	0.18	3,801	4,221	3,959	4,266
4.5-5.0	3.30	0.17	2,673	2,968	4,692	5,080
5.0-6.0	3.83	0.17	2,065	2,294	3,942	4,189
6.0-7.0	4.71	0.16	1,179	1,310	1,682	1,756
7.0-8.0	5.61	0.16	1,059	1,176	1,683	1,695
8.0-9.0	6.27	0.15	1,323	1,470	1,196	1,164
9.0-10.0	7.01	0.14	878	975	487	455

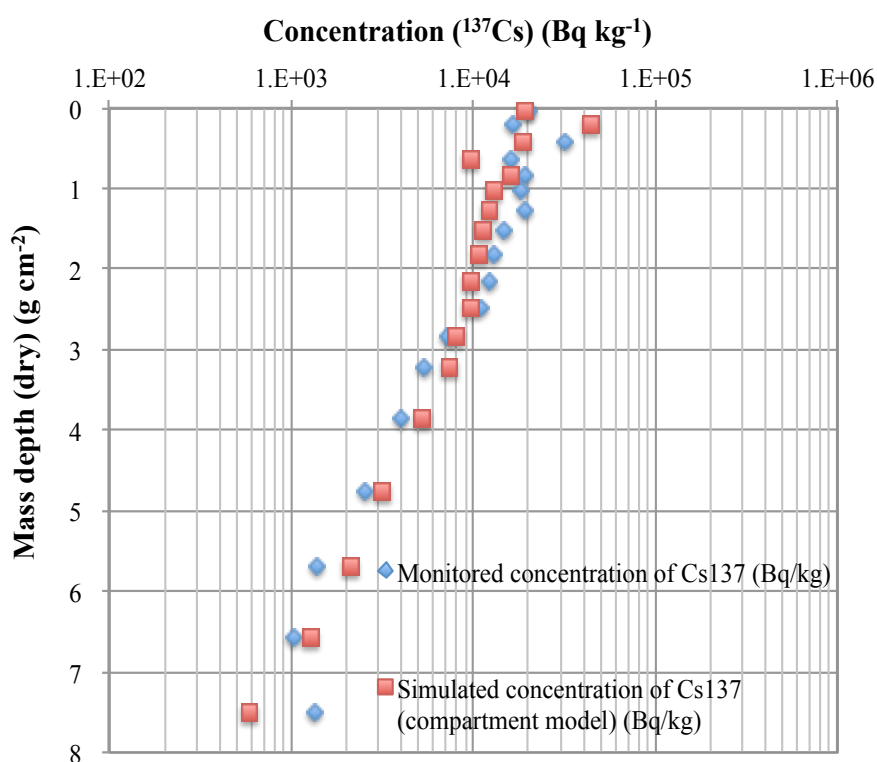
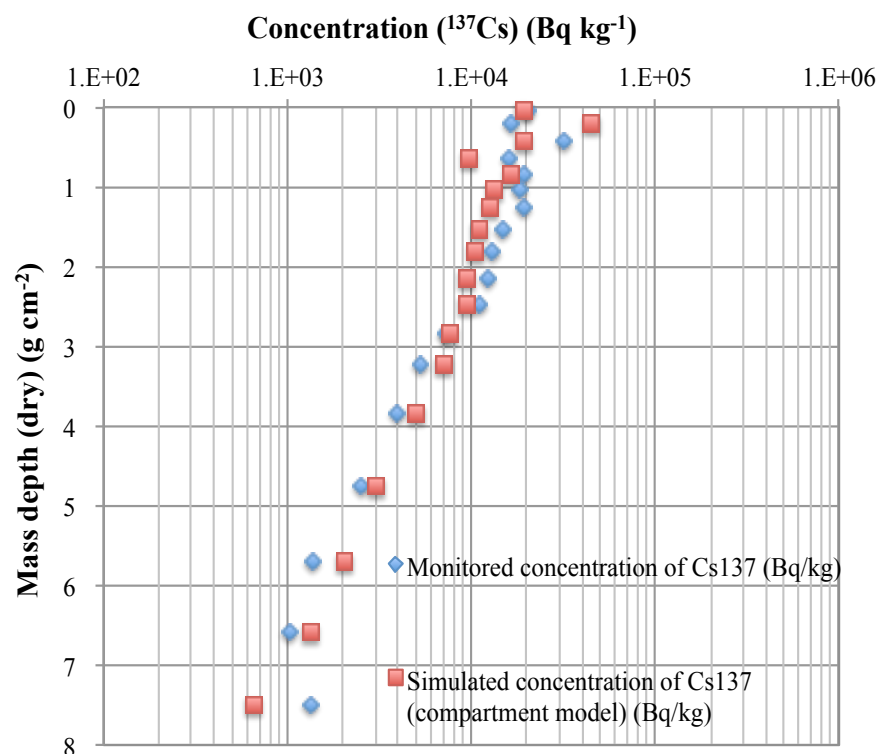


Fig. 4-22 Mass depth profile of radioactive Cs (^{137}Cs) in the forest with *Cryptomeria japonica*, represented by monitored values and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P = aQ^{-1} + b$ (top) and $P = aQ^{-b}$ (bottom).

Table 4-4 Mass depth profile of radioactive Cs (^{137}Cs) in the forest with *Cryptomeria japonica*, represented by monitored values, calculated values by considering physical attenuation, and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm^{-2})	Ignition loss	Monitored concentration of ^{137}Cs (Oct. 2015) (Bq kg^{-1})	Calculated concentration of ^{137}Cs (Mar. 2011) (Bq kg^{-1})	Simulated concentration of ^{137}Cs (Compartment model: $P=aQ^{-1}+b$) (Bq kg^{-1})	Simulated concentration of ^{137}Cs (Compartment model: $P=aQ^{-b}$) (Bq kg^{-1})
L	0.04	0.96	20,257	22,496	19,192	19,140
F	0.20	0.93	16,294	18,095	44,543	44,321
H	0.43	0.64	31,472	34,949	19,267	18,699
0-0.5	0.64	0.31	16,120	17,901	9,755	9,656
0.5-1.0	0.84	0.35	19,274	21,404	16,482	16,150
1.0-1.5	1.03	0.34	18,317	20,341	13,246	13,012
1.5-2.0	1.26	0.33	19,318	21,453	12,470	12,293
2.0-2.5	1.52	0.29	14,737	16,365	11,138	11,139
2.5-3.0	1.82	0.29	12,851	14,271	10,560	10,587
3.0-3.5	2.14	0.27	12,320	13,681	9,559	9,685
3.5-4.0	2.48	0.26	11,066	12,288	9,421	9,610
4.0-4.5	2.84	0.24	7,190	7,985	7,726	7,972
4.5-5.0	3.23	0.23	5,343	5,933	7,057	7,315
5.0-6.0	3.85	0.22	3,967	4,405	5,071	5,232
6.0-7.0	4.75	0.19	2,515	2,793	3,037	3,133
7.0-8.0	5.69	0.16	1,371	1,522	2,052	2,094
8.0-9.0	6.57	0.16	1,018	1,130	1,327	1,275
9.0-10.0	7.50	0.17	1,333	1,481	659	588

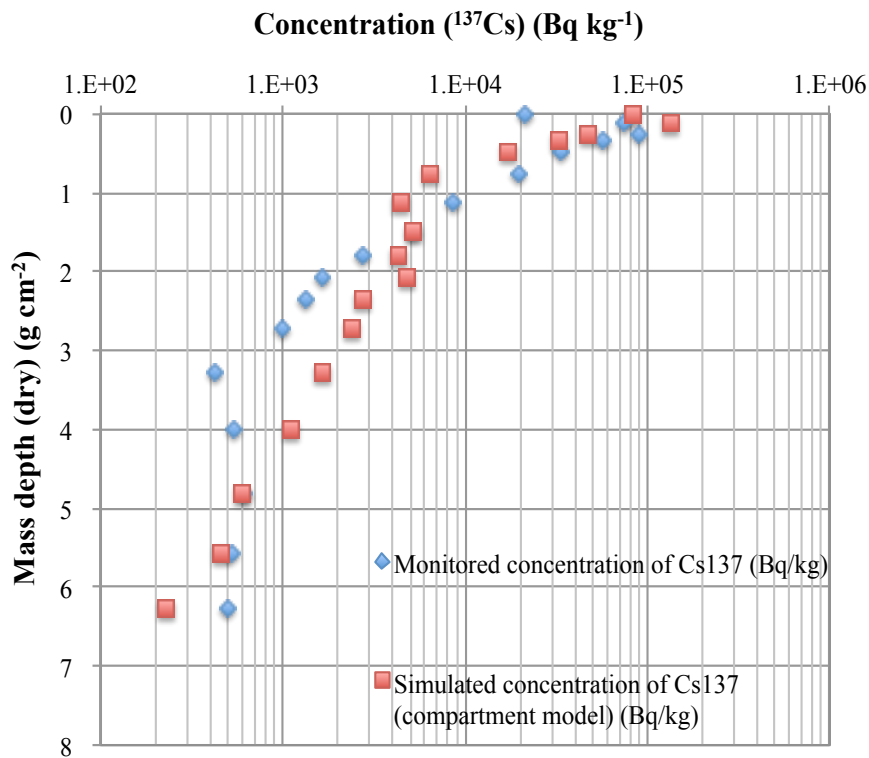
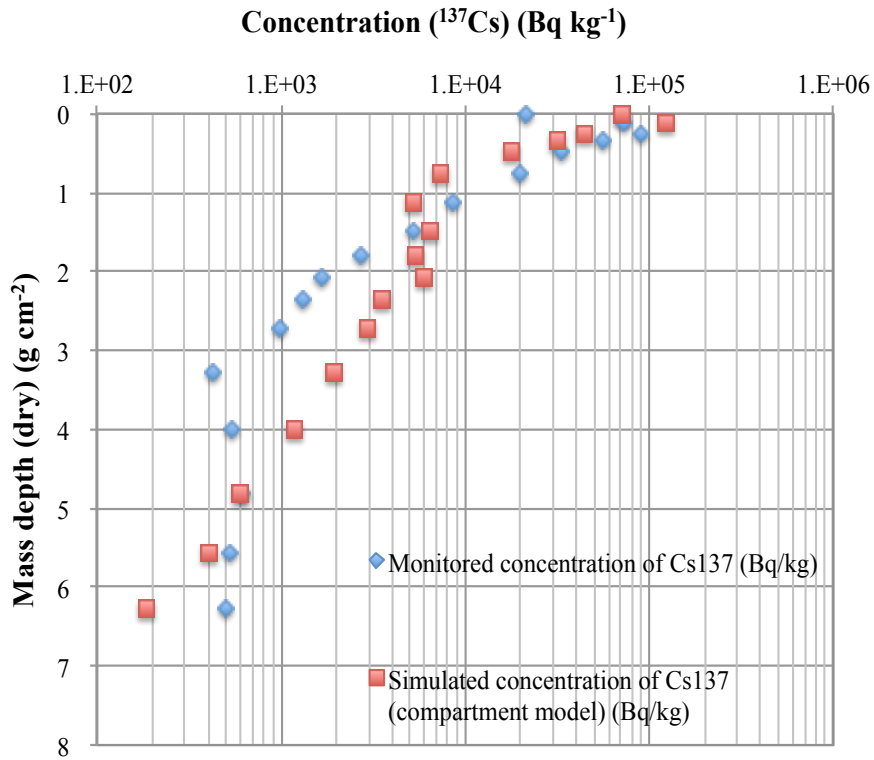


Fig. 4-23 Mass depth profile of radioactive Cs (^{137}Cs) in the forest with *Chamaecyparis obtusa*, represented by monitored values and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-5 Mass depth profile of radioactive Cs (^{137}Cs) in the forest with *Chamaecyparis obtusa*, represented by monitored values, calculated values by considering physical attenuation, and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Monitored concentration of ^{137}Cs (Oct. 2015) (Bq kg ⁻¹)	Calculated concentration of ^{137}Cs (Mar. 2011) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-1}+b)$ (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-b})$ (Bq kg ⁻¹)
L	0.02	0.96	21,493	23,868	70,848	82,364
F	0.12	0.85	73,719	81,864	123,945	133,854
H	-	-	-	-	-	-
0-0.5	0.25	0.60	89,413	99,292	44,887	47,747
0.5-1.0	0.35	0.54	56,444	62,681	31,837	32,316
1.0-1.5	0.49	0.47	33,379	37,067	17,910	17,028
1.5-2.0	0.75	0.41	19,518	21,675	7,299	6,472
2.0-2.5	1.13	0.37	8,595	9,545	5,261	4,412
2.5-3.0	1.48	0.35	5,184	5,756	6,365	5,171
3.0-3.5	1.78	0.34	2,717	3,017	5,394	4,323
3.5-4.0	2.06	0.33	1,670	1,854	5,993	4,767
4.0-4.5	2.36	0.32	1,323	1,469	3,490	2,778
4.5-5.0	2.72	0.32	989	1,098	2,971	2,420
5.0-6.0	3.27	0.31	430	478	1,946	1,662
6.0-7.0	4.01	0.31	544	604	1,181	1,094
7.0-8.0	4.81	0.31	609	676	597	608
8.0-9.0	5.57	0.31	520	578	407	459
9.0-10.0	6.28	0.31	501	556	183	228

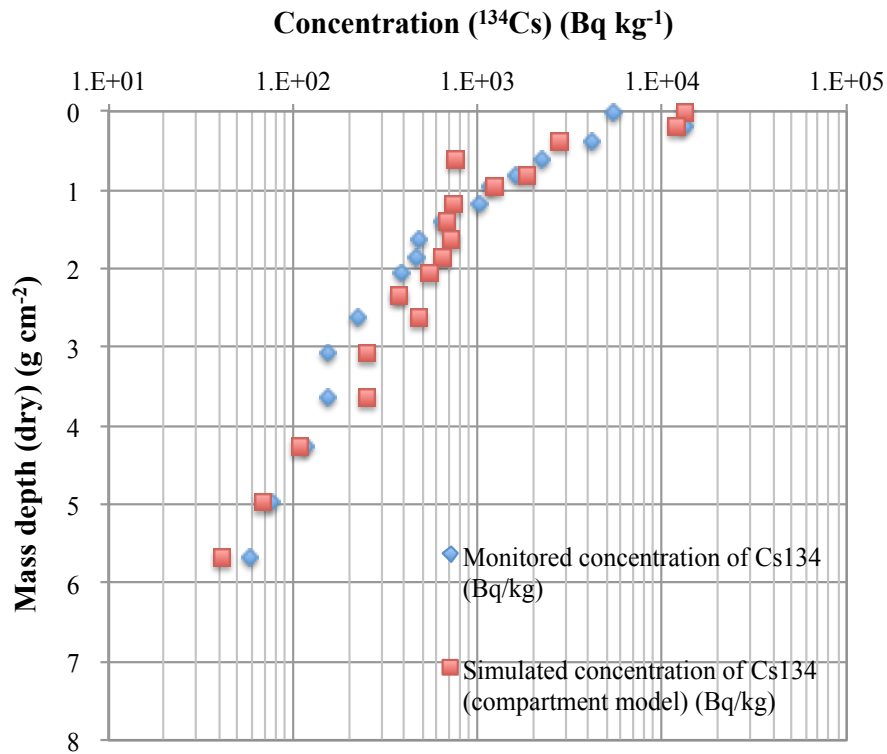
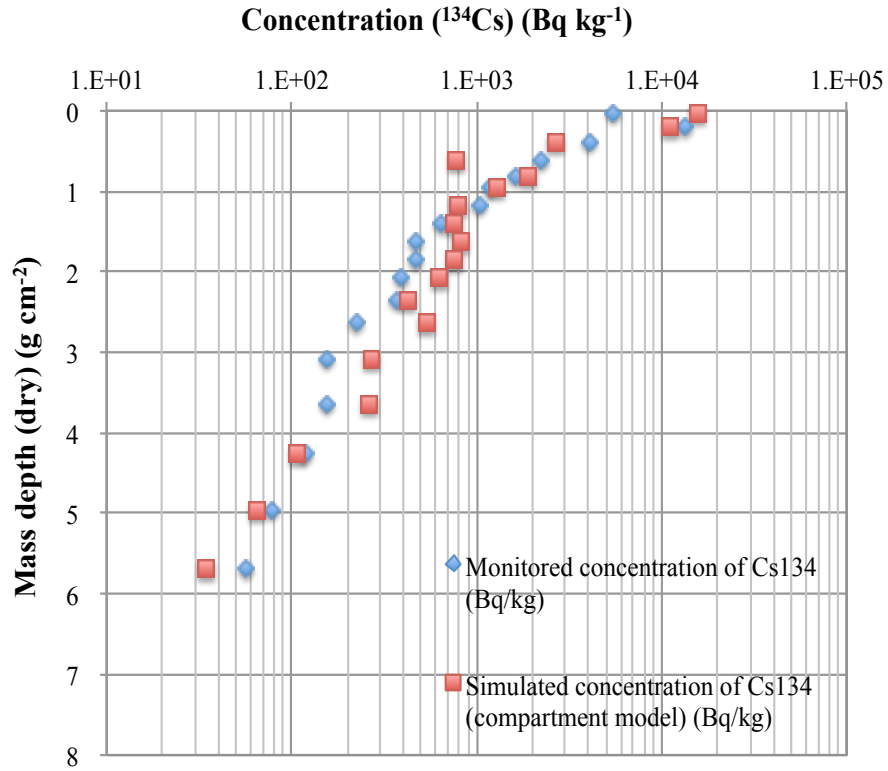


Fig. 4-24 Mass depth profile of radioactive Cs (^{134}Cs) in the forest with *Larix kaempferi*, represented by monitored values and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-6 Mass depth profile of radioactive Cs (^{134}Cs) in the forest with *Larix kaempferi*, represented by monitored values, calculated values by considering physical attenuation, and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Monitored concentration of ^{134}Cs (Oct. 2015) (Bq kg ⁻¹)	Calculated concentration of ^{134}Cs (Mar. 2011) (Bq kg ⁻¹)	Simulated concentration of ^{134}Cs (Compartment model: $P=aQ^{-1}+b$) (Bq kg ⁻¹)	Simulated concentration of ^{134}Cs (Compartment model: $P=aQ^{-b}$) (Bq kg ⁻¹)
L	0.03	0.90	5,502	25,344	15,588	13,352
F	0.19	0.76	13,450	61,961	11,029	12,050
H	0.39	0.54	4,120	18,978	2,679	2,776
0-0.5	0.61	0.50	2,211	10,186	778	766
0.5-1.0	0.82	0.49	1,627	7,493	1,917	1,852
1.0-1.5	0.96	0.48	1,185	5,458	1,292	1,225
1.5-2.0	1.17	0.46	1,034	4,765	800	732
2.0-2.5	1.41	0.45	650	2,993	760	682
2.5-3.0	1.64	0.44	474	2,183	819	723
3.0-3.5	1.85	0.43	464	2,138	745	647
3.5-4.0	2.07	0.43	388	1,786	629	550
4.0-4.5	2.35	0.43	371	1,711	421	372
4.5-5.0	2.62	0.43	226	1,040	533	479
5.0-6.0	3.08	0.43	154	711	272	254
6.0-7.0	3.65	0.42	153	705	260	252
7.0-8.0	4.26	0.41	118	545	107	109
8.0-9.0	4.97	0.39	77	355	64	69
9.0-10.0	5.68	0.38	58	265	35	41

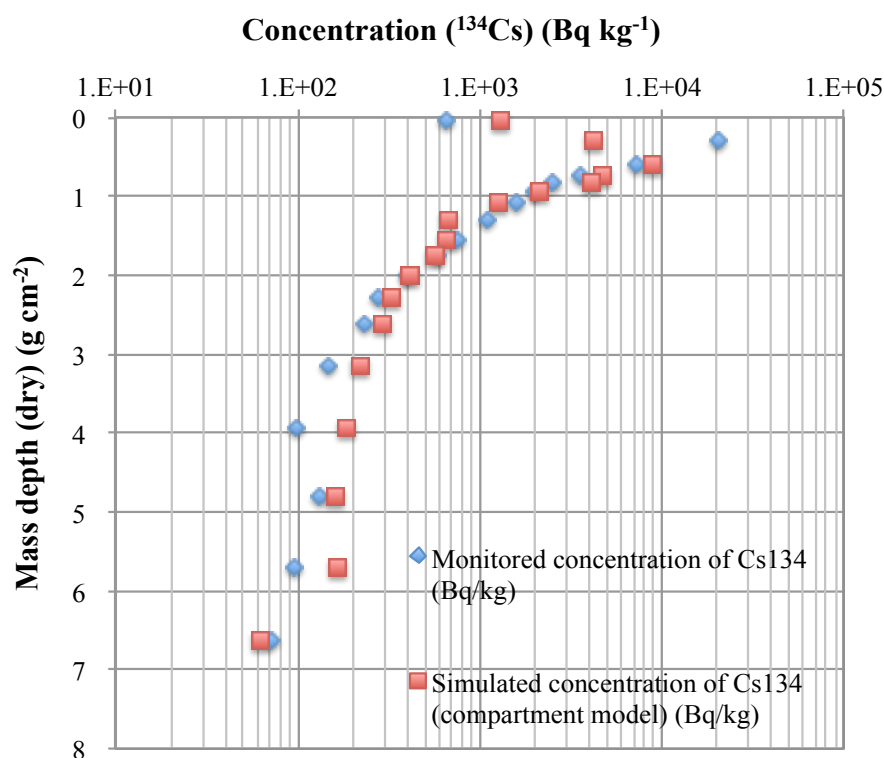
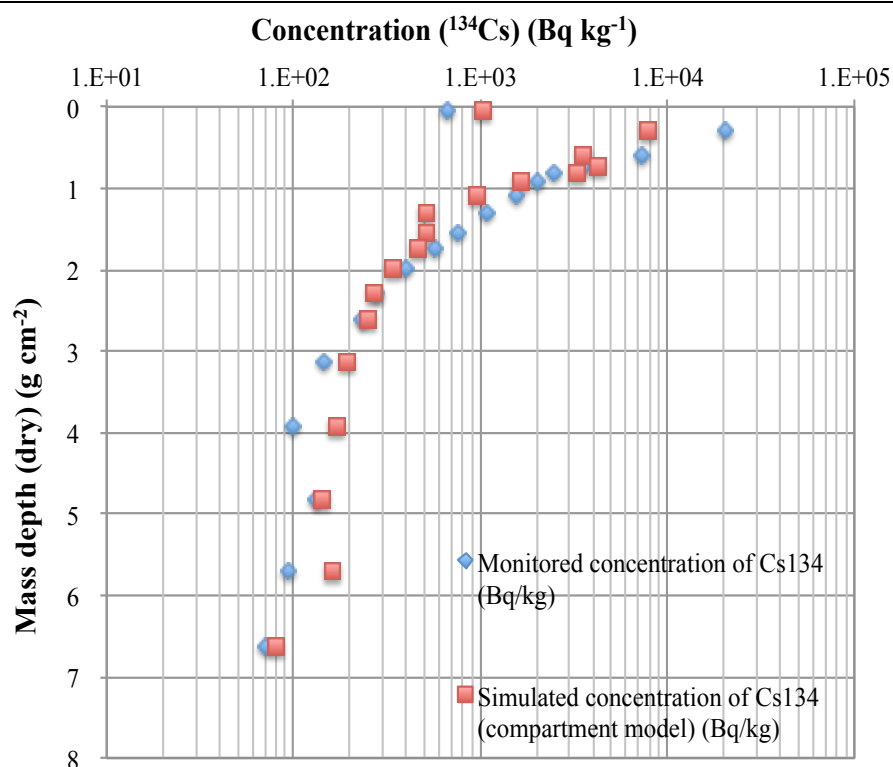


Fig. 4-25 Mass depth profile of radioactive Cs (^{134}Cs) in the forest with *Pinus densiflora*, represented by monitored values and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-7 Mass depth profile of radioactive Cs (^{134}Cs) in the forest with *Pinus densiflora*, represented by monitored values, calculated values by considering physical attenuation, and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Monitored concentration of ^{134}Cs (Oct. 2015) (Bq kg ⁻¹)	Calculated concentration of ^{134}Cs (Mar. 2011) (Bq kg ⁻¹)	Simulated concentration of ^{134}Cs (Compartment model: $P=aQ^{-1}+b$) (Bq kg ⁻¹)	Simulated concentration of ^{134}Cs (Compartment model: $P=aQ^{-b}$) (Bq kg ⁻¹)
L	0.04	0.97	657	3,028	1,029	1,313
F	0.29	0.96	20,703	95,368	7,937	4,205
H	0.60	0.81	7,278	33,526	3,545	8,817
0-0.5	0.74	0.72	3,539	16,300	4,219	4,785
0.5-1.0	0.82	0.61	2,488	11,461	3,275	4,113
1.0-1.5	0.92	0.56	2,010	9,259	1,618	2,098
1.5-2.0	1.08	0.46	1,570	7,234	943	1,249
2.0-2.5	1.30	0.42	1,087	5,007	516	681
2.5-3.0	1.54	0.34	753	3,470	512	651
3.0-3.5	1.75	0.32	575	2,649	459	575
3.5-4.0	2.00	0.30	399	1,839	337	415
4.0-4.5	2.29	0.28	280	1,289	273	328
4.5-5.0	2.61	0.26	234	1,078	252	292
5.0-6.0	3.14	0.24	147	679	191	219
6.0-7.0	3.94	0.23	98	452	169	185
7.0-8.0	4.82	0.22	130	599	142	158
8.0-9.0	5.69	0.20	94	434	160	165
9.0-10.0	6.63	0.19	72	330	80	62

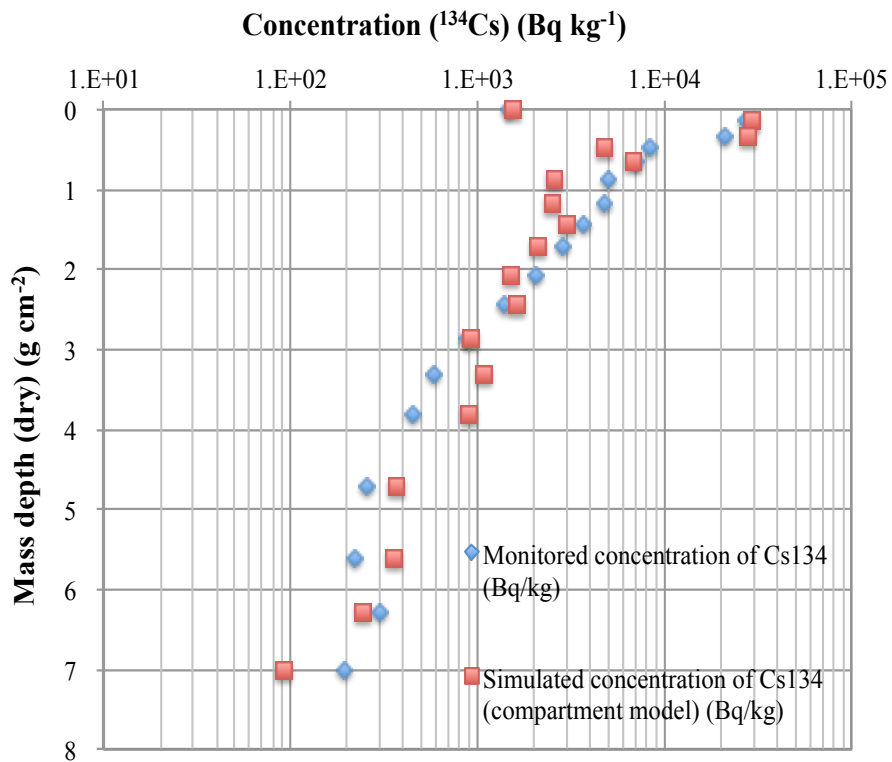
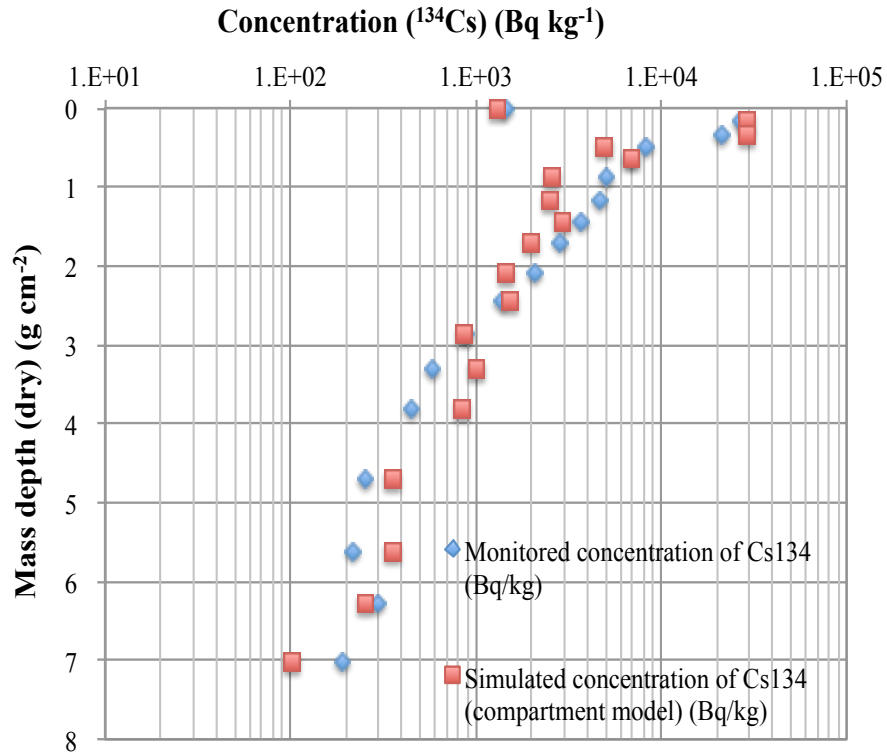


Fig. 4-26 Mass depth profile of radioactive Cs (^{134}Cs) in the forest with Deciduous broadleaf tree, represented by monitored values and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-8 Mass depth profile of radioactive Cs (^{134}Cs) in the forest with Deciduous broadleaf tree, represented by monitored values, calculated values by considering physical attenuation, and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm^{-2})	Ignition loss	Monitored concentration of ^{134}Cs (Oct. 2015) (Bq kg^{-1})	Calculated concentration of ^{134}Cs (Mar. 2011) (Bq kg^{-1})	Simulated concentration of ^{134}Cs (Compartment model: $P=aQ^{-1}+b$) (Bq kg^{-1})	Simulated concentration of ^{134}Cs (Compartment model: $P=aQ^{-b}$) (Bq kg^{-1})
L	0.01	0.98	1,458	6,717	1,303	1,537
F	0.16	0.79	27,069	124,697	29,254	29,111
H	0.35	0.42	21,188	97,602	29,022	27,999
0-0.5	0.49	0.35	8,373	38,571	4,935	4,808
0.5-1.0	0.64	0.30	7,011	32,296	6,889	6,814
1.0-1.5	0.86	0.29	5,016	23,108	2,602	2,591
1.5-2.0	1.17	0.25	4,725	21,765	2,497	2,538
2.0-2.5	1.44	0.24	3,686	16,978	2,957	3,032
2.5-3.0	1.72	0.23	2,825	13,012	2,009	2,079
3.0-3.5	2.08	0.21	2,073	9,551	1,444	1,517
3.5-4.0	2.44	0.19	1,396	6,429	1,523	1,624
4.0-4.5	2.86	0.18	882	4,064	856	918
4.5-5.0	3.30	0.17	582	2,683	1,015	1,092
5.0-6.0	3.83	0.17	450	2,072	852	896
6.0-7.0	4.71	0.16	255	1,177	361	371
7.0-8.0	5.61	0.16	220	1,013	361	357
8.0-9.0	6.27	0.15	297	1,369	255	242
9.0-10.0	7.01	0.14	192	882	101	91

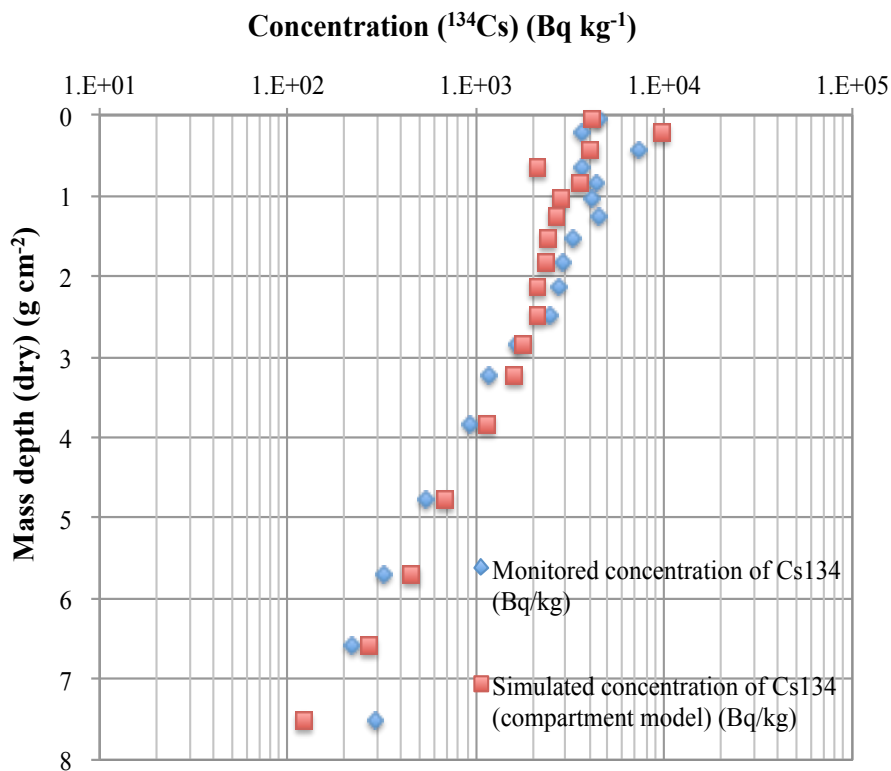
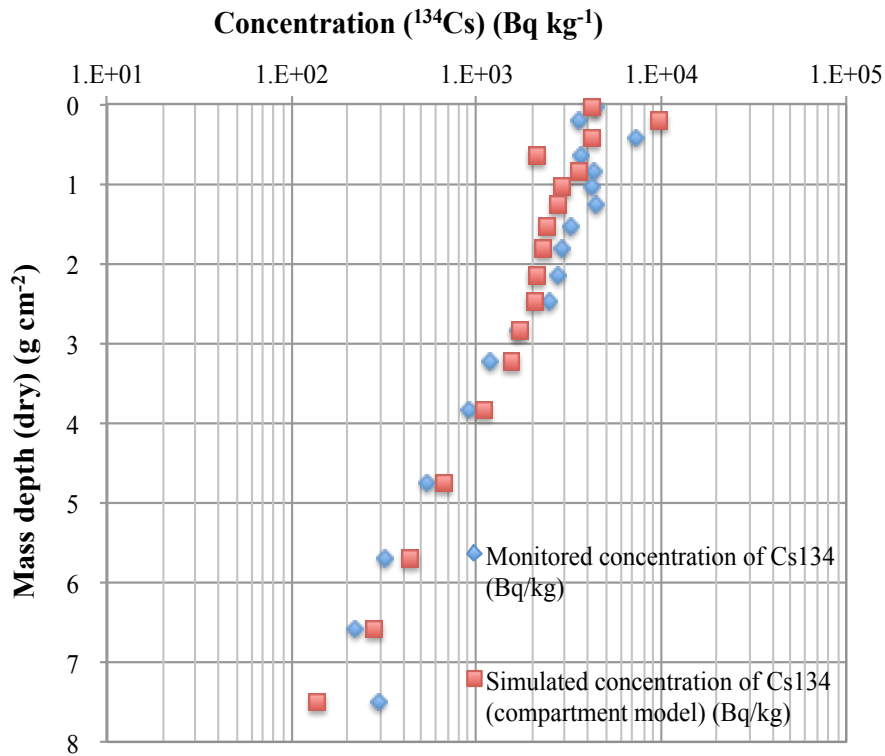


Fig. 4-27 Mass depth profile of radioactive Cs (^{134}Cs) in the forest with *Cryptomeria japonica*, represented by monitored values and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-9 Mass depth profile of radioactive Cs (^{134}Cs) in the forest with *Cryptomeria japonica*, represented by monitored values, calculated values by considering physical attenuation, and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Monitored concentration of ^{134}Cs (Oct. 2015) (Bq kg ⁻¹)	Calculated concentration of ^{134}Cs (Mar. 2011) (Bq kg ⁻¹)	Simulated concentration of ^{134}Cs (Compartment model: $P=aQ^{-1}+b$) (Bq kg ⁻¹)	Simulated concentration of ^{134}Cs (Compartment model: $P=aQ^{-b}$) (Bq kg ⁻¹)
L	0.04	0.96	4,465	20,567	4,153	4,114
F	0.20	0.93	3,623	16,691	9,693	9,615
H	0.43	0.64	7,367	33,936	4,199	4,067
0-0.5	0.64	0.31	3,640	16,767	2,133	2,109
0.5-1.0	0.84	0.35	4,330	19,949	3,607	3,532
1.0-1.5	1.03	0.34	4,151	19,124	2,900	2,848
1.5-2.0	1.26	0.33	4,422	20,371	2,732	2,693
2.0-2.5	1.52	0.29	3,257	15,002	2,443	2,443
2.5-3.0	1.82	0.29	2,918	13,442	2,316	2,323
3.0-3.5	2.14	0.27	2,776	12,786	2,097	2,126
3.5-4.0	2.48	0.26	2,465	11,355	2,067	2,110
4.0-4.5	2.84	0.24	1,659	7,640	1,694	1,750
4.5-5.0	3.23	0.23	1,184	5,454	1,546	1,605
5.0-6.0	3.85	0.22	922	4,248	1,107	1,144
6.0-7.0	4.75	0.19	545	2,510	659	682
7.0-8.0	5.69	0.16	320	1,475	442	453
8.0-9.0	6.57	0.16	222	1,022	283	273
9.0-10.0	7.50	0.17	294	1,353	137	123

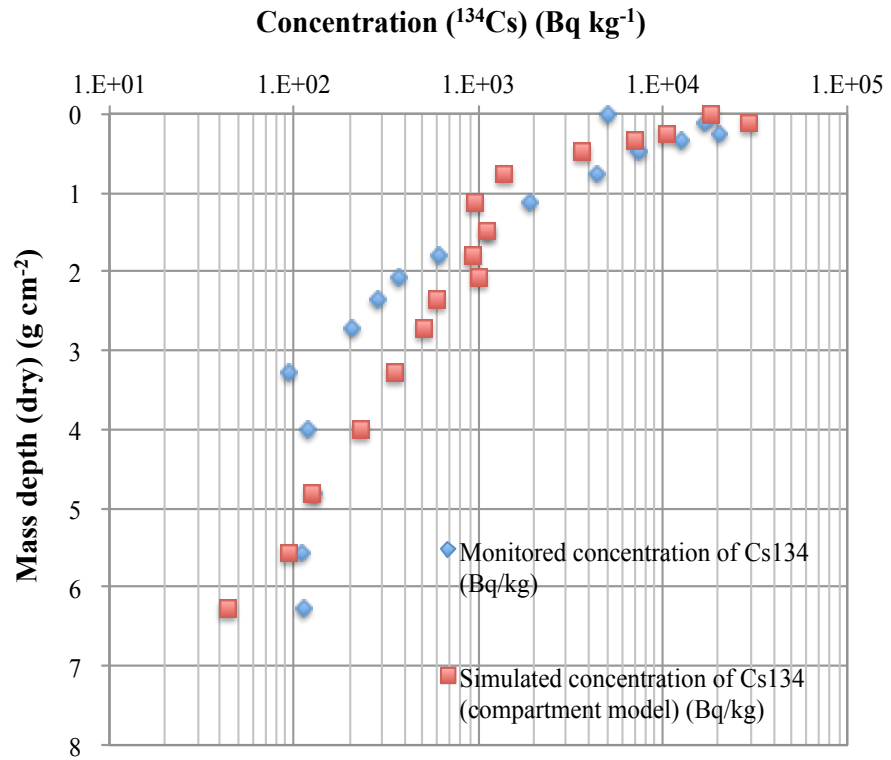
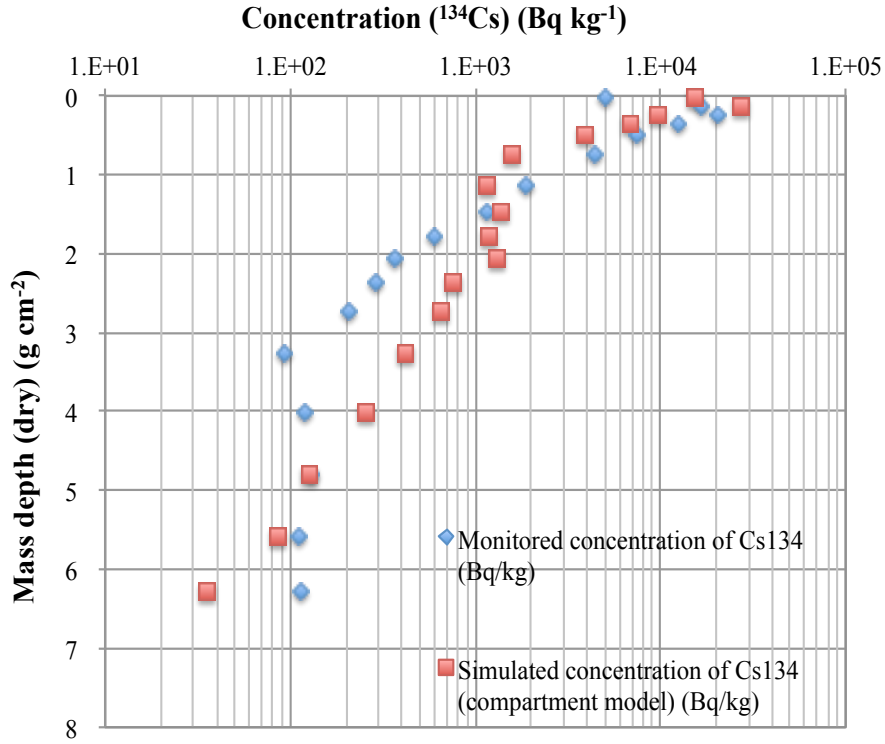


Fig. 4-28 Mass depth profile of radioactive Cs (^{134}Cs) in the forest with *Chamaecyparis obtusa*, represented by monitored values and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-10 Mass depth profile of radioactive Cs (^{134}Cs) in the forest with *Chamaecyparis obtusa*, represented by monitored values, calculated values by considering physical attenuation, and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm^{-2})	Ignition loss	Monitored concentration of ^{134}Cs (Oct. 2015) (Bq kg^{-1})	Calculated concentration of ^{134}Cs (Mar. 2011) (Bq kg^{-1})	Simulated concentration of ^{134}Cs (Compartment model: $P=aQ^{-1}+b$) (Bq kg^{-1})	Simulated concentration of ^{134}Cs (Compartment model: $P=aQ^{-b}$) (Bq kg^{-1})
L	0.02	0.96	5,055	23,284	15,573	18,360
F	0.12	0.85	16,839	77,571	27,005	29,283
H	-	-	-	-	-	-
0-0.5	0.25	0.60	20,243	93,252	9,740	10,389
0.5-1.0	0.35	0.54	12,623	58,147	6,900	7,009
1.0-1.5	0.49	0.47	7,468	34,400	3,877	3,680
1.5-2.0	0.75	0.41	4,402	20,278	1,576	1,392
2.0-2.5	1.13	0.37	1,888	8,695	1,135	945
2.5-3.0	1.48	0.35	1,135	5,229	1,375	1,107
3.0-3.5	1.78	0.34	606	2,791	1,165	924
3.5-4.0	2.06	0.33	369	1,700	1,296	1,018
4.0-4.5	2.36	0.32	288	1,325	753	591
4.5-5.0	2.72	0.32	209	962	642	514
5.0-6.0	3.27	0.31	94	431	420	351
6.0-7.0	4.01	0.31	119	548	254	229
7.0-8.0	4.81	0.31	130	599	126	125
8.0-9.0	5.57	0.31	110	507	85	93
9.0-10.0	6.28	0.31	114	523	36	44

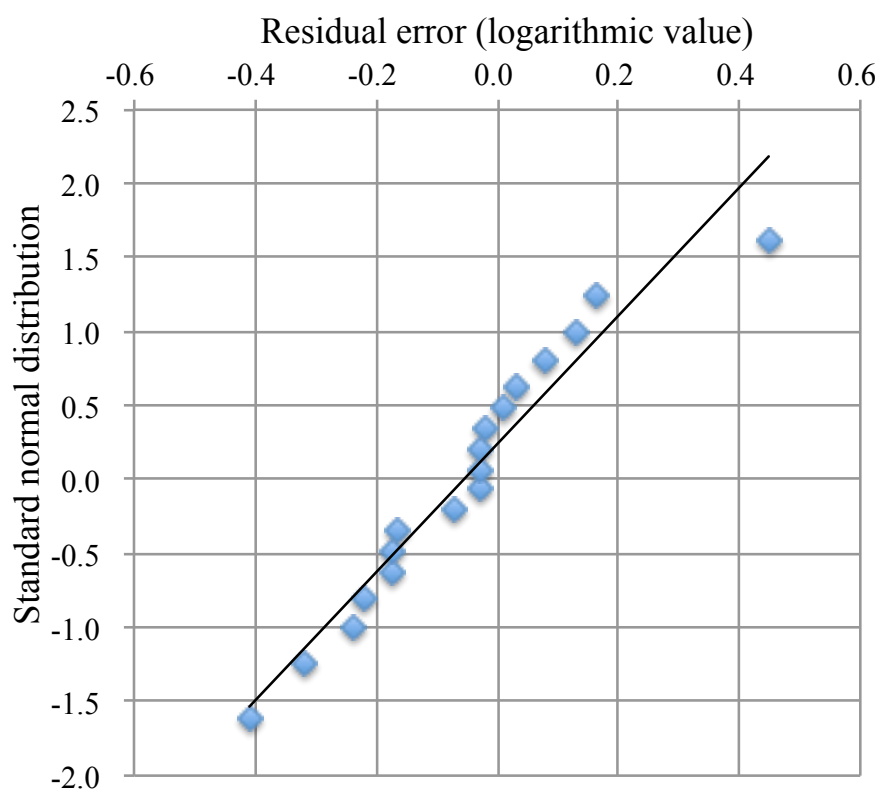
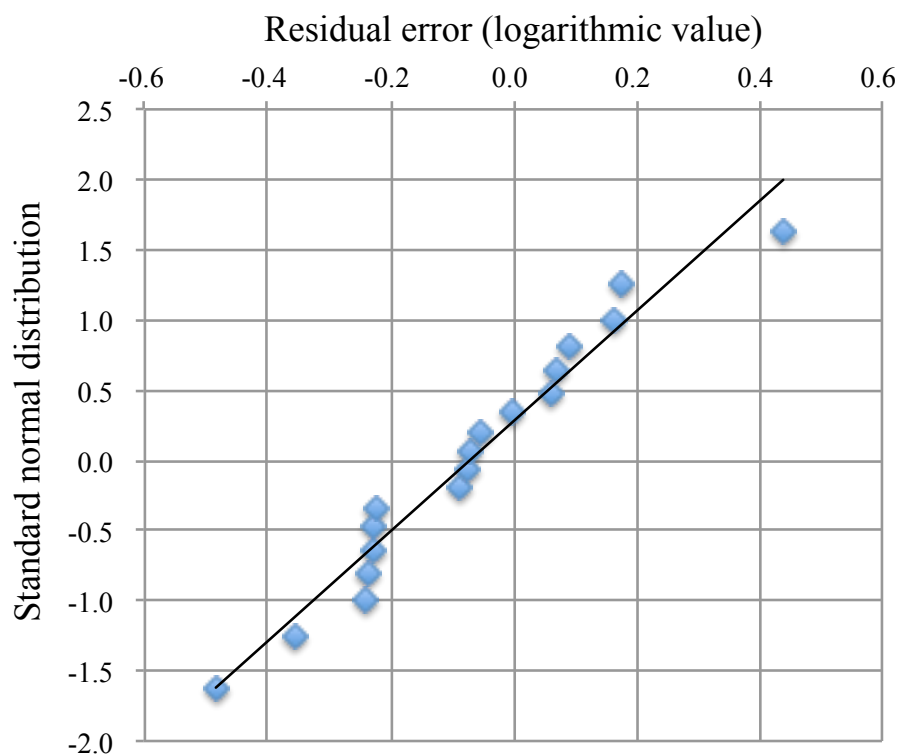


Fig. 4-29 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{137}Cs) in the forest with *Larix kaempferi*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-11 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{137}Cs) in the forest with *Larix kaempferi*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Standard normal distribution	Residual errors of concentrations of ^{137}Cs (logarithmic value) ($P=aQ^{-1}+b$)	Layer ($P=aQ^{-1}+b$)	Residual errors of concentrations of ^{137}Cs (logarithmic value) ($P=aQ^{-b}$)	Layer ($P=aQ^{-b}$)
-1.619856	-0.484470	L	-0.409414	L
-1.252120	-0.357100	4.5-5.0	-0.315895	4.5-5.0
-1.003148	-0.241811	5.0-6.0	-0.236861	6.0-7.0
-0.804596	-0.238019	6.0-7.0	-0.221448	5.0-6.0
-0.633640	-0.227471	2.5-3.0	-0.174475	2.5-3.0
-0.479506	-0.226197	3.5-4.0	-0.171385	3.5-4.0
-0.336038	-0.223799	3.0-3.5	-0.164876	3.0-3.5
-0.199201	-0.086962	0.5-1.0	-0.070827	0.5-1.0
-0.066012	-0.073528	2.0-2.5	-0.029717	1.0-1.5
0.066012	-0.068750	4.0-4.5	-0.027481	2.0-2.5
0.199201	-0.053460	1.0-1.5	-0.026269	7.0-8.0
0.336038	-0.001310	7.0-8.0	-0.019888	4.0-4.5
0.479506	0.060767	8.0-9.0	0.011027	8.0-9.0
0.633640	0.069503	F	0.032127	F
0.804596	0.092717	1.5-2.0	0.076926	9.0-10.0
1.003148	0.165643	9.0-10.0	0.131237	1.5-2.0
1.252120	0.177903	H	0.164132	H
1.619856	0.439245	0-0.5	0.447981	0-0.5
Means of residual errors ($P=aQ^{-1}+b$)	-0.070950	Means of residual errors ($P=aQ^{-b}$)	-0.055839	

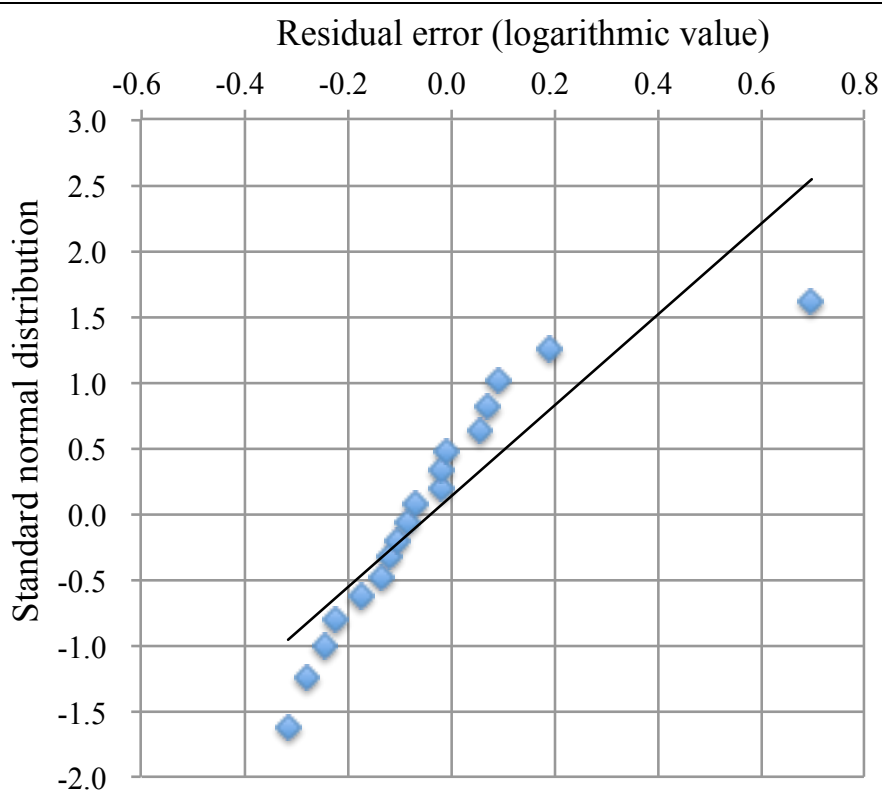
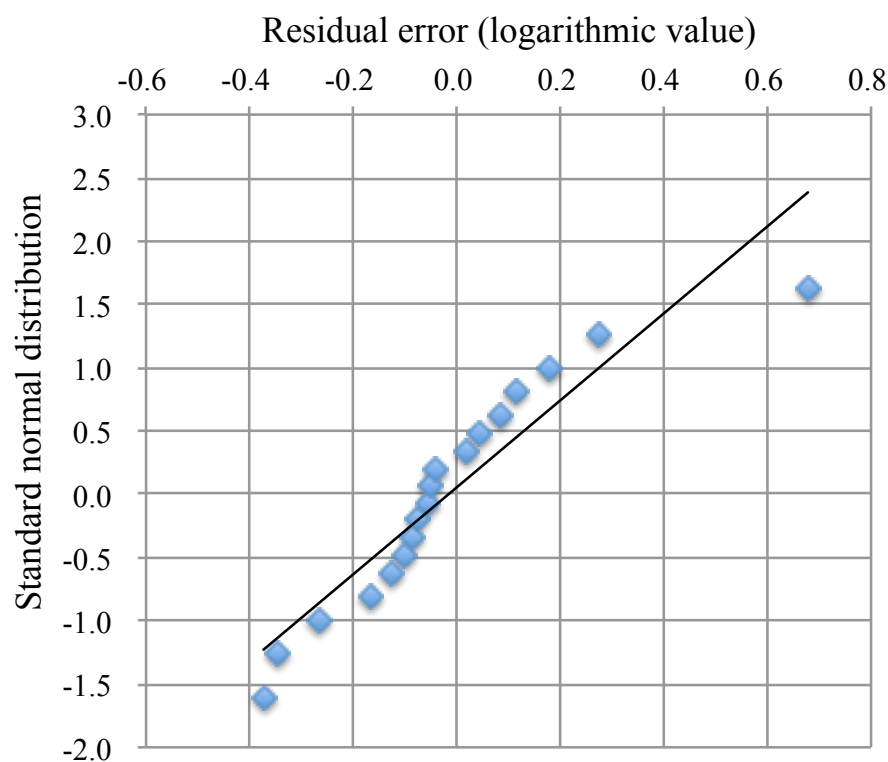


Fig. 4-30 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{137}Cs) in the forest with *Pinus densiflora*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-12 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{137}Cs) in the forest with *Pinus densiflora*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Standard normal distribution	Residual errors of concentrations of ^{137}Cs (logarithmic value) ($P=aQ^{-1}+b$)	Layer ($P=aQ^{-1}+b$)	Residual errors of concentrations of ^{137}Cs (logarithmic value) ($P=aQ^{-b}$)	Layer ($P=aQ^{-b}$)
-1.619856	-0.373479	8.0-9.0	-0.314664	8.0-9.0
-1.252120	-0.344312	L	-0.279065	L
-1.003148	-0.265168	6.0-7.0	-0.240723	6.0-7.0
-0.804596	-0.165001	5.0-6.0	-0.223266	0.5-1.0
-0.633640	-0.125367	0.5-1.0	-0.170910	5.0-6.0
-0.479506	-0.099826	4.5-5.0	-0.134974	0-0.5
-0.336038	-0.088489	7.0-8.0	-0.116391	H
-0.199201	-0.074366	9.0-10.0	-0.104074	4.5-5.0
-0.066012	-0.057588	H	-0.081657	7.0-8.0
0.066012	-0.051791	0-0.5	-0.066129	3.0-3.5
0.199201	-0.040350	4.0-4.5	-0.018311	3.5-4.0
0.336038	0.019466	3.5-4.0	-0.017683	1.0-1.5
0.479506	0.041764	3.0-3.5	-0.006653	4.0-4.5
0.633640	0.082813	1.0-1.5	0.057335	2.5-3.0
0.804596	0.114992	2.5-3.0	0.071416	9.0-10.0
1.003148	0.181274	1.5-2.0	0.089482	1.5-2.0
1.252120	0.274330	2.0-2.5	0.190455	2.0-2.5
1.619856	0.677137	F	0.699036	F
Means of residual errors ($P=aQ^{-1}+b$)	-0.016331	Means of residual errors ($P=aQ^{-b}$)	-0.037043	

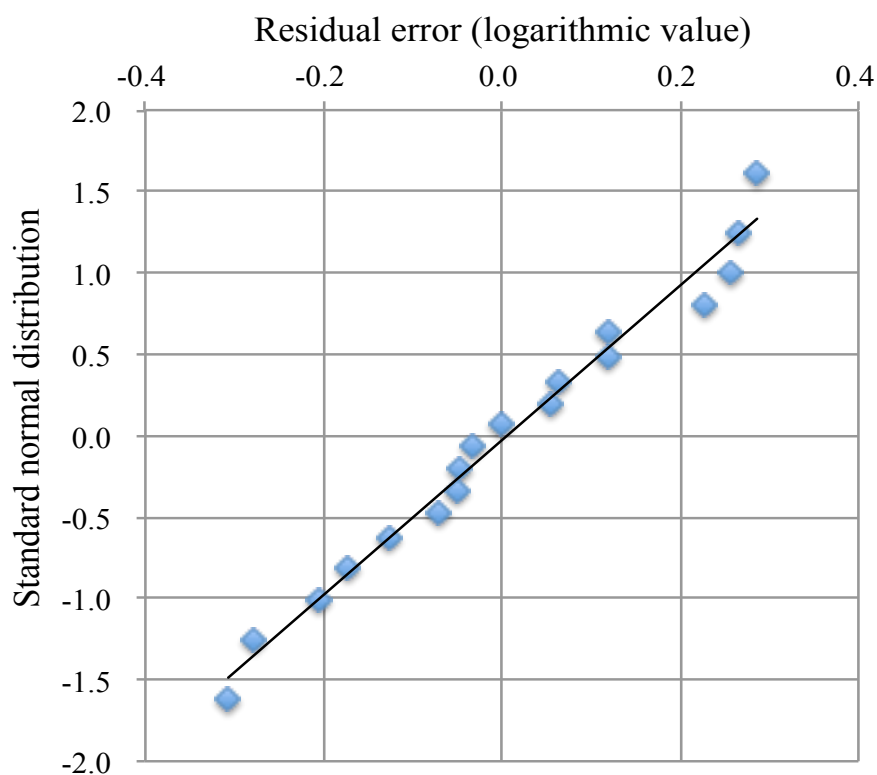
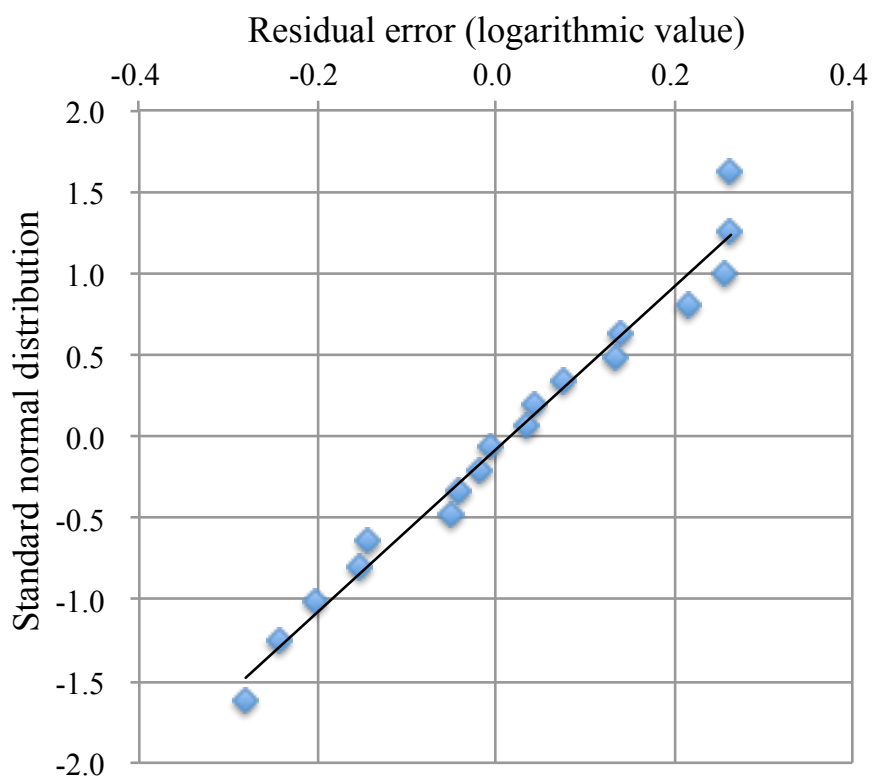


Fig. 4-31 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{137}Cs) in the forest with Deciduous broadleaf tree. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-13 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{137}Cs) in the forest with Deciduous broadleaf tree. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Standard normal distribution	Residual errors of concentrations of ^{137}Cs (logarithmic value) ($P=aQ^{-1}+b$)	Layer ($P=aQ^{-1}+b$)	Residual errors of concentrations of ^{137}Cs (logarithmic value) ($P=aQ^{-b}$)	Layer ($P=aQ^{-b}$)
-1.619856	-0.280753	5.0-6.0	-0.307110	5.0-6.0
-1.252120	-0.244360	4.5-5.0	-0.278878	4.5-5.0
-1.003148	-0.201199	7.0-8.0	-0.204204	7.0-8.0
-0.804596	-0.154184	6.0-7.0	-0.172921	6.0-7.0
-0.633640	-0.143538	H	-0.126760	H
-0.479506	-0.050791	F	-0.072264	3.5-4.0
-0.336038	-0.042934	3.5-4.0	-0.050057	4.0-4.5
-0.199201	-0.017684	4.0-4.5	-0.047610	F
-0.066012	-0.006528	0.5-1.0	-0.032486	L
0.066012	0.033239	L	-0.000659	0.5-1.0
0.199201	0.044066	8.0-9.0	0.055651	8.0-9.0
0.336038	0.074555	2.0-2.5	0.063866	2.0-2.5
0.479506	0.133753	2.5-3.0	0.118060	3.0-3.5
0.633640	0.140056	3.0-3.5	0.118817	2.5-3.0
0.804596	0.214744	0-0.5	0.227235	0-0.5
1.003148	0.256083	9.0-10.0	0.255522	1.5-2.0
1.252120	0.262052	1.5-2.0	0.266047	1.0-1.5
1.619856	0.263319	1.0-1.5	0.285719	9.0-10.0
Means of residual errors ($P=aQ^{-1}+b$)	0.015550	Means of residual errors ($P=aQ^{-b}$)	0.005443	

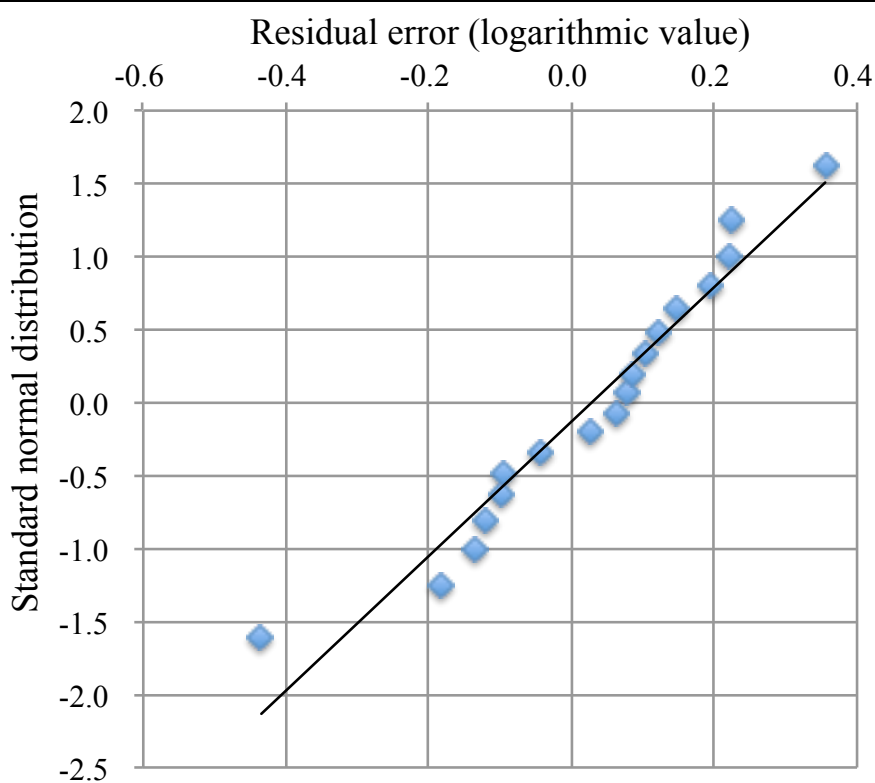
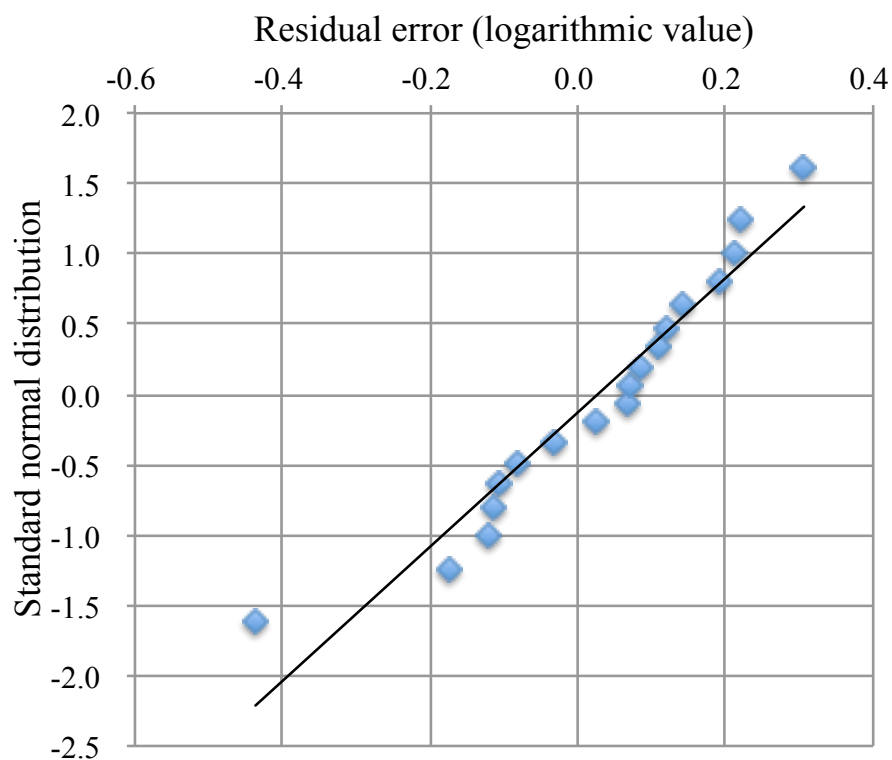


Fig. 4-32 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{137}Cs) in the forest with *Cryptomeria japonica*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-14 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{137}Cs) in the forest with *Cryptomeria japonica*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Standard normal distribution	Residual errors of concentrations of ^{137}Cs (logarithmic value) ($P=aQ^{-1}+b$)	Layer ($P=aQ^{-1}+b$)	Residual errors of concentrations of ^{137}Cs (logarithmic value) ($P=aQ^{-b}$)	Layer ($P=aQ^{-b}$)
-1.619856	-0.436741	F	-0.434580	F
-1.252120	-0.175364	7.0-8.0	-0.184081	7.0-8.0
-1.003148	-0.120873	4.5-5.0	-0.136478	4.5-5.0
-0.804596	-0.115124	8.0-9.0	-0.120234	5.0-6.0
-0.633640	-0.106699	5.0-6.0	-0.098008	8.0-9.0
-0.479506	-0.082005	6.0-7.0	-0.095528	6.0-7.0
-0.336038	-0.031209	4.0-4.5	-0.044817	4.0-4.5
-0.199201	0.023454	L	0.024635	L
-0.066012	0.067972	0.5-1.0	0.061273	3.5-4.0
0.066012	0.069878	3.5-4.0	0.076798	0.5-1.0
0.199201	0.085265	2.5-3.0	0.084170	2.5-3.0
0.336038	0.110214	3.0-3.5	0.104492	3.0-3.5
0.479506	0.121607	2.0-2.5	0.121553	2.0-2.5
0.633640	0.140797	1.0-1.5	0.148523	1.0-1.5
0.804596	0.190110	1.5-2.0	0.196313	1.5-2.0
1.003148	0.213110	H	0.222561	0-0.5
1.252120	0.218145	0-0.5	0.226101	H
1.619856	0.306343	9.0-10.0	0.355365	9.0-10.0
Means of residual errors ($P=aQ^{-1}+b$)	0.026604	Means of residual errors ($P=aQ^{-b}$)	0.028225	

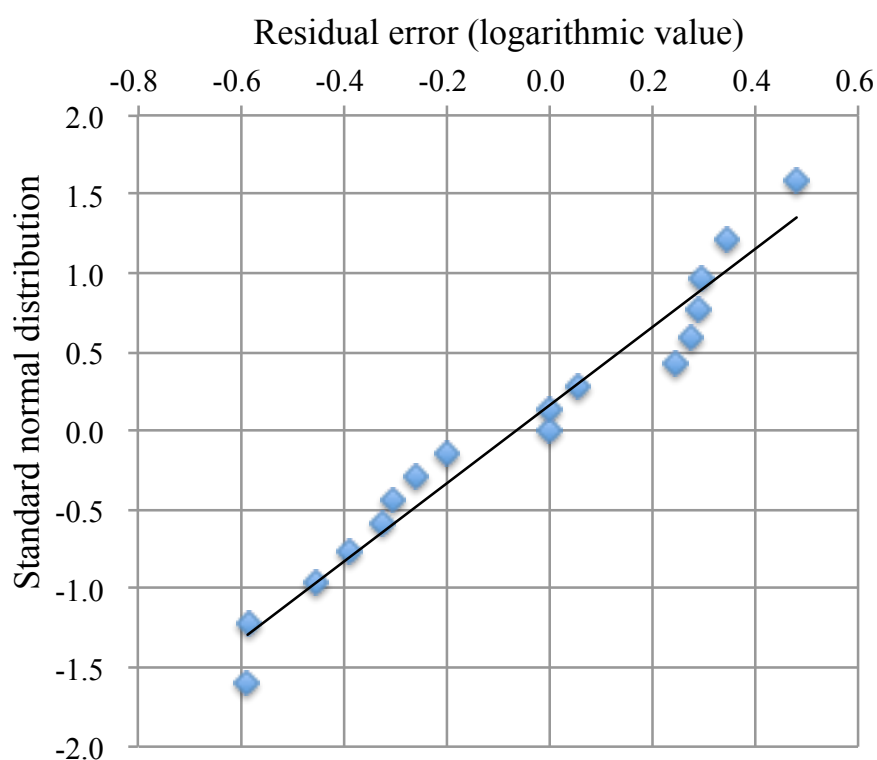
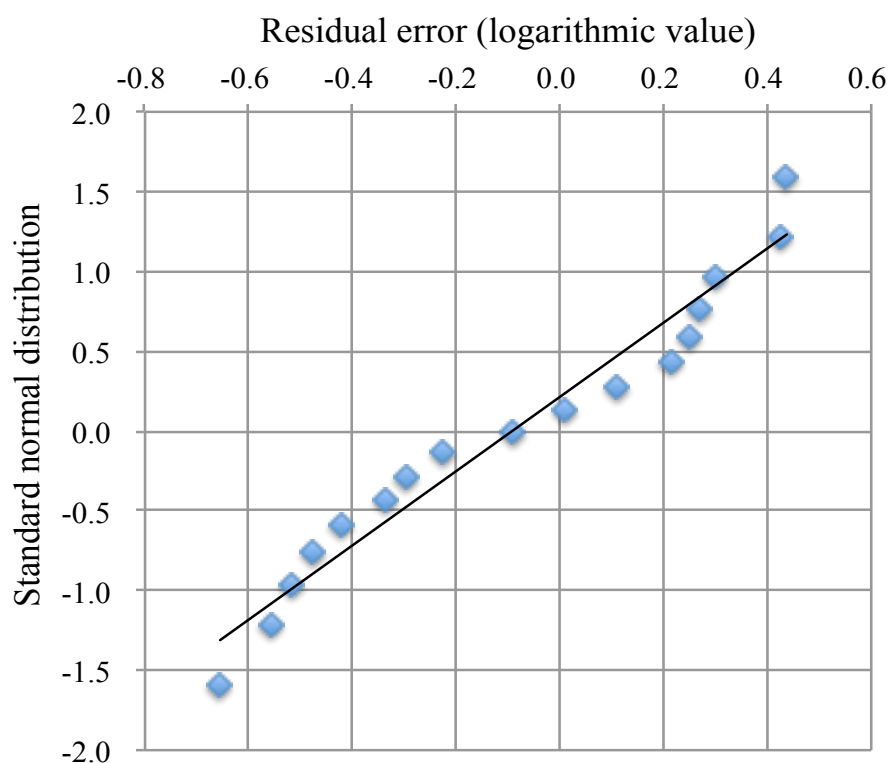


Fig. 4-33 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{137}Cs) in the forest with *Chamaecyparis obtusa*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-15 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{137}Cs) in the forest with *Chamaecyparis obtusa*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Standard normal distribution	Residual errors of concentrations of ^{137}Cs (logarithmic value) ($P=aQ^{-1}+b$)	Layer ($P=aQ^{-1}+b$)	Residual errors of concentrations of ^{137}Cs (logarithmic value) ($P=aQ^{-b}$)	Layer ($P=aQ^{-b}$)
-1.593219	-0.655207	5.0-6.0	-0.586852	L
-1.220640	-0.555040	3.5-4.0	-0.583443	5.0-6.0
-0.967422	-0.518032	L	-0.455667	3.5-4.0
-0.764710	-0.477726	4.5-5.0	-0.388650	4.5-5.0
-0.589456	-0.421329	4.0-4.5	-0.322232	4.0-4.5
-0.430727	-0.337042	6.0-7.0	-0.303826	6.0-7.0
-0.282216	-0.297861	3.0-3.5	-0.259055	F
-0.139710	-0.225651	F	-0.201724	3.0-3.5
0.000000	-0.089197	2.5-3.0	0.001051	7.0-8.0
0.139710	0.008691	7.0-8.0	0.001063	2.5-3.0
0.282216	0.106877	8.0-9.0	0.054624	8.0-9.0
0.430727	0.213131	2.0-2.5	0.242205	0.5-1.0
0.589456	0.248682	0.5-1.0	0.272453	0-0.5
0.764710	0.270379	1.0-1.5	0.289636	2.0-2.5
0.967422	0.299278	0-0.5	0.292304	1.0-1.5
1.220640	0.427202	1.5-2.0	0.342302	9.0-10.0
1.593219	0.437333	9.0-10.0	0.479421	1.5-2.0
Means of residual errors ($P=aQ^{-1}+b$)	-0.092089	Means of residual errors ($P=aQ^{-b}$)	-0.066258	

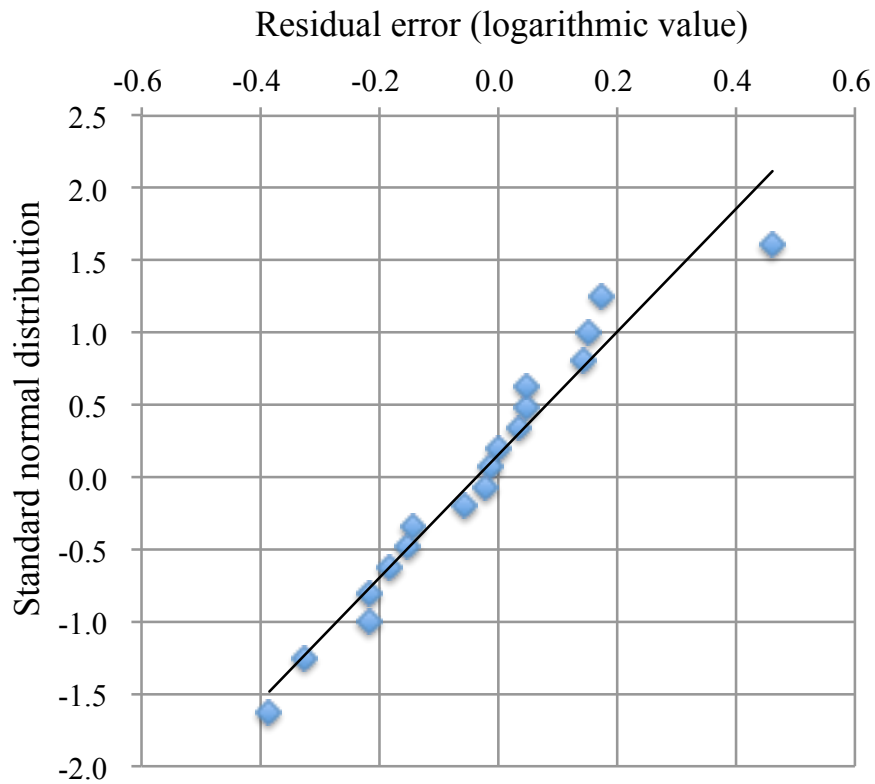
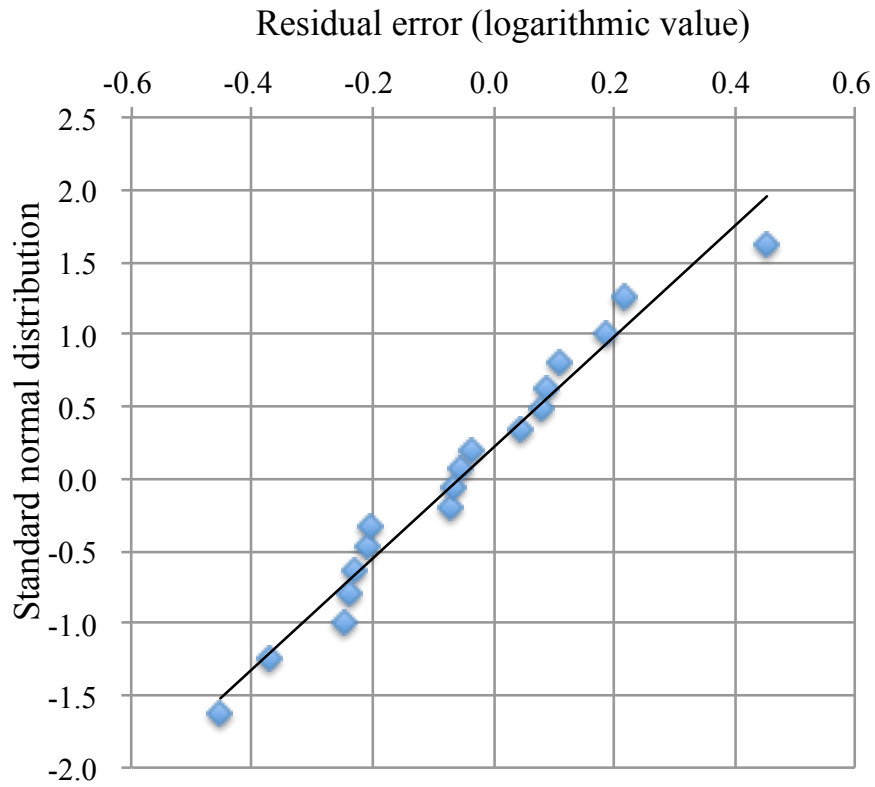


Fig. 4-34 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{134}Cs) in the forest with *Larix kaempferi*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-16 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{134}Cs) in the forest with *Larix kaempferi*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Standard normal distribution	Residual errors of concentrations of ^{134}Cs (logarithmic value) ($P=aQ^{-1}+b$)	Layer ($P=aQ^{-1}+b$)	Residual errors of concentrations of ^{134}Cs (logarithmic value) ($P=aQ^{-b}$)	Layer ($P=aQ^{-b}$)
-1.619856	-0.452279	L	-0.385034	L
-1.252120	-0.373413	4.5-5.0	-0.326441	4.5-5.0
-1.003148	-0.245694	5.0-6.0	-0.216138	5.0-6.0
-0.804596	-0.237720	2.5-3.0	-0.216031	6.0-7.0
-0.633640	-0.229818	6.0-7.0	-0.183451	2.5-3.0
-0.479506	-0.209795	3.5-4.0	-0.151811	3.5-4.0
-0.336038	-0.205538	3.0-3.5	-0.144519	3.0-3.5
-0.199201	-0.071389	0.5-1.0	-0.056457	0.5-1.0
-0.066012	-0.067839	2.0-2.5	-0.021223	2.0-2.5
0.066012	-0.054009	4.0-4.5	-0.014480	1.0-1.5
0.199201	-0.037560	1.0-1.5	-0.000615	4.0-4.5
0.336038	0.045398	7.0-8.0	0.036160	7.0-8.0
0.479506	0.077718	8.0-9.0	0.045502	8.0-9.0
0.633640	0.086209	F	0.047740	F
0.804596	0.111506	1.5-2.0	0.145030	9.0-10.0
1.003148	0.186947	H	0.149924	1.5-2.0
1.252120	0.218590	9.0-10.0	0.171490	H
1.619856	0.453509	0-0.5	0.460656	0-0.5
Means of residual errors ($P=aQ^{-1}+b$)	-0.055843	Means of residual errors ($P=aQ^{-b}$)	-0.0366499	

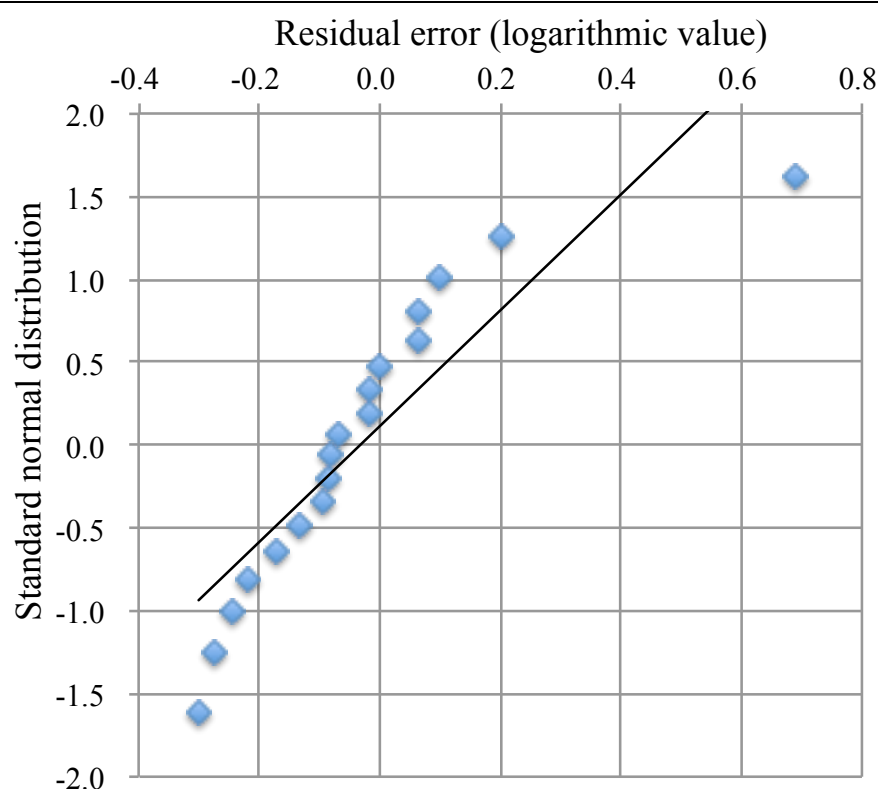
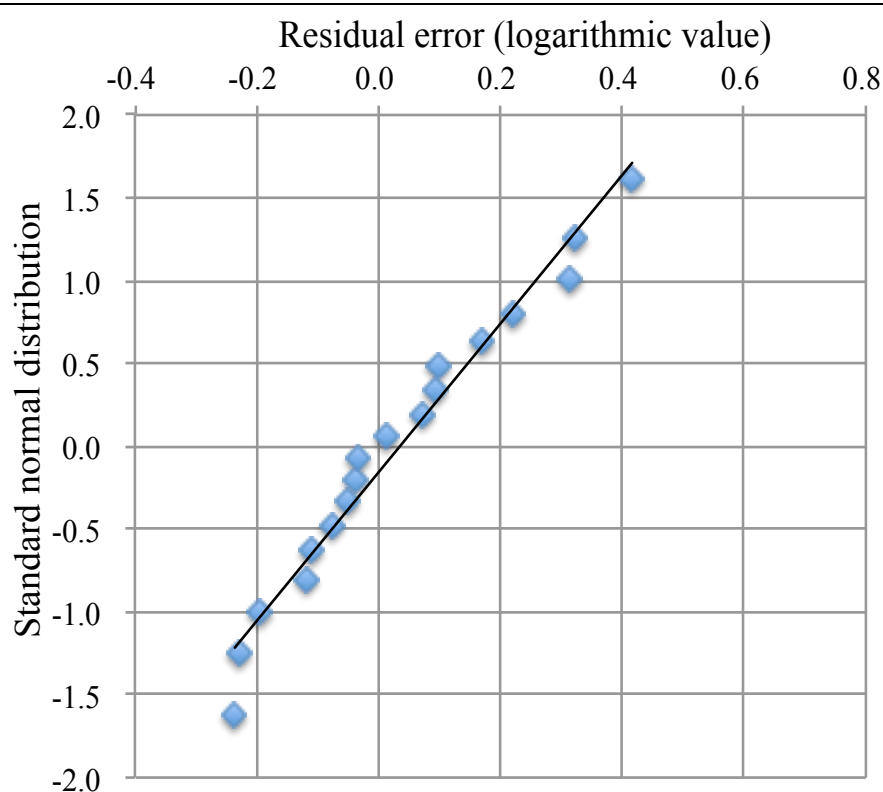


Fig. 4-35 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{134}Cs) in the forest with *Pinus densiflora*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-17 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{134}Cs) in the forest with *Pinus densiflora*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Standard normal distribution	Residual errors of concentrations of ^{134}Cs (logarithmic value) ($P=aQ^{-1}+b$)	Layer ($P=aQ^{-1}+b$)	Residual errors of concentrations of ^{134}Cs (logarithmic value) ($P=aQ^{-b}$)	Layer ($P=aQ^{-b}$)
-1.619856	-0.235907	6.0-7.0	-0.300483	L
-1.252120	-0.230214	8.0-9.0	-0.275542	6.0-7.0
-1.003148	-0.194561	L	-0.242842	8.0-9.0
-0.804596	-0.119347	0.5-1.0	-0.218305	0.5-1.0
-0.633640	-0.112051	5.0-6.0	-0.172478	5.0-6.0
-0.479506	-0.076430	0-0.5	-0.131093	0-0.5
-0.336038	-0.049413	9.0-10.0	-0.096204	4.5-5.0
-0.199201	-0.037969	7.0-8.0	-0.084770	7.0-8.0
-0.066012	-0.032482	4.5-5.0	-0.083315	H
0.066012	0.011105	4.0-4.5	-0.068917	4.0-4.5
0.199201	0.073377	3.5-4.0	-0.018666	1.0-1.5
0.336038	0.094157	1.0-1.5	-0.016347	3.5-4.0
0.479506	0.098214	3.0-3.5	0.000429	3.0-3.5
0.633640	0.167882	2.5-3.0	0.062769	9.0-10.0
0.804596	0.221287	1.5-2.0	0.063569	2.5-3.0
1.003148	0.312385	H	0.099428	1.5-2.0
1.252120	0.323824	2.0-2.5	0.203226	2.0-2.5
1.619856	0.416343	F	0.692207	F
Means of residual errors ($P=aQ^{-1}+b$)	0.035011	Means of residual errors ($P=aQ^{-b}$)	-0.032630	

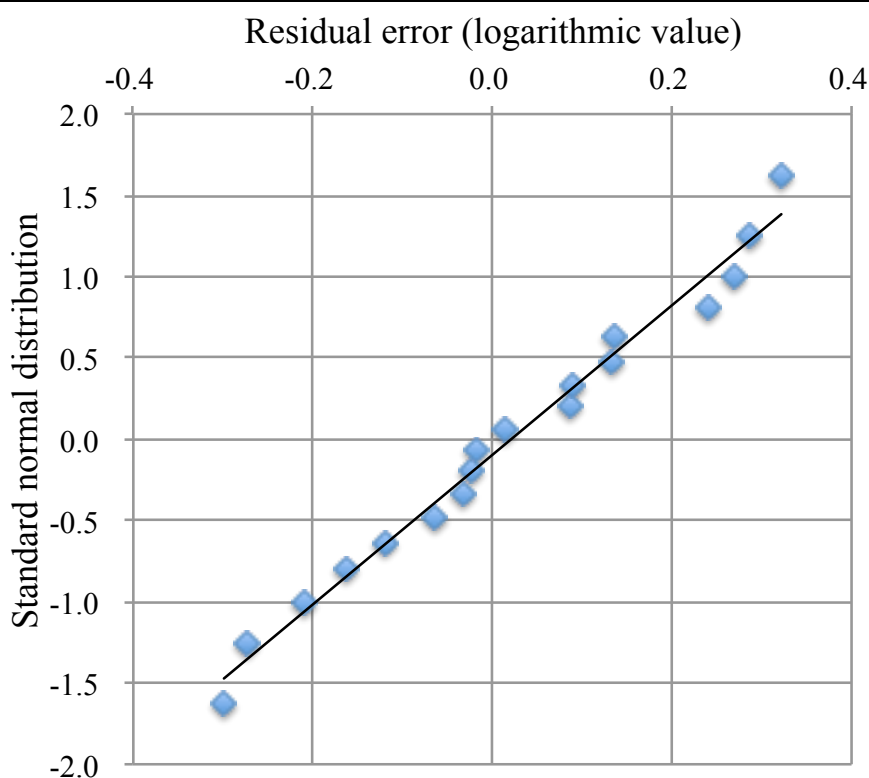
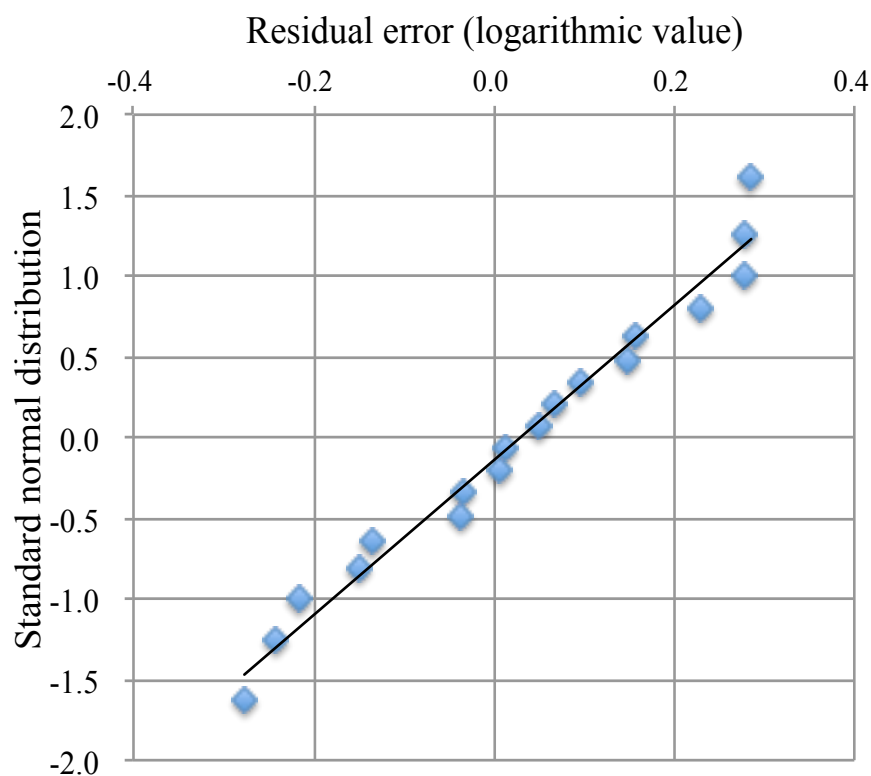


Fig. 4-36 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (¹³⁴Cs) in the forest with Deciduous broadleaf tree. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-18 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{134}Cs) in the forest with Deciduous broadleaf tree. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Standard normal distribution	Residual errors of concentrations of ^{134}Cs (logarithmic value) ($P=aQ^{-1}+b$)	Layer ($P=aQ^{-1}+b$)	Residual errors of concentrations of ^{134}Cs (logarithmic value) ($P=aQ^{-b}$)	Layer ($P=aQ^{-b}$)
-1.619856	-0.277079	5.0-6.0	-0.299167	5.0-6.0
-1.252120	-0.241447	4.5-5.0	-0.272965	4.5-5.0
-1.003148	-0.214948	7.0-8.0	-0.210037	7.0-8.0
-0.804596	-0.150464	6.0-7.0	-0.162423	6.0-7.0
-0.633640	-0.136635	H	-0.121057	H
-0.479506	-0.037780	3.5-4.0	-0.065917	3.5-4.0
-0.336038	-0.033718	F	-0.031585	F
-0.199201	0.007599	0.5-1.0	-0.022807	L
-0.066012	0.013069	4.0-4.5	-0.017310	4.0-4.5
0.066012	0.048783	L	0.012388	0.5-1.0
0.199201	0.066087	8.0-9.0	0.084782	2.0-2.5
0.336038	0.095757	2.0-2.5	0.088456	8.0-9.0
0.479506	0.147985	2.5-3.0	0.133192	2.5-3.0
0.633640	0.156990	3.0-3.5	0.135775	3.0-3.5
0.804596	0.229610	0-0.5	0.240943	0-0.5
1.003148	0.277014	1.5-2.0	0.269864	1.5-2.0
1.252120	0.278859	9.0-10.0	0.286929	1.0-1.5
1.619856	0.284999	1.0-1.5	0.321165	9.0-10.0
Means of residual errors ($P=aQ^{-1}+b$)	0.028593	Means of residual errors ($P=aQ^{-b}$)	0.020568	

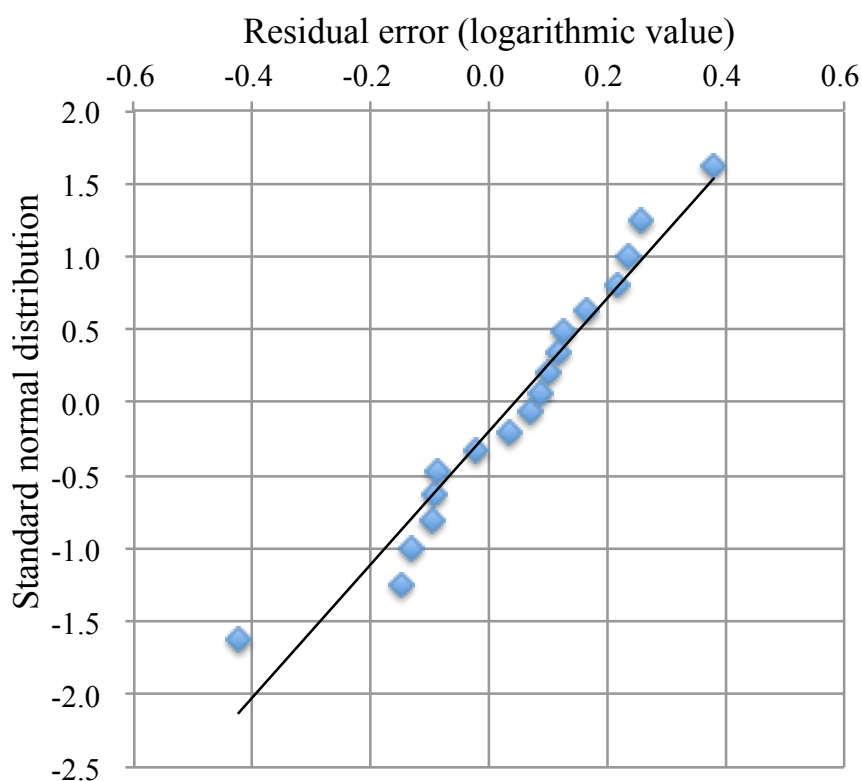
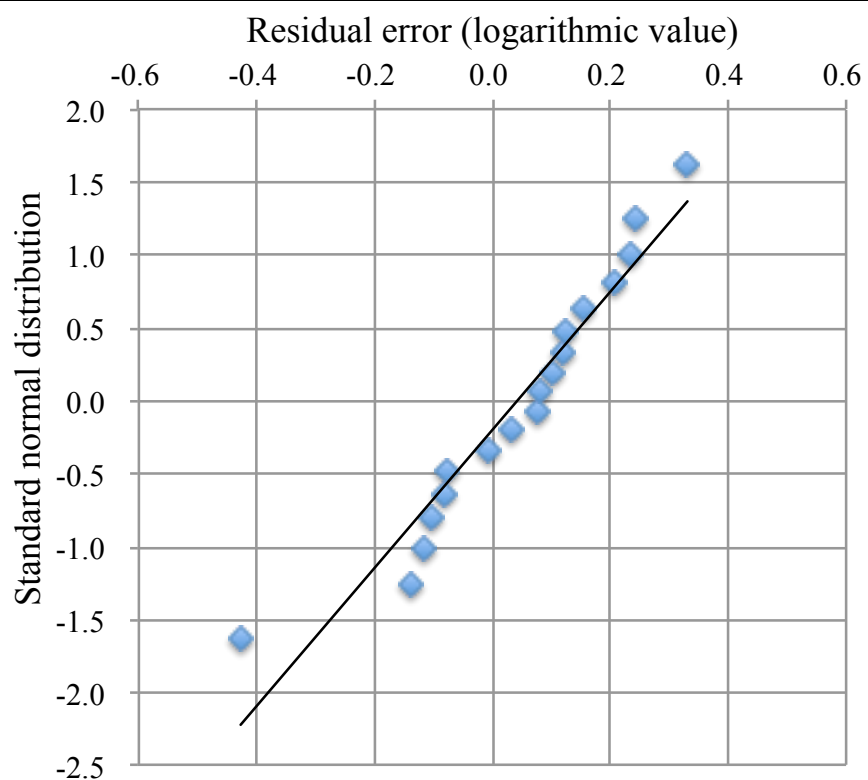


Fig. 4-37 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{134}Cs) in the forest with *Cryptomeria japonica*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P = aQ^{-1} + b$ (top) and $P = aQ^{-b}$ (bottom).

Table 4-19 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{134}Cs) in the forest with *Cryptomeria japonica*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Standard normal distribution	Residual errors of concentrations of ^{137}Cs (logarithmic value) ($P=aQ^{-1}+b$)	Layer ($P=aQ^{-1}+b$)	Residual errors of concentrations of ^{137}Cs (logarithmic value) ($P=aQ^{-b}$)	Layer ($P=aQ^{-b}$)
-1.619856	-0.427349	F	-0.423835	F
-1.252120	-0.140284	7.0-8.0	-0.150442	7.0-8.0
-1.003148	-0.115792	4.5-5.0	-0.132192	4.5-5.0
-0.804596	-0.105071	8.0-9.0	-0.097407	6.0-7.0
-0.633640	-0.082586	6.0-7.0	-0.093803	5.0-6.0
-0.479506	-0.079199	5.0-6.0	-0.089297	8.0-9.0
-0.336038	-0.009118	4.0-4.5	-0.023373	4.0-4.5
-0.199201	0.031472	L	0.035475	L
-0.066012	0.076556	3.5-4.0	0.067447	3.5-4.0
0.066012	0.079360	0.5-1.0	0.088547	0.5-1.0
0.199201	0.100309	2.5-3.0	0.099009	2.5-3.0
0.336038	0.121773	3.0-3.5	0.115700	3.0-3.5
0.479506	0.124915	2.0-2.5	0.124810	2.0-2.5
0.633640	0.155763	1.0-1.5	0.163715	1.0-1.5
0.804596	0.209147	1.5-2.0	0.215433	1.5-2.0
1.003148	0.232051	0-0.5	0.236972	0-0.5
1.252120	0.244165	H	0.257990	H
1.619856	0.330817	9.0-10.0	0.379628	9.0-10.0
Means of residual errors ($P=aQ^{-1}+b$)	0.041496	Means of residual errors ($P=aQ^{-b}$)	0.043021	

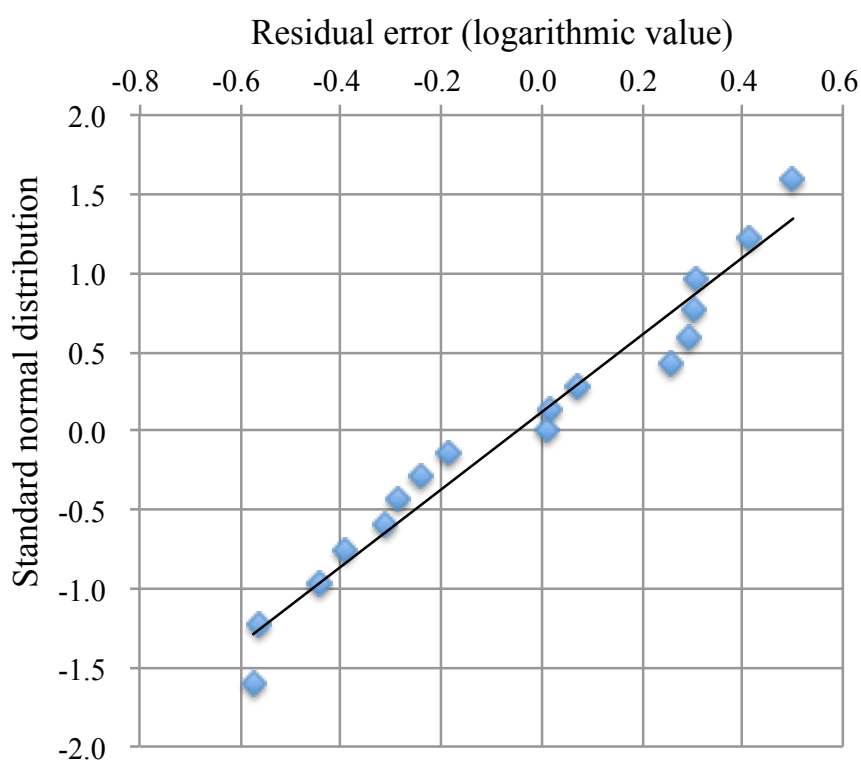
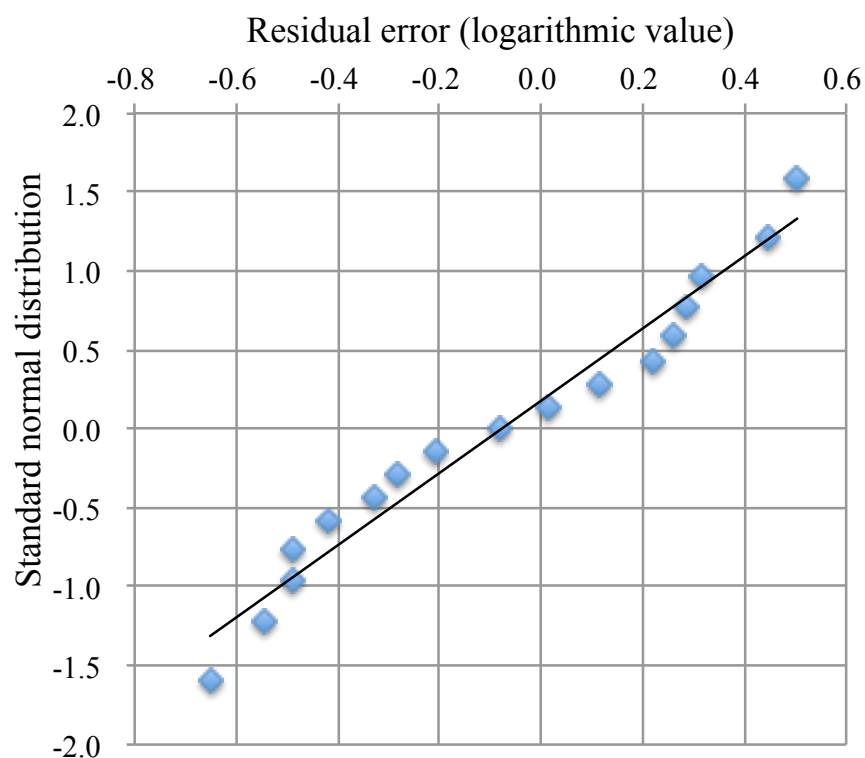


Fig. 4-38 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{134}Cs) in the forest with *Chamaecyparis obtusa*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-20 Standard normal distribution plot analyses for the residual errors of monitored concentrations and simulated concentrations (logarithmic values) of radioactive Cs (^{134}Cs) in the forest with *Chamaecyparis obtusa*. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Standard normal distribution	Residual errors of concentrations of ^{134}Cs (logarithmic value) ($P=aQ^{-1}+b$)	Layer ($P=aQ^{-1}+b$)	Residual errors of concentrations of ^{134}Cs (logarithmic value) ($P=aQ^{-b}$)	Layer ($P=aQ^{-b}$)
-1.593219	-0.651600	5.0-6.0	-0.573835	5.0-6.0
-1.220640	-0.545605	3.5-4.0	-0.560173	L
-0.967422	-0.488692	L	-0.440792	3.5-4.0
-0.764710	-0.487593	4.5-5.0	-0.390923	4.5-5.0
-0.589456	-0.418377	4.0-4.5	-0.312629	4.0-4.5
-0.430727	-0.328772	6.0-7.0	-0.284686	6.0-7.0
-0.282216	-0.283914	3.0-3.5	-0.240299	F
-0.139710	-0.205122	F	-0.183175	3.0-3.5
0.000000	-0.083190	2.5-3.0	0.010768	2.5-3.0
0.139710	0.012294	7.0-8.0	0.016246	7.0-8.0
0.282216	0.112844	8.0-9.0	0.071331	8.0-9.0
0.430727	0.220879	2.0-2.5	0.255480	0.5-1.0
0.589456	0.262315	0.5-1.0	0.289693	0-0.5
0.764710	0.284736	1.0-1.5	0.300259	2.0-2.5
0.967422	0.317741	0-0.5	0.307311	1.0-1.5
1.220640	0.446001	1.5-2.0	0.412298	9.0-10.0
1.593219	0.503653	9.0-10.0	0.499996	1.5-2.0
Means of residual errors ($P=aQ^{-1}+b$)	-0.078377	Means of residual errors ($P=aQ^{-b}$)	-0.048419	

Table 4-21 Transfer coefficients, the results of validation for compartment model, and soil characteristics for each forest with different types of vegetation (*Larix kaempferi*, *Pinus densiflora*, Deciduous broadleaf tree, *Cryptomeria japonica* and *Chamaecyparis obtusa*). Transfer coefficients are calculated under the two hypotheses that transition coefficient (P) and ignition loss (Q) are represented by two equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$. Means of residual errors and the standard errors are calculated according to the equation (9) and (10), where $C_{m,i}$, $C_{s,i}$, N are the monitored concentration of ^{137}Cs , the simulated concentration of ^{137}Cs by using compartment model and the number of layer in each forest, respectively. In forests dominated by *Larix kaempferi*, *Pinus densiflora*, Deciduous broadleaf tree and *Cryptomeria japonica*, N is 18. In forest dominated by *Chamaecyparis obtusa*, N is 17 because the organic layer is so immature that layer H can't be identified.

		Larix kaempferi	Pinus densiflora	Deciduous broadleaf tree	Cryptome ria japonica	Chamaecy paris obtusa
¹³⁷ Cs	P=aQ ⁻¹ +b	a	0.1140	0.3075	0.0250	0.0124
		b	-0.0996	-0.2026	0.0317	0.0983
		Means of residual errors	-0.0710	-0.0163	0.0156	0.0266
		Standard errors	0.24	0.25	0.18	0.19
	P=aQ ^{-b}	a	0.0224	0.1118	0.0556	0.1105
		b	2.4778	1.6203	0.6286	0.2002
		Means of residual errors	-0.0558	-0.0370	0.0054	0.0282
		Standard errors	0.21	0.24	0.19	0.19
¹³⁴ Cs	P=aQ ⁻¹ +b	a	0.1122	0.3241	0.0250	0.0121
		b	-0.0979	-0.2649	0.0315	0.0991
		Means of residual errors	-0.0559	0.0350	0.0286	0.0415
		Standard errors	0.24	0.20	0.19	0.19
	P=aQ ^{-b}	a	0.0222	0.1099	0.0553	0.1110
		b	2.4622	1.6344	0.6307	0.1947
		Means of residual errors	-0.0367	-0.0326	0.0206	0.0430
		Standard errors	0.21	0.24	0.20	0.20
Saturated hydraulic conductivity (cm s ⁻¹)	0 - 5 cm	0.17	0.74	0.37	0.96	0.27
	5 - 10 cm	0.14	0.23	0.16	0.98	0.31
Field capacity (g cm ⁻³)	0 - 5 cm	0.60	0.41	0.57	0.53	0.51
	5 - 10 cm	0.56	0.46	0.52	0.49	0.50
Voidage	0 - 5 cm	0.89	0.81	0.86	0.91	0.85
	5 - 10 cm	0.88	0.74	0.77	0.84	0.83
CEC (meq (100 g) ⁻¹)	0 - 5 cm	43	48	28	39	57
	5 - 10 cm	52	23	16	23	42

$$\text{Means of residual errors} = \frac{1}{N} \sum_{i=1}^N (\log_{10} C_{m,i} - \log_{10} C_{s,i}) \quad (9)$$

$$\text{Standard errors} = \sqrt{\sum_{i=1}^N (\log_{10} C_{m,i} - \log_{10} C_{s,i})^2 / (N - 2)} \quad (10)$$

4.4 Discussion and conclusions

It was previously reported that the degree of infiltration of radioactive Cs and the properties of the organic layer could influence forest decontamination (Mori et al., 2016). In this report, the infiltration of radioactive Cs, which changes over time, was examined with respect to various factors by examining the depth profile. There are no particular correlations with the field capacity or voidage, but a slight correlation with the CEC and a strong correlation with the saturated hydraulic conductivity were observed.

Based on the strong correlation between the ignition loss and the CEC, simulation of the monitored values was attempted using a compartment model, taking the ignition loss as a parameter.

As a result of the analyses, the simulated values were comparable with the monitored values in each forest with different types of vegetation, although some inconsistencies were seen in the middle of the soil layer. Further improvement, especially for the parameter and transition coefficient, is needed to precisely reproduce the monitored value.

It is known that radioactive Cs in its soluble form can be converted into exchange form with an electrostatically moderate binding ability with the negative charges in the soil, followed by conversion into the fixed form, which has a strong affinity with FES created by the weathering of mica mineral (Yamaguchi et al., 2012).

Considering that the transition speed has been reported to decrease each year (Yamaguchi et al., 2012), radioactive Cs might not move down at constant velocity but instead was moved down over a short period of time early after the accident by natural events, such as water flow caused by heavy rainfall, and was then adsorbed by soil particles.

Based on the compartment model, the future concentration of radioactive Cs was estimated. Fig. 4-39 - Fig. 4-53 and Table 4-22 – Table 4-36 represent the predicted depth profile of Mar. 2021, 2031 and 2041, respectively. The example of the VBA program to estimate the concentration of radioactive Cs is shown in Appendix 2.

In these simulations, only ^{137}Cs was used without ^{134}Cs which has so shorter half-time than ^{137}Cs and that we can ignore the influence of ^{134}Cs . The simulations were conducted as follows:

a) Physical attenuation of monitored ^{137}Cs concentration

Future concentration of monitored ^{137}Cs was estimated based on the half-time of ^{137}Cs (30.17 years) and physical attenuation, assuming that radioactive ^{137}Cs wouldn't infiltrate downward during this period.

b) The future prediction of radioactive Cs using compartment model

The future concentration of ^{137}Cs was estimated, assuming that the ^{137}Cs infiltrate according to the transition coefficients shown in Table 4-21 and they are constant during the estimation period.

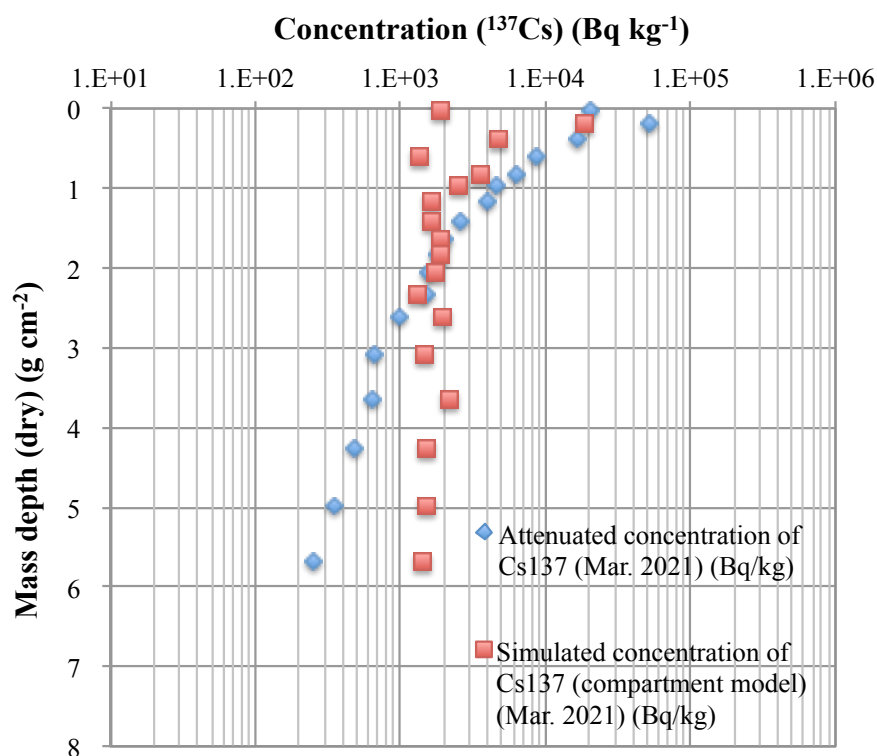
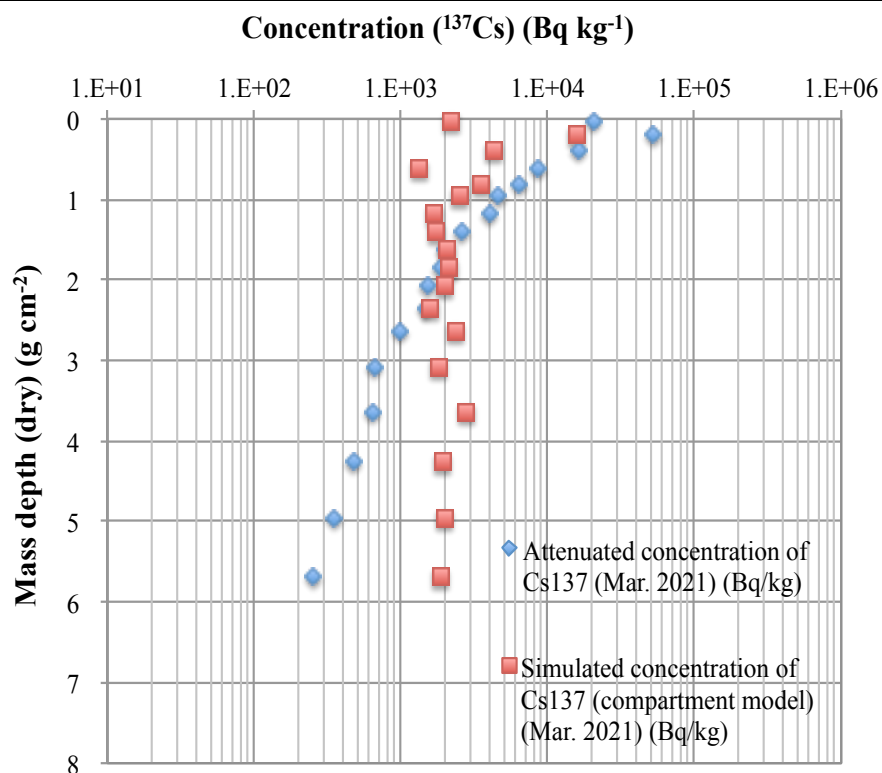


Fig. 4-39 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2021 in the forest with *Larix kaempferi*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-22 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2021 in the forest with *Larix kaempferi*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2021) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-1}+b)$ (Mar. 2021) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-b})$ (Mar. 2021) (Bq kg ⁻¹)
L	0.03	0.90	20,487	2,222	1,887
F	0.19	0.76	52,328	15,764	18,436
H	0.39	0.54	16,322	4,258	4,691
0-0.5	0.61	0.50	8,701	1,331	1,385
0.5-1.0	0.82	0.49	6,366	3,474	3,536
1.0-1.5	0.96	0.48	4,646	2,529	2,514
1.5-2.0	1.17	0.46	4,046	1,703	1,623
2.0-2.5	1.41	0.45	2,626	1,764	1,634
2.5-3.0	1.64	0.44	1,991	2,092	1,881
3.0-3.5	1.85	0.43	1,833	2,117	1,845
3.5-4.0	2.07	0.43	1,546	2,022	1,743
4.0-4.5	2.35	0.43	1,499	1,566	1,336
4.5-5.0	2.62	0.43	981	2,333	1,966
5.0-6.0	3.08	0.43	665	1,796	1,486
6.0-7.0	3.65	0.42	650	2,744	2,199
7.0-8.0	4.26	0.41	478	1,904	1,496
8.0-9.0	4.97	0.39	347	1,973	1,495
9.0-10.0	5.68	0.38	255	1,881	1,425

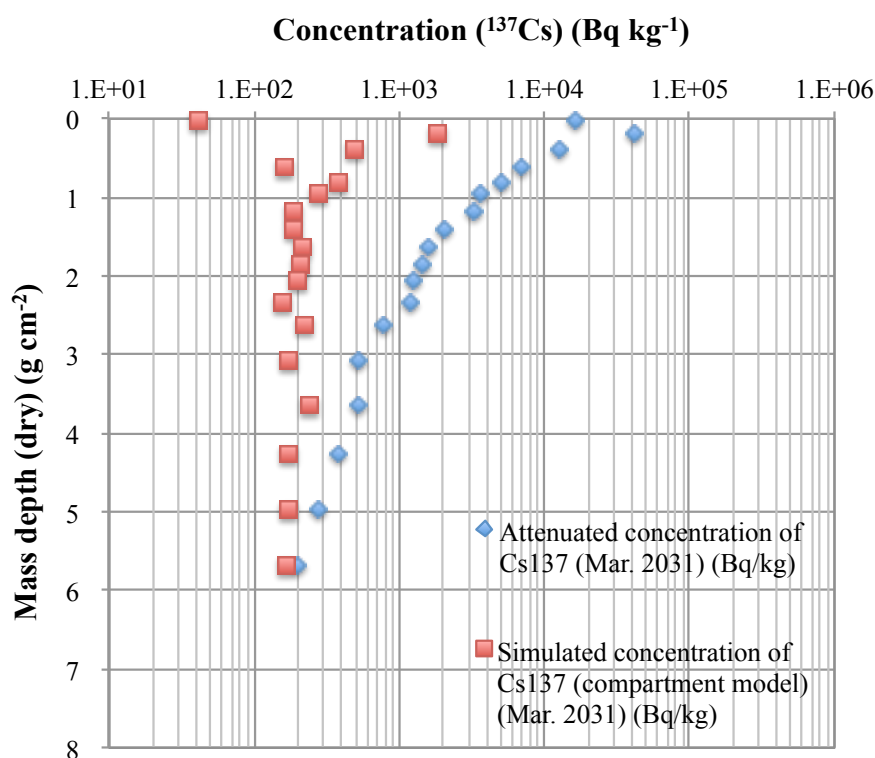
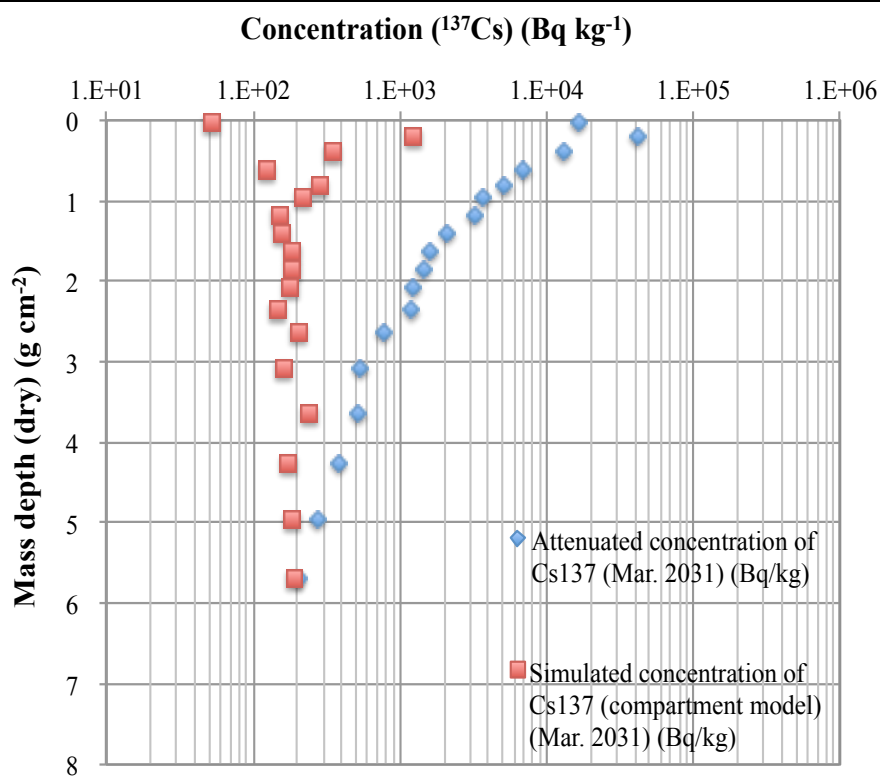


Fig. 4-40 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2031 in the forest with *Larix kaempferi*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-23 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2031 in the forest with *Larix kaempferi*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2031) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: ($P=aQ^{-1}+b$) (Mar. 2031) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: ($P=aQ^{-b}$) (Mar. 2031) (Bq kg ⁻¹)
L	0.03	0.90	16,279	52	41
F	0.19	0.76	41,581	1,212	1,855
H	0.39	0.54	12,970	345	491
0-0.5	0.61	0.50	6,914	122	159
0.5-1.0	0.82	0.49	5,058	288	378
1.0-1.5	0.96	0.48	3,692	216	276
1.5-2.0	1.17	0.46	3,215	153	186
2.0-2.5	1.41	0.45	2,086	158	187
2.5-3.0	1.64	0.44	1,582	184	213
3.0-3.5	1.85	0.43	1,456	187	210
3.5-4.0	2.07	0.43	1,228	180	200
4.0-4.5	2.35	0.43	1,191	144	158
4.5-5.0	2.62	0.43	780	205	223
5.0-6.0	3.08	0.43	528	162	172
6.0-7.0	3.65	0.42	517	238	243
7.0-8.0	4.26	0.41	380	175	171
8.0-9.0	4.97	0.39	275	187	171
9.0-10.0	5.68	0.38	202	191	167

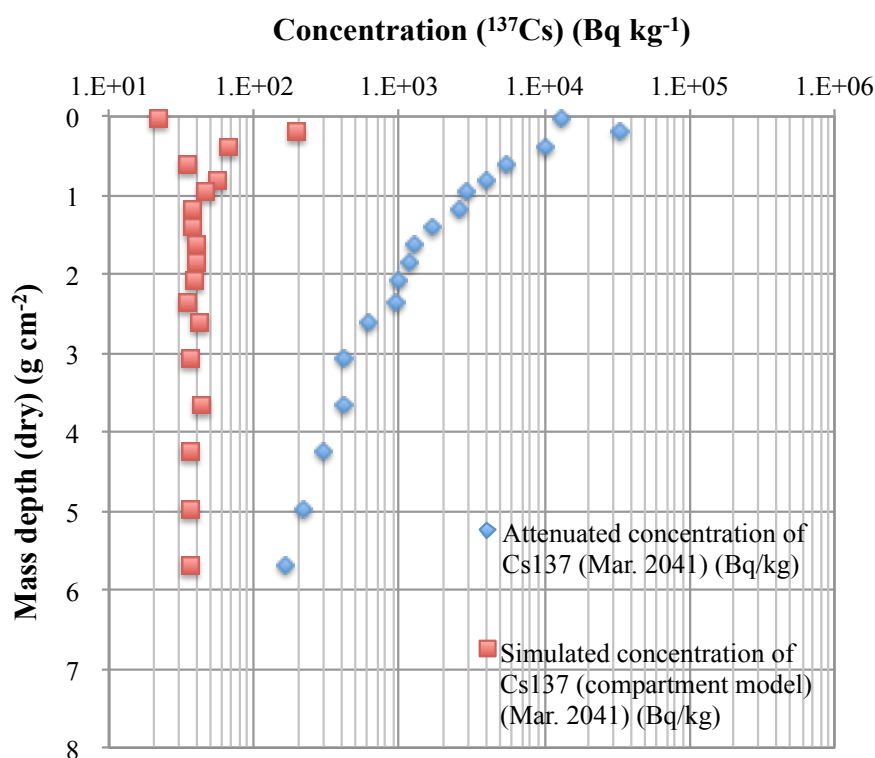
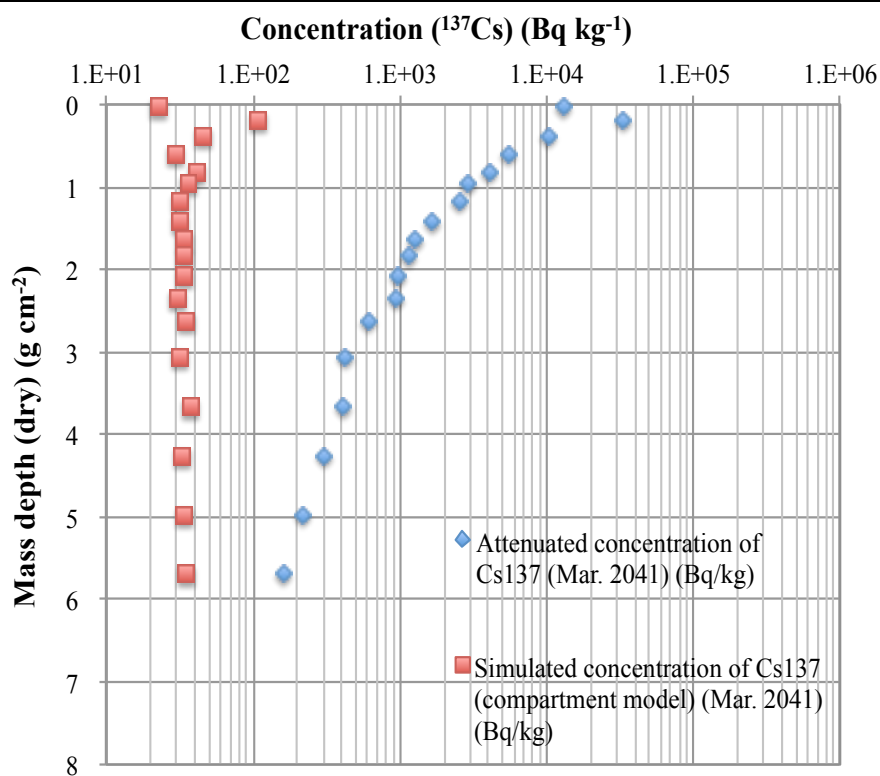


Fig. 4-41 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2041 in the forest with *Larix kaempferi*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-24 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2041 in the forest with *Larix kaempferi*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2041) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-1}+b)$ (Mar. 2041) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-b})$ (Mar. 2041) (Bq kg ⁻¹)
L	0.03	0.90	12,935	22	22
F	0.19	0.76	33,040	107	198
H	0.39	0.54	10,306	45	67
0-0.5	0.61	0.50	5,494	29	35
0.5-1.0	0.82	0.49	4,019	41	56
1.0-1.5	0.96	0.48	2,934	36	46
1.5-2.0	1.17	0.46	2,554	31	38
2.0-2.5	1.41	0.45	1,658	32	38
2.5-3.0	1.64	0.44	1,257	34	40
3.0-3.5	1.85	0.43	1,157	34	40
3.5-4.0	2.07	0.43	976	33	39
4.0-4.5	2.35	0.43	946	31	35
4.5-5.0	2.62	0.43	620	35	41
5.0-6.0	3.08	0.43	420	32	37
6.0-7.0	3.65	0.42	411	38	43
7.0-8.0	4.26	0.41	302	33	36
8.0-9.0	4.97	0.39	219	34	36
9.0-10.0	5.68	0.38	161	34	36

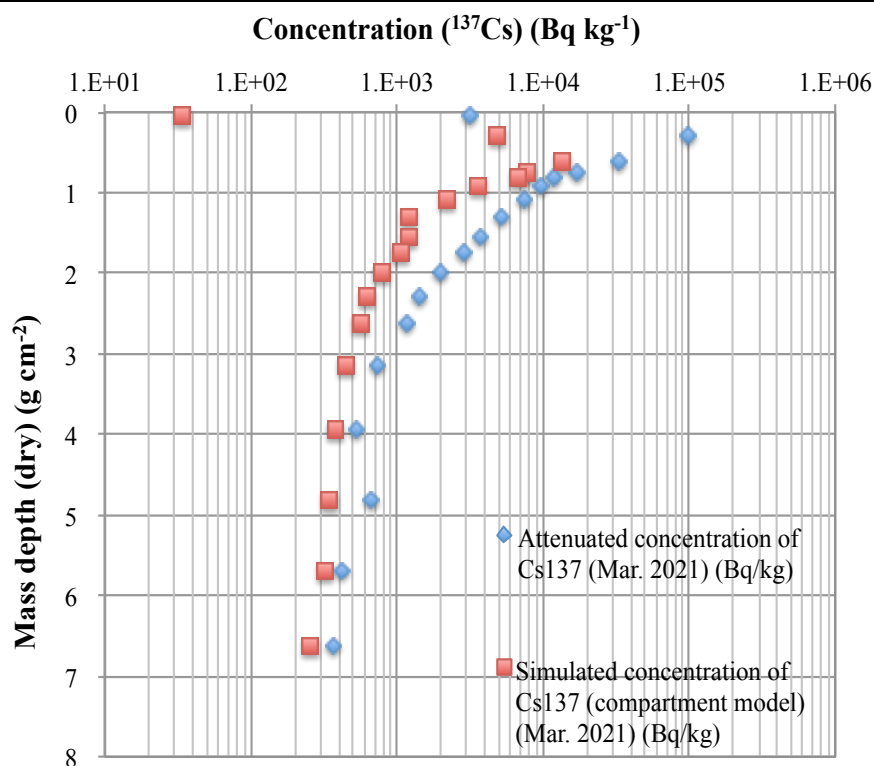
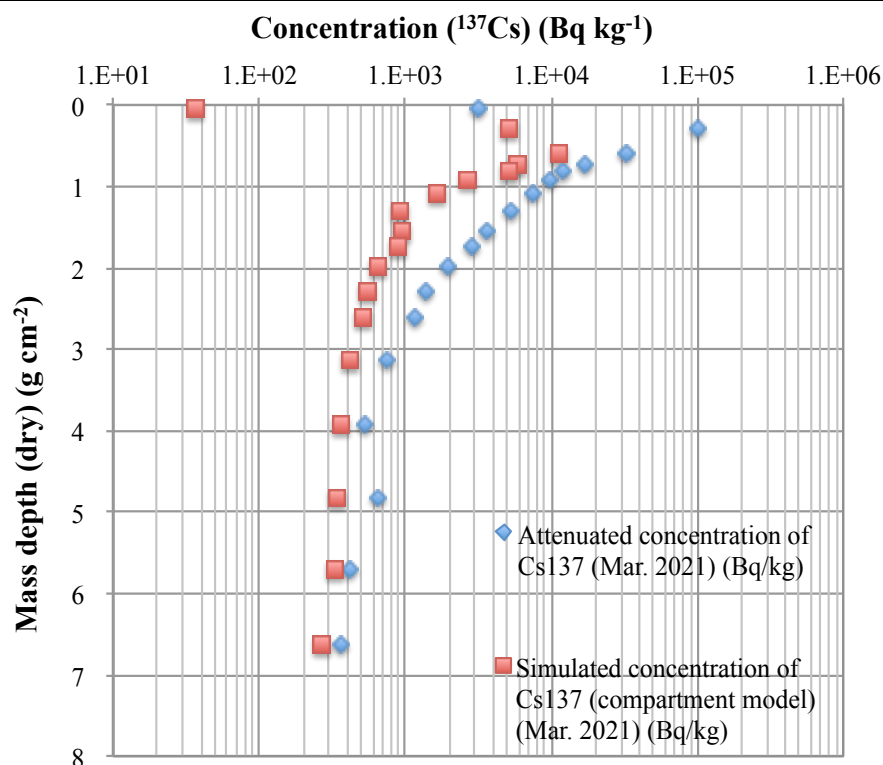


Fig. 4-42 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2021 in the forest with *Pinus densiflora*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-25 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2021 in the forest with *Pinus densiflora*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2021) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-1}+b)$ (Mar. 2021) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-b})$ (Mar. 2021) (Bq kg ⁻¹)
L	0.04	0.97	3,141	36	34
F	0.29	0.96	100,051	5,107	4,886
H	0.60	0.81	33,033	11,144	13,482
0-0.5	0.74	0.72	17,018	5,916	7,616
0.5-1.0	0.82	0.61	11,983	5,050	6,763
1.0-1.5	0.92	0.56	9,822	2,631	3,561
1.5-2.0	1.08	0.46	7,553	1,637	2,179
2.0-2.5	1.30	0.42	5,224	933	1,221
2.5-3.0	1.54	0.34	3,678	961	1,187
3.0-3.5	1.75	0.32	2,810	879	1,065
3.5-4.0	2.00	0.30	1,977	663	784
4.0-4.5	2.29	0.28	1,404	549	632
4.5-5.0	2.61	0.26	1,154	507	566
5.0-6.0	3.14	0.24	743	414	445
6.0-7.0	3.94	0.23	532	358	377
7.0-8.0	4.82	0.22	663	334	344
8.0-9.0	5.69	0.20	422	331	325
9.0-10.0	6.63	0.19	367	268	257

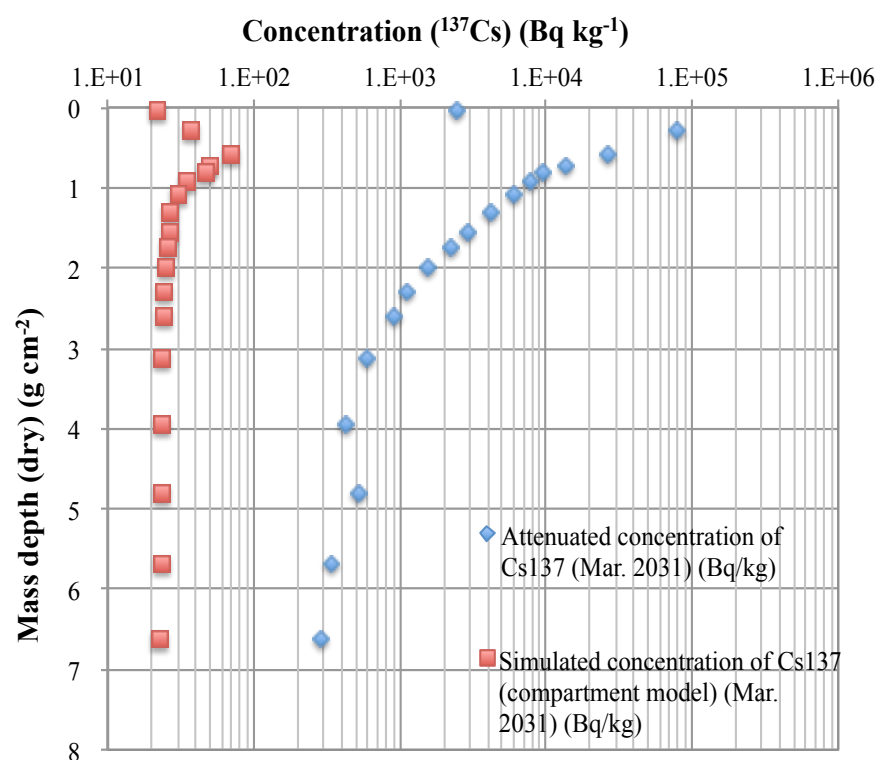
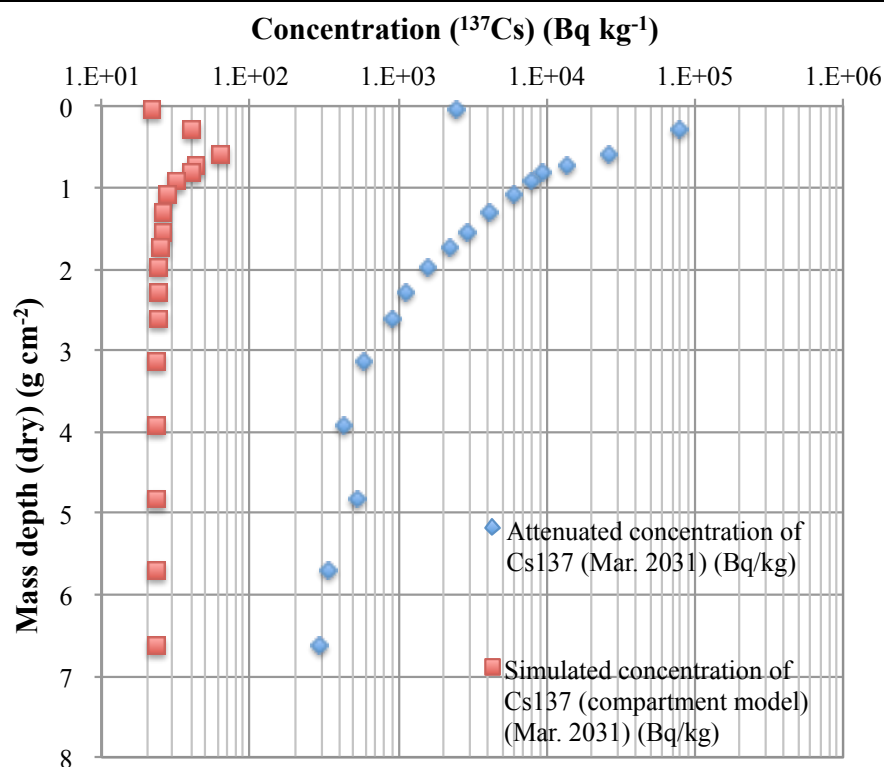


Fig. 4-43 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2031 in the forest with *Pinus densiflora*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-26 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2031 in the forest with *Pinus densiflora*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2031) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-1}+b)$ (Mar. 2031) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-b})$ (Mar. 2031) (Bq kg ⁻¹)
L	0.04	0.97	2,496	22	22
F	0.29	0.96	79,504	40	38
H	0.60	0.81	26,249	63	70
0-0.5	0.74	0.72	13,523	44	49
0.5-1.0	0.82	0.61	9,522	41	47
1.0-1.5	0.92	0.56	7,805	32	35
1.5-2.0	1.08	0.46	6,002	28	30
2.0-2.5	1.30	0.42	4,151	25	26
2.5-3.0	1.54	0.34	2,922	26	26
3.0-3.5	1.75	0.32	2,233	25	26
3.5-4.0	2.00	0.30	1,571	24	25
4.0-4.5	2.29	0.28	1,116	24	24
4.5-5.0	2.61	0.26	917	24	24
5.0-6.0	3.14	0.24	591	23	24
6.0-7.0	3.94	0.23	422	23	23
7.0-8.0	4.82	0.22	527	23	23
8.0-9.0	5.69	0.20	335	23	23
9.0-10.0	6.63	0.19	291	23	23

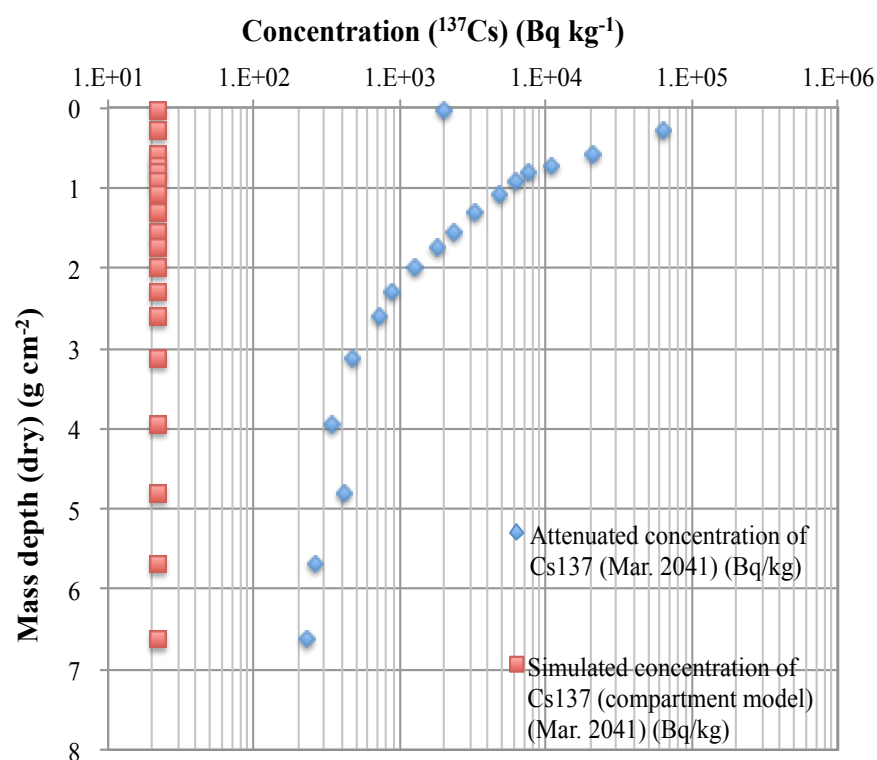
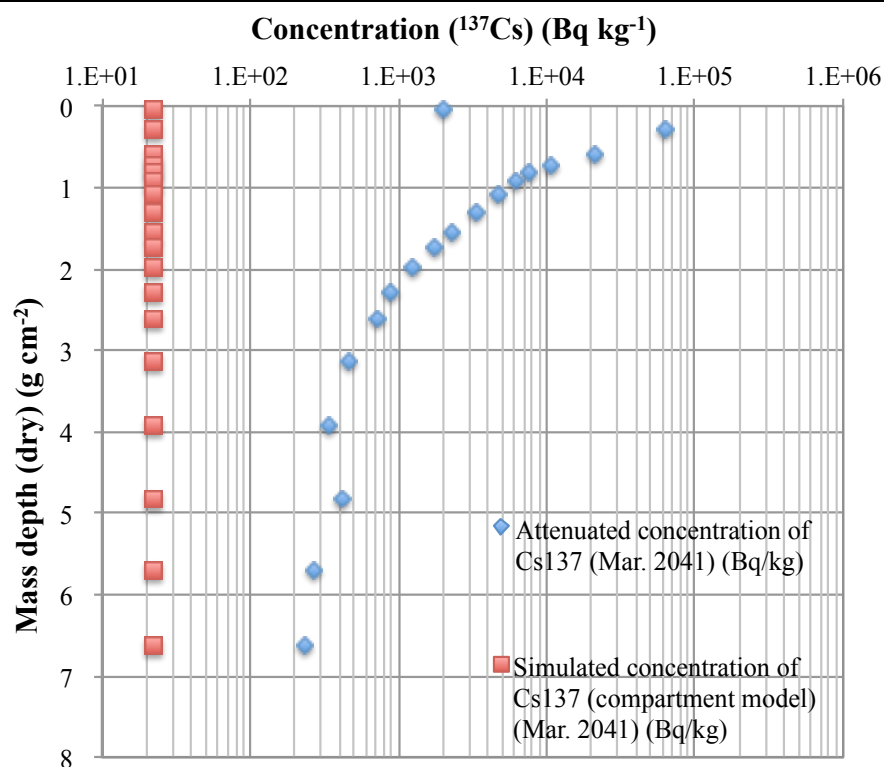


Fig. 4-44 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2041 in the forest with *Pinus densiflora*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-27 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2041 in the forest with *Pinus densiflora*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2041) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-1}+b)$ (Mar. 2041) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-b})$ (Mar. 2041) (Bq kg ⁻¹)
L	0.04	0.97	1,984	22	22
F	0.29	0.96	63,173	22	22
H	0.60	0.81	20,857	22	22
0-0.5	0.74	0.72	10,745	22	22
0.5-1.0	0.82	0.61	7,566	22	22
1.0-1.5	0.92	0.56	6,202	22	22
1.5-2.0	1.08	0.46	4,769	22	22
2.0-2.5	1.30	0.42	3,299	22	22
2.5-3.0	1.54	0.34	2,322	22	22
3.0-3.5	1.75	0.32	1,774	22	22
3.5-4.0	2.00	0.30	1,248	22	22
4.0-4.5	2.29	0.28	887	22	22
4.5-5.0	2.61	0.26	729	22	22
5.0-6.0	3.14	0.24	469	22	22
6.0-7.0	3.94	0.23	336	22	22
7.0-8.0	4.82	0.22	419	22	22
8.0-9.0	5.69	0.20	266	22	22
9.0-10.0	6.63	0.19	232	22	22

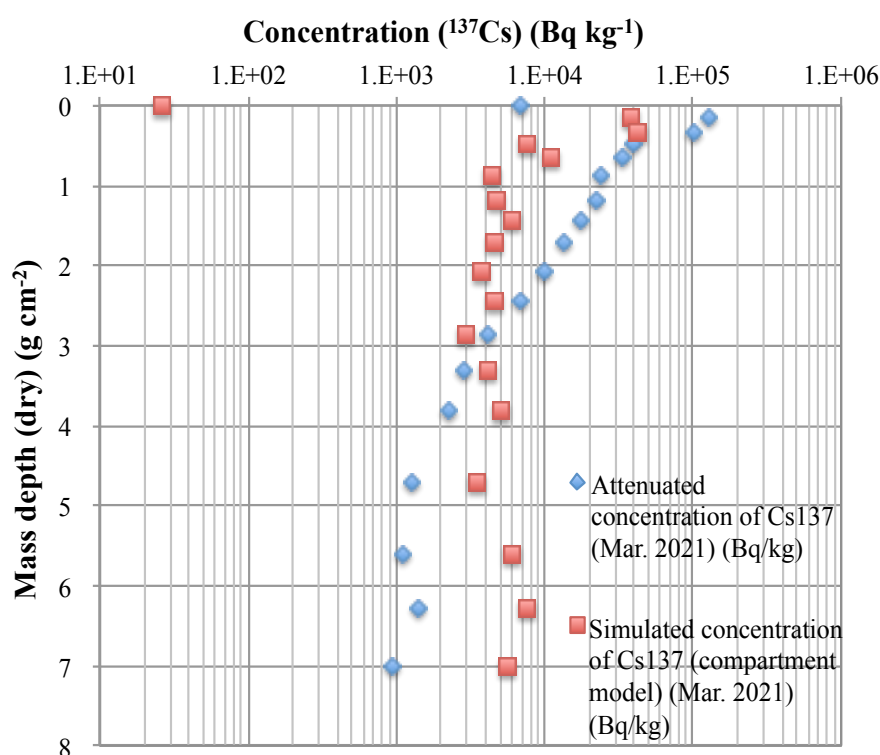
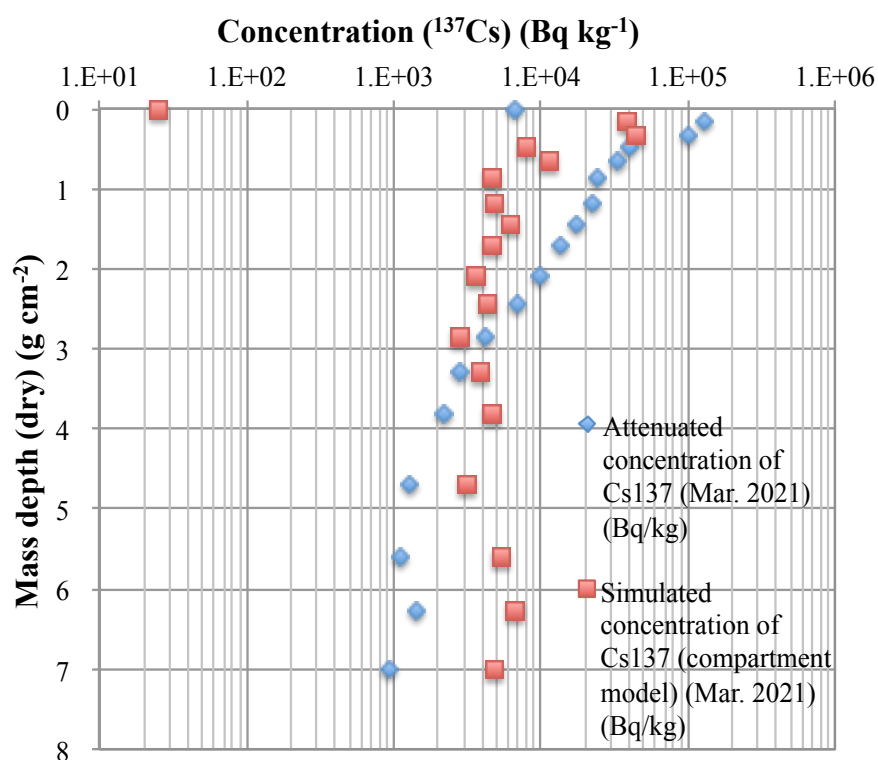


Fig. 4-45 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2021 in the forest with Deciduous broadleaf tree, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-28 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2021 in the forest with Deciduous broadleaf tree, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2021) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-1}+b)$ (Mar. 2021) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-b})$ (Mar. 2021) (Bq kg ⁻¹)
L	0.01	0.98	6,769	26	26
F	0.16	0.79	128,346	38,949	38,189
H	0.35	0.42	102,764	44,315	41,693
0-0.5	0.49	0.35	40,073	7,891	7,477
0.5-1.0	0.64	0.30	33,623	11,567	11,099
1.0-1.5	0.86	0.29	23,753	4,657	4,488
1.5-2.0	1.17	0.25	22,678	4,781	4,697
2.0-2.5	1.44	0.24	17,490	6,128	6,069
2.5-3.0	1.72	0.23	13,597	4,584	4,581
3.0-3.5	2.08	0.21	9,941	3,670	3,731
3.5-4.0	2.44	0.19	6,846	4,346	4,513
4.0-4.5	2.86	0.18	4,133	2,795	2,944
4.5-5.0	3.30	0.17	2,872	3,832	4,103
5.0-6.0	3.83	0.17	2,219	4,680	5,074
6.0-7.0	4.71	0.16	1,266	3,106	3,455
7.0-8.0	5.61	0.16	1,128	5,283	5,940
8.0-9.0	6.27	0.15	1,430	6,674	7,643
9.0-10.0	7.01	0.14	943	4,883	5,662

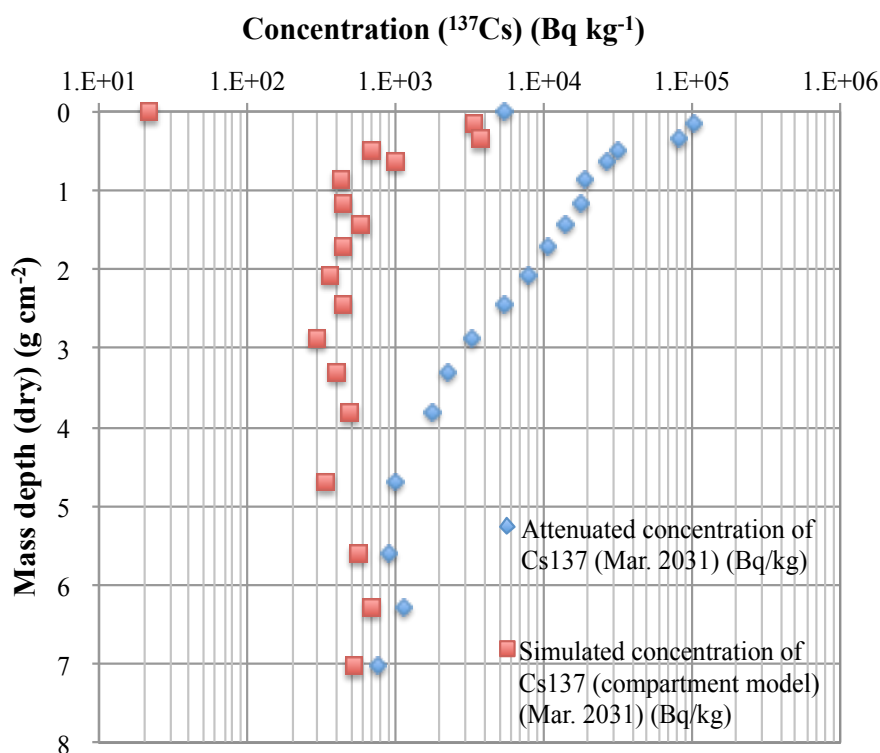
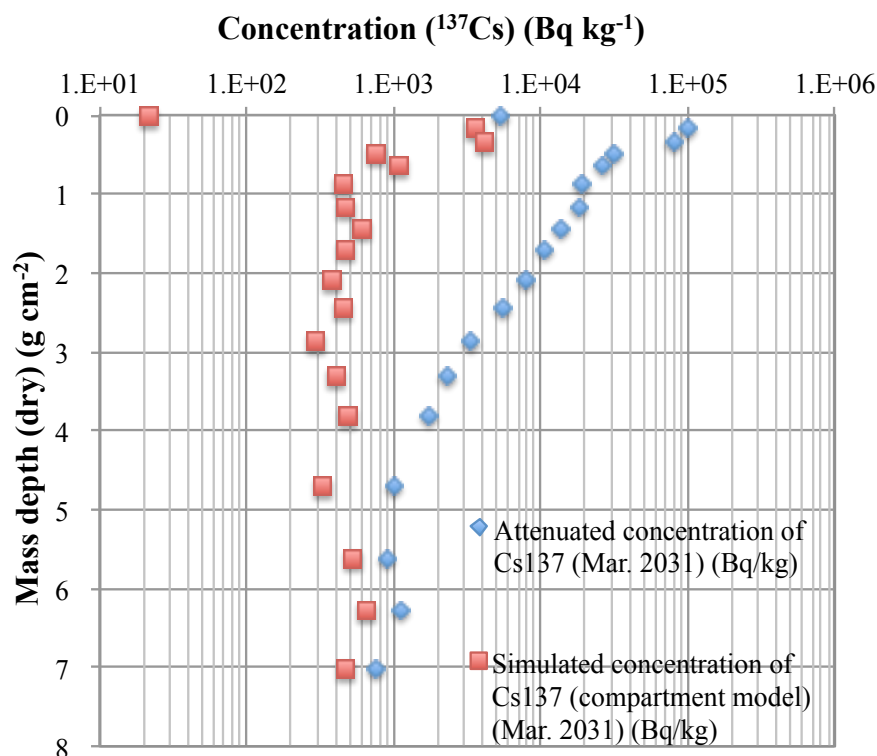


Fig. 4-46 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2031 in the forest with Deciduous broadleaf tree, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-29 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2031 in the forest with Deciduous broadleaf tree, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm^{-2})	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2031) (Bq kg^{-1})	Simulated concentration of ^{137}Cs (Compartment model: ($P=aQ^{-1}+b$) (Mar. 2031) (Bq kg^{-1})	Simulated concentration of ^{137}Cs (Compartment model: ($P=aQ^{-b}$) (Mar. 2031) (Bq kg^{-1})
L	0.01	0.98	5,379	22	22
F	0.16	0.79	101,989	3,542	3,352
H	0.35	0.42	81,660	4,104	3,709
0-0.5	0.49	0.35	31,843	751	684
0.5-1.0	0.64	0.30	26,718	1,098	1,011
1.0-1.5	0.86	0.29	18,875	457	423
1.5-2.0	1.17	0.25	18,021	473	445
2.0-2.5	1.44	0.24	13,898	605	573
2.5-3.0	1.72	0.23	10,804	462	441
3.0-3.5	2.08	0.21	7,899	377	365
3.5-4.0	2.44	0.19	5,440	447	441
4.0-4.5	2.86	0.18	3,284	297	296
4.5-5.0	3.30	0.17	2,283	402	407
5.0-6.0	3.83	0.17	1,764	486	497
6.0-7.0	4.71	0.16	1,006	325	339
7.0-8.0	5.61	0.16	897	528	555
8.0-9.0	6.27	0.15	1,136	648	698
9.0-10.0	7.01	0.14	750	474	523

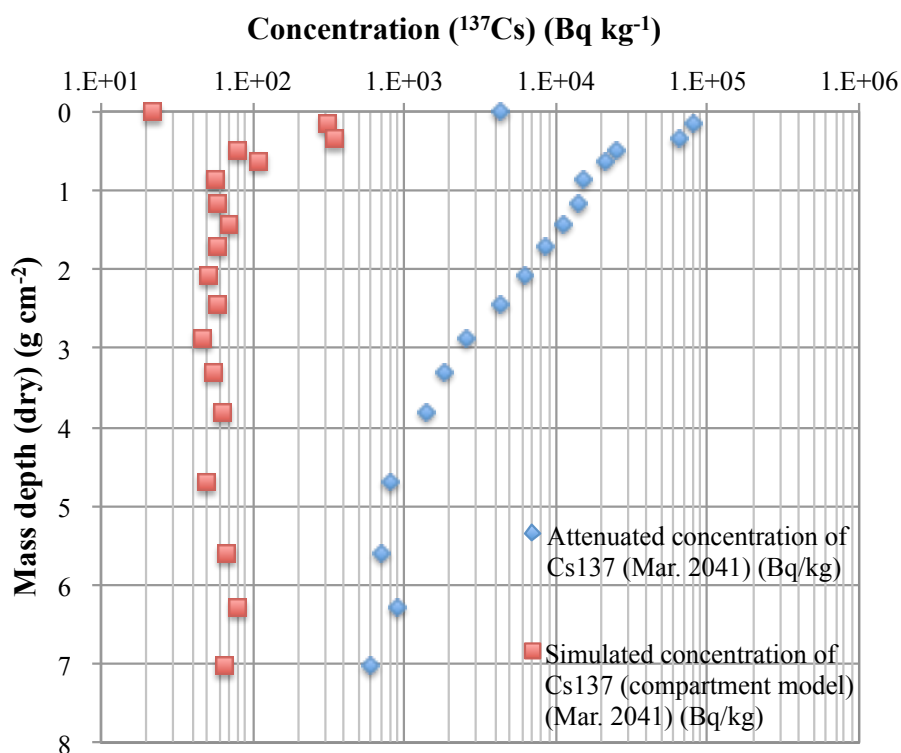
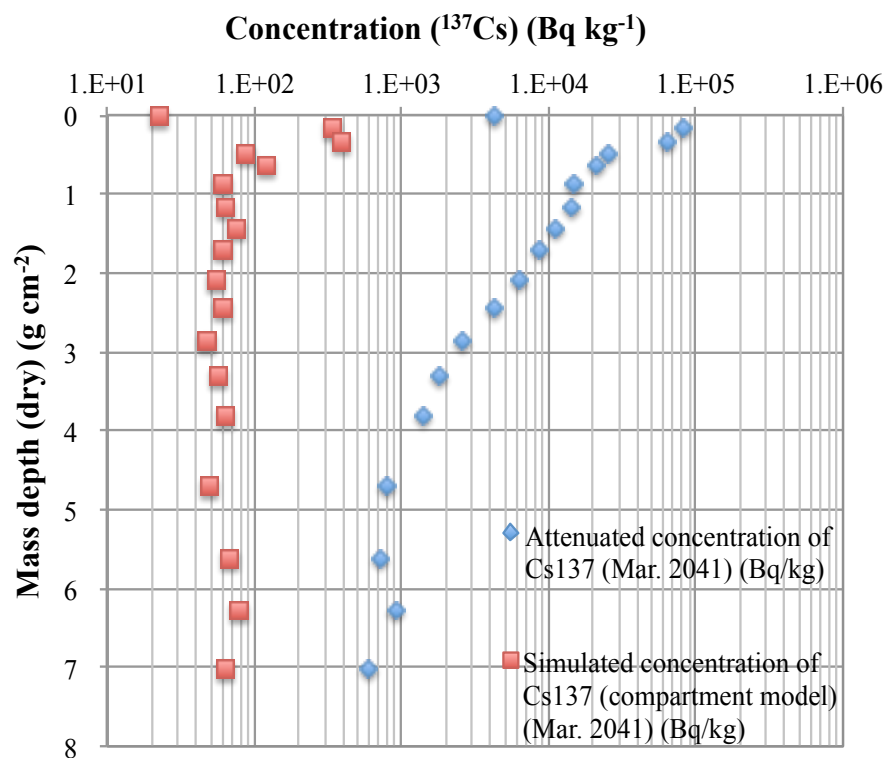


Fig. 4-47 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2041 in the forest with Deciduous broadleaf tree, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-30 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2041 in the forest with Deciduous broadleaf tree, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2041) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-1}+b)$ (Mar. 2041) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-b})$ (Mar. 2041) (Bq kg ⁻¹)
L	0.01	0.98	4,274	22	22
F	0.16	0.79	81,039	340	312
H	0.35	0.42	64,886	391	344
0-0.5	0.49	0.35	25,302	88	80
0.5-1.0	0.64	0.30	21,229	119	108
1.0-1.5	0.86	0.29	14,998	61	57
1.5-2.0	1.17	0.25	14,319	63	59
2.0-2.5	1.44	0.24	11,043	75	70
2.5-3.0	1.72	0.23	8,585	62	59
3.0-3.5	2.08	0.21	6,276	54	52
3.5-4.0	2.44	0.19	4,323	60	59
4.0-4.5	2.86	0.18	2,609	47	46
4.5-5.0	3.30	0.17	1,814	56	56
5.0-6.0	3.83	0.17	1,401	64	63
6.0-7.0	4.71	0.16	799	49	50
7.0-8.0	5.61	0.16	712	68	69
8.0-9.0	6.27	0.15	903	79	81
9.0-10.0	7.01	0.14	596	63	66

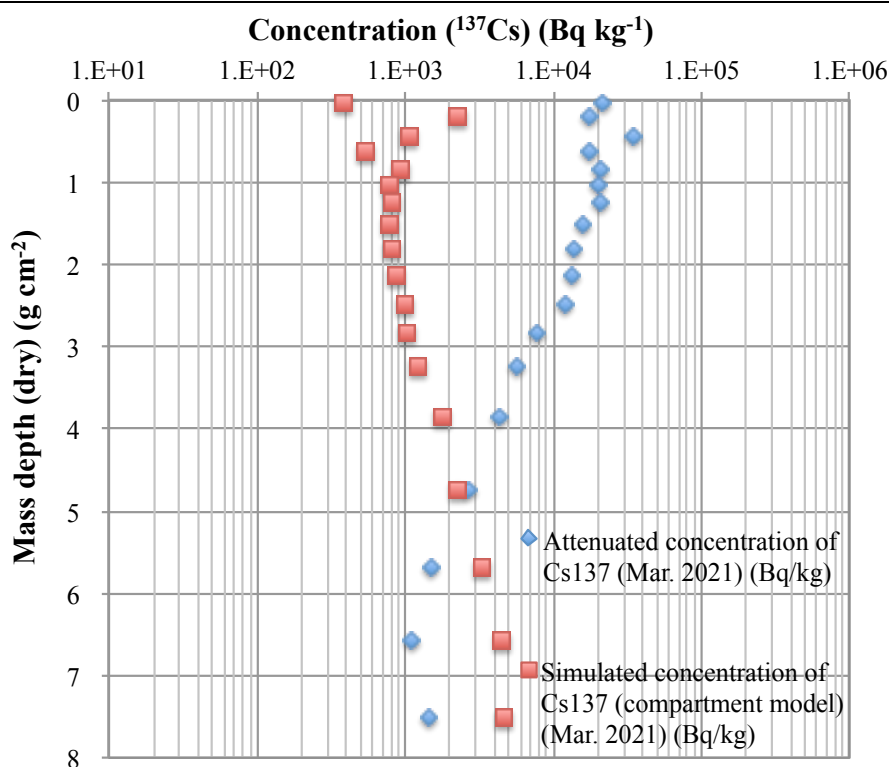
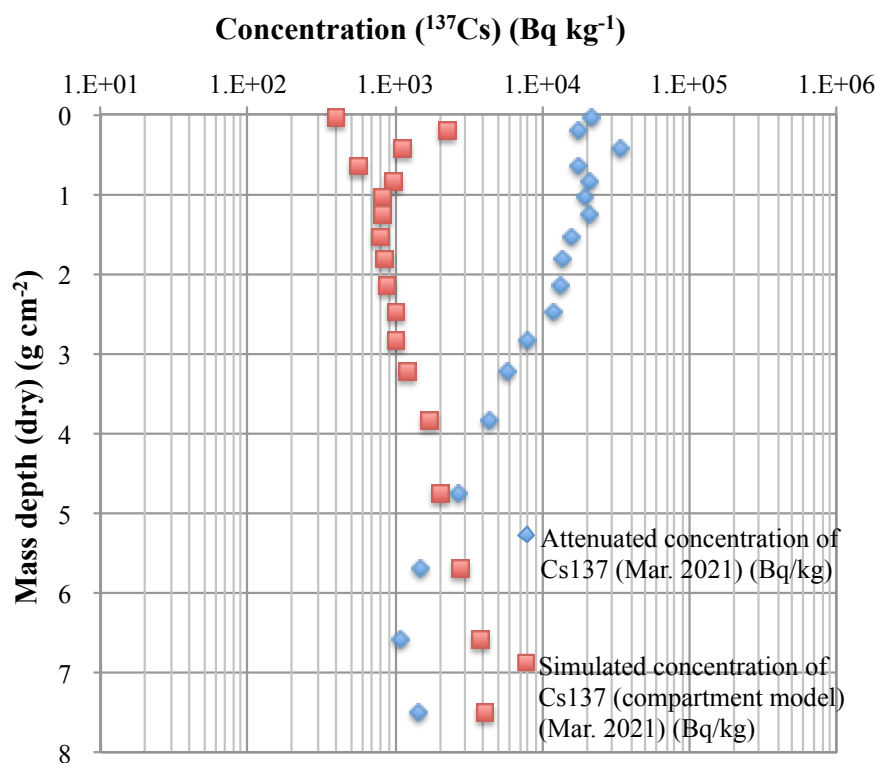


Fig. 4-48 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2021 in the forest with *Cryptomeria japonica*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-31 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2021 in the forest with *Cryptomeria japonica*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2021) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-1}+b)$ (Mar. 2021) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-b})$ (Mar. 2021) (Bq kg ⁻¹)
L	0.04	0.96	21,814	391	389
F	0.20	0.93	17,575	2,263	2,242
H	0.43	0.64	34,270	1,114	1,072
0-0.5	0.64	0.31	17,436	558	546
0.5-1.0	0.84	0.35	20,828	967	934
1.0-1.5	1.03	0.34	19,826	821	794
1.5-2.0	1.26	0.33	20,948	826	798
2.0-2.5	1.52	0.29	15,877	802	783
2.5-3.0	1.82	0.29	13,914	845	824
3.0-3.5	2.14	0.27	13,320	875	860
3.5-4.0	2.48	0.26	11,939	1,020	1,008
4.0-4.5	2.84	0.24	7,808	1,031	1,033
4.5-5.0	3.23	0.23	5,759	1,205	1,224
5.0-6.0	3.85	0.22	4,314	1,689	1,768
6.0-7.0	4.75	0.19	2,700	2,055	2,267
7.0-8.0	5.69	0.16	1,492	2,808	3,292
8.0-9.0	6.57	0.16	1,094	3,793	4,478
9.0-10.0	7.50	0.17	1,436	4,087	4,708

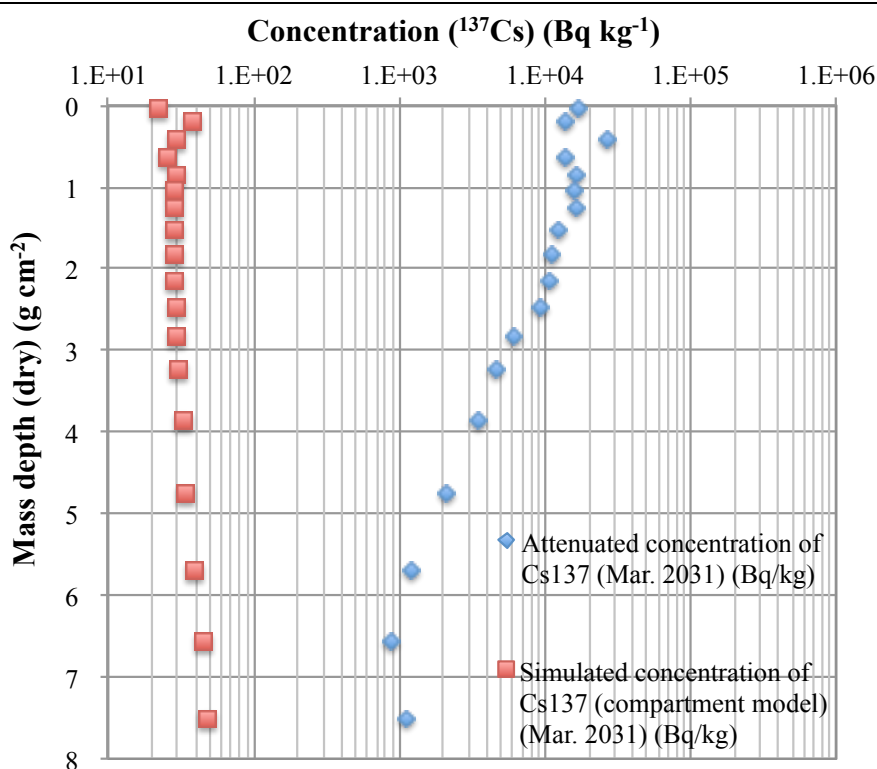
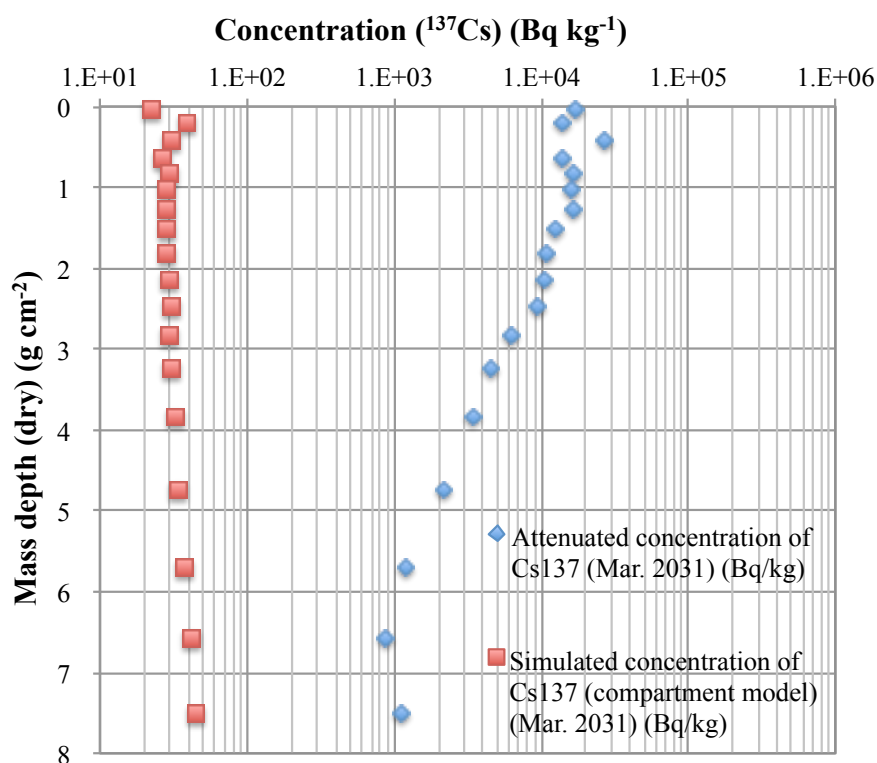


Fig. 4-49 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2031 in the forest with *Cryptomeria japonica*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-32 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2031 in the forest with *Cryptomeria japonica*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2031) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: ($P=aQ^{-1}+b$) (Mar. 2031) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: ($P=aQ^{-b}$) (Mar. 2031) (Bq kg ⁻¹)
L	0.04	0.96	17,334	22	22
F	0.20	0.93	13,966	39	38
H	0.43	0.64	27,232	30	30
0-0.5	0.64	0.31	13,855	26	26
0.5-1.0	0.84	0.35	16,551	30	29
1.0-1.5	1.03	0.34	15,754	28	28
1.5-2.0	1.26	0.33	16,646	29	28
2.0-2.5	1.52	0.29	12,617	28	28
2.5-3.0	1.82	0.29	11,057	29	29
3.0-3.5	2.14	0.27	10,585	29	29
3.5-4.0	2.48	0.26	9,487	30	30
4.0-4.5	2.84	0.24	6,204	30	30
4.5-5.0	3.23	0.23	4,576	31	31
5.0-6.0	3.85	0.22	3,428	33	33
6.0-7.0	4.75	0.19	2,145	34	35
7.0-8.0	5.69	0.16	1,185	37	39
8.0-9.0	6.57	0.16	869	42	46
9.0-10.0	7.50	0.17	1,141	45	49

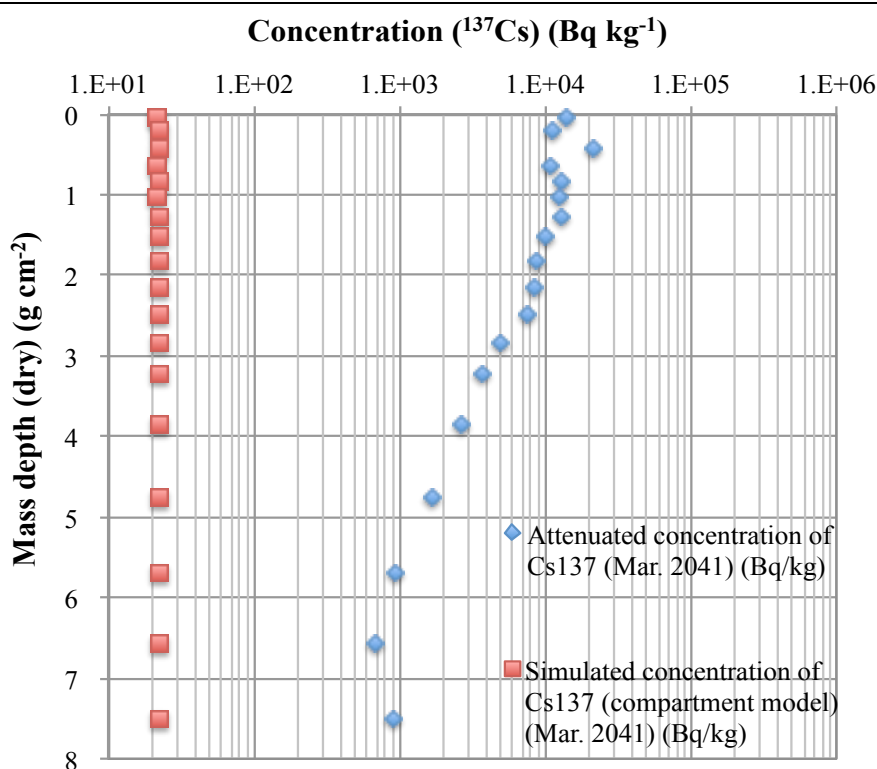
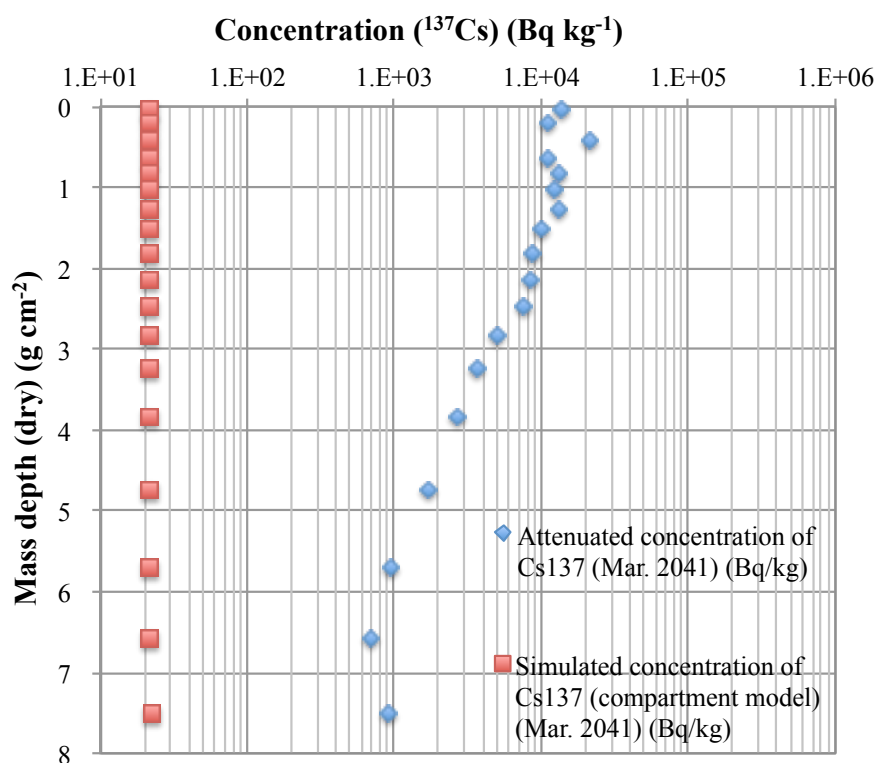


Fig. 4-50 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2041 in the forest with *Cryptomeria japonica*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-33 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2041 in the forest with *Cryptomeria japonica*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2041) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-1}+b)$ (Mar. 2041) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-b})$ (Mar. 2041) (Bq kg ⁻¹)
L	0.04	0.96	13,774	22	22
F	0.20	0.93	11,097	22	22
H	0.43	0.64	21,638	22	22
0-0.5	0.64	0.31	11,009	22	22
0.5-1.0	0.84	0.35	13,151	22	22
1.0-1.5	1.03	0.34	12,518	22	22
1.5-2.0	1.26	0.33	13,227	22	22
2.0-2.5	1.52	0.29	10,025	22	22
2.5-3.0	1.82	0.29	8,785	22	22
3.0-3.5	2.14	0.27	8,410	22	22
3.5-4.0	2.48	0.26	7,538	22	22
4.0-4.5	2.84	0.24	4,930	22	22
4.5-5.0	3.23	0.23	3,636	22	22
5.0-6.0	3.85	0.22	2,724	22	22
6.0-7.0	4.75	0.19	1,705	22	22
7.0-8.0	5.69	0.16	942	22	22
8.0-9.0	6.57	0.16	691	22	22
9.0-10.0	7.50	0.17	907	22	22

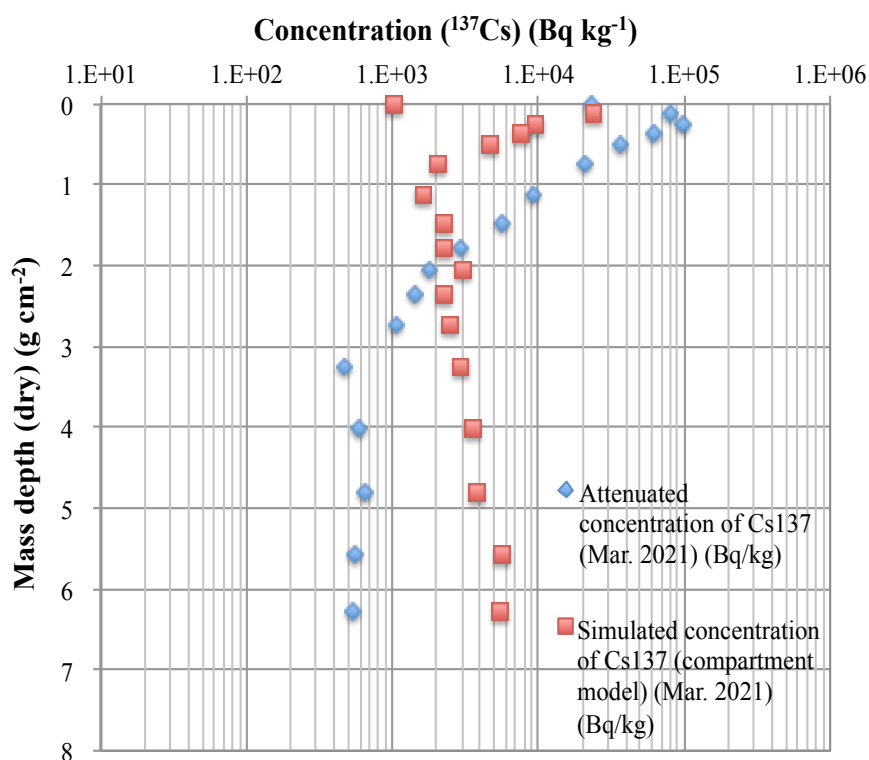
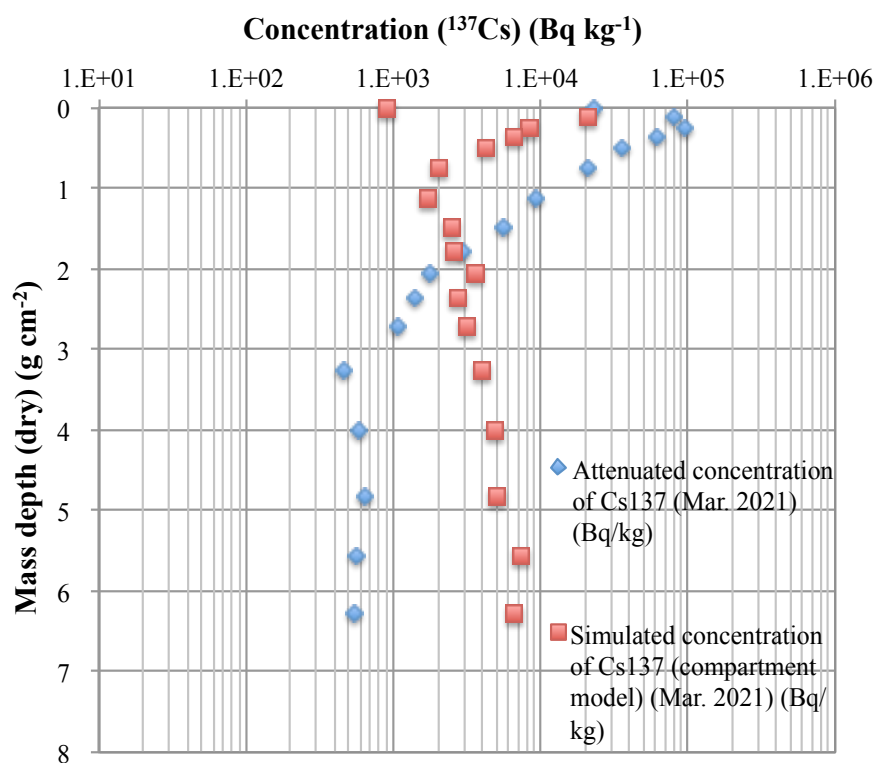


Fig. 4-51 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2021 in the forest with *Chamaecyparis obtusa*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-34 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2021 in the forest with *Chamaecyparis obtusa*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2021) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-1}+b)$ (Mar. 2021) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-b})$ (Mar. 2021) (Bq kg ⁻¹)
L	0.02	0.96	23,425	891	1,020
F	0.12	0.85	79,906	21,127	23,920
H	-	-	-	-	-
0-0.5	0.25	0.60	96,758	8,392	9,575
0.5-1.0	0.35	0.54	60,943	6,699	7,481
1.0-1.5	0.49	0.47	36,042	4,307	4,602
1.5-2.0	0.75	0.41	21,107	2,033	2,047
2.0-2.5	1.13	0.37	9,249	1,716	1,633
2.5-3.0	1.48	0.35	5,575	2,475	2,260
3.0-3.5	1.78	0.34	2,932	2,581	2,279
3.5-4.0	2.06	0.33	1,799	3,627	3,084
4.0-4.5	2.36	0.32	1,421	2,747	2,244
4.5-5.0	2.72	0.32	1,057	3,150	2,507
5.0-6.0	3.27	0.31	462	3,982	2,981
6.0-7.0	4.01	0.31	585	4,893	3,609
7.0-8.0	4.81	0.31	652	5,093	3,827
8.0-9.0	5.57	0.31	556	7,260	5,724
9.0-10.0	6.28	0.31	542	6,544	5,540

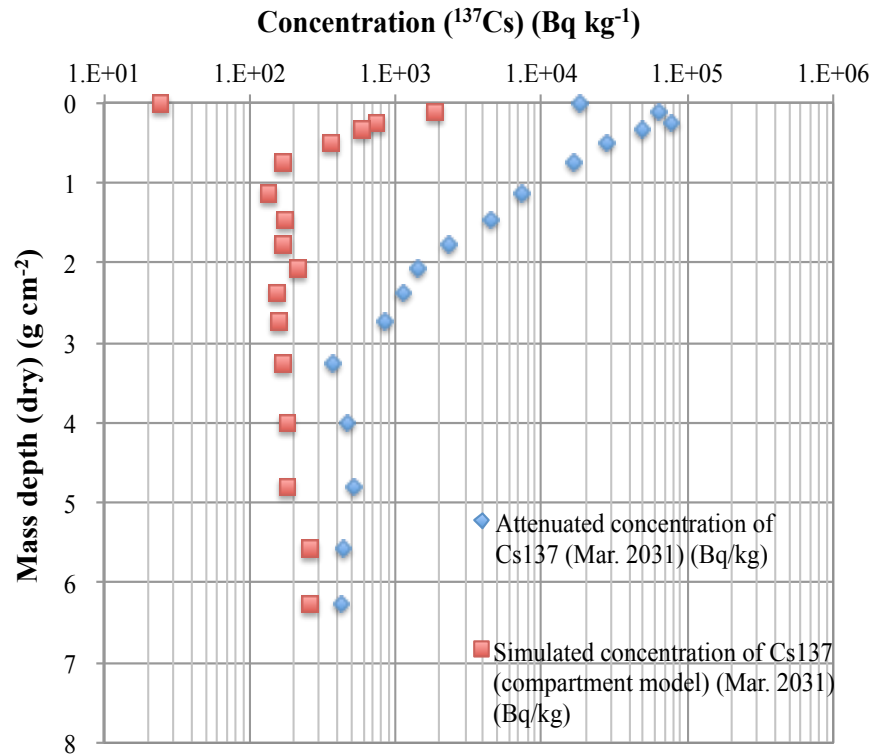
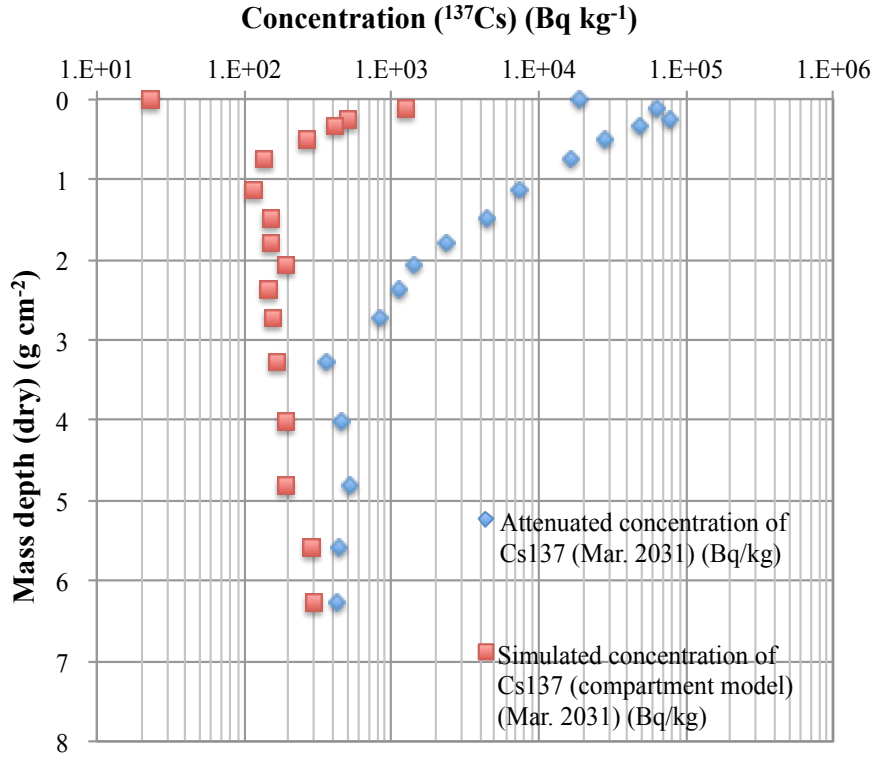


Fig. 4-52 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2031 in the forest with *Cryptomeria japonica*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-35 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2031 in the forest with *Chamaecyparis obtusa*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2031) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: ($P=aQ^{-1}+b$) (Mar. 2031) (Bq kg ⁻¹))	Simulated concentration of ^{137}Cs (Compartment model: ($P=aQ^{-b}$) (Mar. 2031) (Bq kg ⁻¹))
L	0.02	0.96	18,614	23	25
F	0.12	0.85	63,496	1,243	1,843
H	-	-	-	-	-
0-0.5	0.25	0.60	76,887	508	751
0.5-1.0	0.35	0.54	48,427	408	586
1.0-1.5	0.49	0.47	28,640	267	362
1.5-2.0	0.75	0.41	16,772	135	169
2.0-2.5	1.13	0.37	7,350	114	135
2.5-3.0	1.48	0.35	4,430	151	174
3.0-3.5	1.78	0.34	2,330	151	169
3.5-4.0	2.06	0.33	1,429	194	213
4.0-4.5	2.36	0.32	1,129	145	154
4.5-5.0	2.72	0.32	840	154	161
5.0-6.0	3.27	0.31	367	170	170
6.0-7.0	4.01	0.31	465	190	183
7.0-8.0	4.81	0.31	518	194	182
8.0-9.0	5.57	0.31	442	284	256
9.0-10.0	6.28	0.31	431	294	257

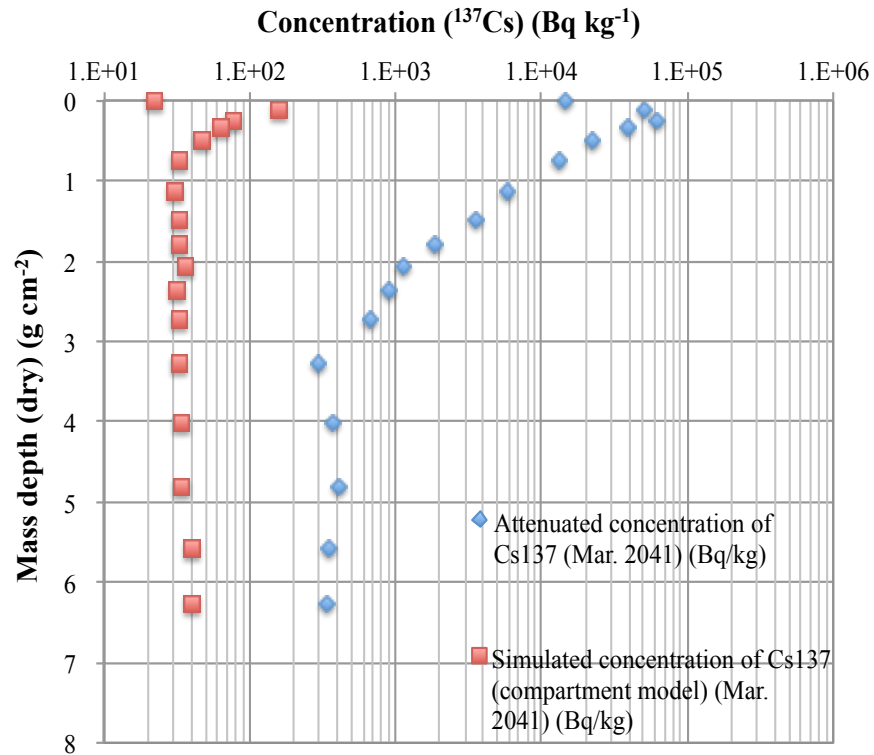
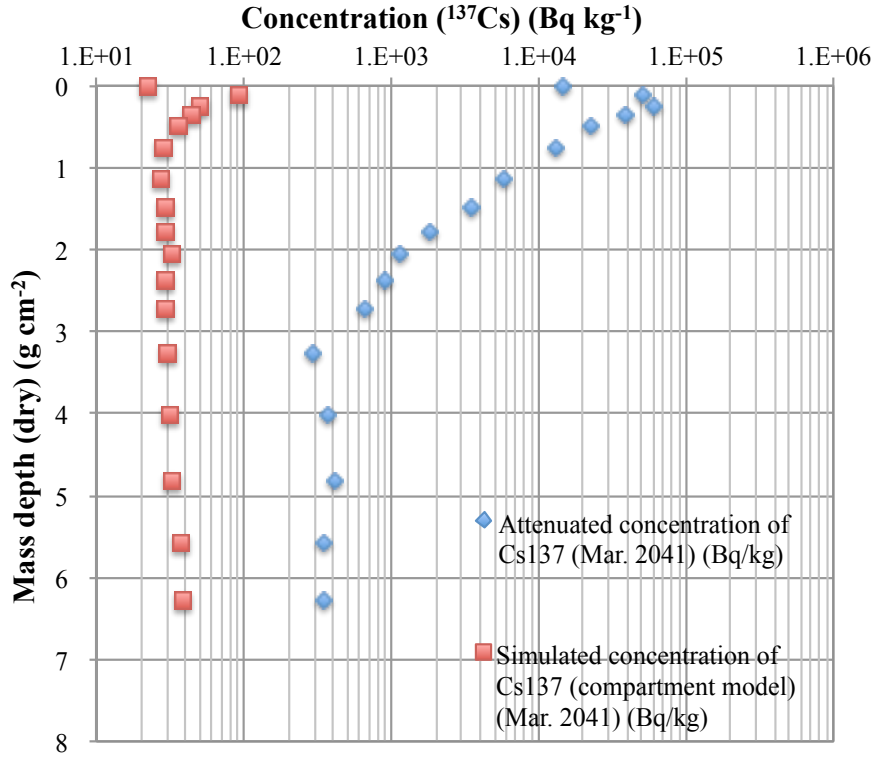


Fig. 4-53 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2041 in the forest with *Chamaecyparis obtusa*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

Table 4-36 Future mass depth profile of radioactive Cs (^{137}Cs) in Mar. 2041 in the forest with *Chamaecyparis obtusa*, represented by calculated values based on the physical attenuation and values simulated by the compartment model based on the ignition loss. In the compartment model, the transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ and $P=aQ^{-b}$.

Layer	Mass depth (g cm ⁻²)	Ignition loss	Attenuated concentration of ^{137}Cs (Mar. 2041) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-1}+b)$ (Mar. 2041) (Bq kg ⁻¹)	Simulated concentration of ^{137}Cs (Compartment model: $(P=aQ^{-b})$ (Mar. 2041) (Bq kg ⁻¹)
L	0.02	0.96	14,791	22	22
F	0.12	0.85	50,453	93	159
H	-	-	-	-	-
0-0.5	0.25	0.60	61,093	50	77
0.5-1.0	0.35	0.54	38,480	44	64
1.0-1.5	0.49	0.47	22,757	36	48
1.5-2.0	0.75	0.41	13,327	29	33
2.0-2.5	1.13	0.37	5,840	27	31
2.5-3.0	1.48	0.35	3,520	29	33
3.0-3.5	1.78	0.34	1,851	29	33
3.5-4.0	2.06	0.33	1,136	32	36
4.0-4.5	2.36	0.32	897	29	32
4.5-5.0	2.72	0.32	667	30	32
5.0-6.0	3.27	0.31	292	31	33
6.0-7.0	4.01	0.31	369	32	34
7.0-8.0	4.81	0.31	412	32	34
8.0-9.0	5.57	0.31	351	37	40
9.0-10.0	6.28	0.31	342	38	40

As a result of analyses, in all forests with different types of vegetation, the concentration of ^{137}Cs decreased by with time and was smaller than the values calculated only by considering the physical attenuation. In Mar. 2041, all concentration got lower than 100 Bq kg^{-1} in any forests and in any depths.

Given the fact that ^{137}Cs released through nuclear weapon testing in 1950s (UNSCEAR, 2008) was able to be detected with the peak in the soil layer within 10 cm from the top of the ground (Kang et al., 2017), it couldn't happen that the concentrations of ^{137}Cs in all depth will get as low as the background level in 30 years after the accident.

Some researchers reported that the depth profile of radioactive Cs was mainly determined by the initial migration during the first spell of rain (Schimmack et al., 1989), or the first 3 months after the first rainy season after the Fukushima Nuclear Power Plant accident (Matsunaga et al., 2013).

In addition, considering the academic report that migration speed became slower year by year (Rosen et al., 1999), the transition coefficients should be monitored because they gradually decreased.

In the wake of these results, the infiltration of ^{137}Cs will possibly be overestimated, if the constant transition coefficients are applied toward future prediction.

It also could be assumed that coefficient a and b don't represent the constant phenomena regarding the radioactive Cs infiltration, but represent the early stage after the accident which determined the distribution of radioactive Cs. Given the reports that the migration speed couldn't be different between the populated vegetations, transition coefficient "P" can be useful to compare the migration velocity between the different types of forests after the accident. In comparison of migration speed of each forest, in forests populated with *Pinus densiflora* and *Cryptomeria japonica* with large transition coefficient, in 30 years after the accident, the concentration of radioactive Cs decline to around the background level. On the other hand, in forests populated with *Larix kaempferi*, Deciduous broadleaf tree and *Chamaecyparis obtusa*, whose transition coefficients in organic layer are smaller, the radioactive Cs remain in organic layer, which is presumed to provide the radioactive Cs to soil layer comparatively for a long time (Fig. 4-54).

Comprehensive research should be continuously conducted to examine the mechanism of the adsorption of radioactive Cs to negative charges in soil followed by its downward migration. The method for evaluating residual radioactive Cs on surfaces (Mori et al., 2017) should also be also improved to aid in more effective decontamination activities.

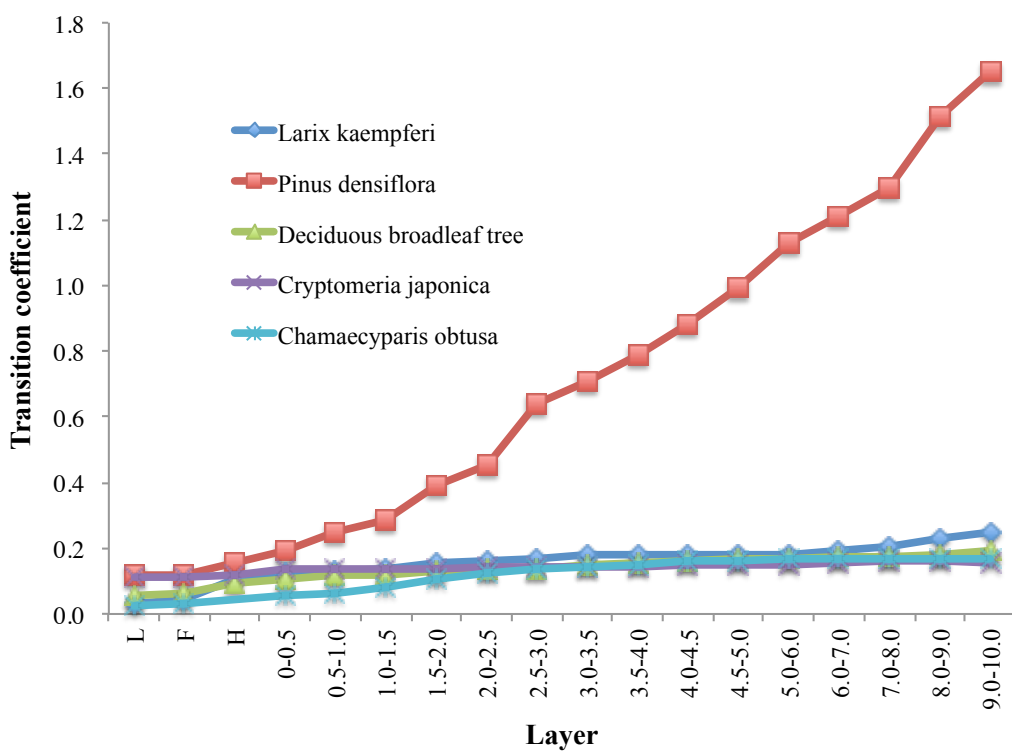
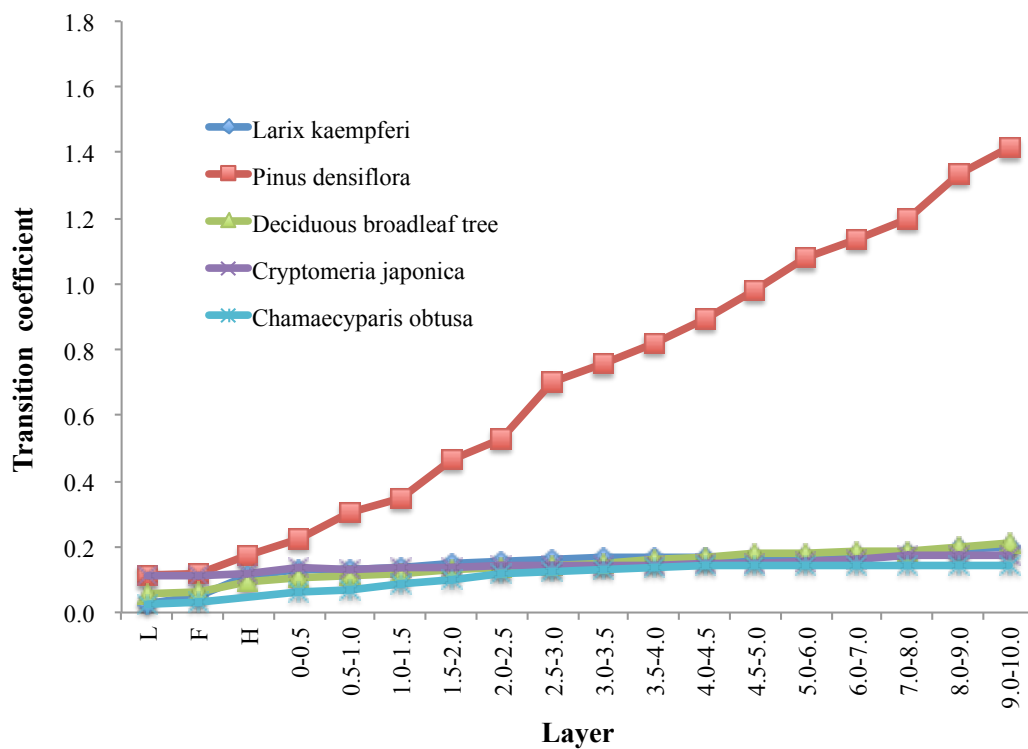


Fig. 4-54 Transition coefficient of each layer in five forests with different types of vegetation. The transition coefficient (P) was assumed to be expressed by the ignition loss (Q) through the equations: $P=aQ^{-1}+b$ (top) and $P=aQ^{-b}$ (bottom).

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5.1 Introduction

Radioactive substances scattered by the Fukushima Dai-ichi nuclear accidents have been removed through decontamination works from living areas based on guideline practices such as the wiping of roofs and walls in residences, the removal of topsoils in schools and parks, and the removal of organic matters in forests. The progress of decontamination activities in Special Decontamination Area (SDA) is separately represented in houses, farmlands, forests, and roads (MOE, 2017). Decontamination activities can be effective with an accurate grasp of the behaviors of radioactive substances, including the conditions of residual radioactive substances on surfaces. The combination of a scraper plate and Ge semiconductor detector, for example, is effective for estimating an accurate depth profile. Yet such a method incurs considerable time and cost for sampling, conveying, and monitoring.

Different types of radiation have different properties. Alpha rays can be shielded by thin paper, for example, while beta rays require shielding by plates of metal like aluminum and gamma rays require thick lead or iron (MOE, 2014). A scintillation survey meter detects only gamma rays, while a GM survey meter detects both beta rays and gamma rays, albeit with only low count efficiency for the latter (MOE, 2013a). A picture of the condition of residual radioactive Cs can be pieced together by accounting for the differences in characteristics between surface contamination concentration results with and without the use of an acrylic plate to eliminate background radiation or more accurately evaluate the radiation levels on surfaces (MOE, 2013b). This method, however, is applied in limited points among a great deal of monitoring points. The method cannot be realistically applied at all monitoring points, and depth profiles cannot be assumed from monitoring results obtained in the past.

In this research we tried to develop a method to evaluate the residual condition easily and inexpensively at decontamination sites with a focus on differences in radiation properties and in the detectors usually utilized in decontamination activities.

5.2 Materials and Methods

5.2.1 Scatter plot analyses of surface dose rates and surface contamination concentrations

There has yet to be sufficient research done to evaluate the influences of the nuclide-emitting beta rays such as ^{135}Cs and ^{90}Sr derived from the nuclear power plant accidents. We therefore consider only ^{134}Cs and ^{137}Cs , the two main types thought to remain in the environment.

Scatter plots were produced using mainly surface dose rates (ambient dose equivalent $H^*(10)$; monitoring point, 1 cm from the ground) and surface contamination concentrations (“dose rates” hereinafter) obtained by NaI scintillation survey meters (e.g., TCS-172B [then manufactured by Hitachi-Aloka Medical]) and GM survey meters (e.g., TGS-146 [then manufactured by Hitachi-Aloka Medical]). The monitoring data obtained under the snowy conditions were eliminated.

The data were obtained before decontamination activities (Sep. 2012 – Dec. 2015) were performed in forests and on paved and unpaved roads in SDA based on The Act on Special Measures Concerning the Handling of Radioactive Pollution.

While the dose rates in SDA are comparatively high, background radiation attributed to natural soil could not be ignored in low-dose-rate environments. Therefore, data indicating surface dose rates exceeding $0.6 \mu\text{Sv h}^{-1}$ and surface contamination concentration exceeding 300 cpm, values ranging from nearly several to ten times those measured in the uncontaminated area, were used. Dose rate monitoring was conducted at 20 - 50 m intervals along the edges of forests and at 10 - 30 m intervals along roads, respectively (MOE, 2013c).

5.2.2 Dose rate monitoring and depth profile analyses of radioactive Cs in forest areas

After the dose rates were monitored on the surface, depth profiles were analyzed in five different types of forests in a municipality of Fukushima Prefecture. The surface contamination concentration was monitored with and without acrylic plates. Specifically, three organic layers (L, F, H) and fifteen soil layers (ten at 0.5 cm intervals in the first 5 cm of depth and five at 1.0 cm intervals at 5 - 10 cm of depth) were monitored in forest areas dominated by the species *Larix kaempferi*, *Pinus densiflora*, Deciduous broadleaf tree, *Cryptomeria japonica*, and *Chamaecyparis obtusa*.

The L (Litter) layer on the top of the ground mainly consisted of fallen leaves and branches that remained almost undegraded. The F (Fermented) layer, the second layer from the top, mainly consisted of organic matter broken apart and decomposed by small animals and microorganisms. Though the original forms of the plants were unidentifiable, plant tissues could be confirmed by the naked eye. The material composing the H (Humus) layers was further degraded, wholly precluding any identification of the original forms. These materials took on a powdery state when dry and a fatty state when wet (JFTA, 2001).

The collected samples were preserved in U8 containers and monitored by a Ge semiconductor detector (ORTEC GMX-30190) to determine radiation concentrations. All concentrations were re-calculated using attenuated correction up to Oct. 1, 2015.

The relation between the concentration of radioactive Cs and mass depth (wet) was analyzed. The relaxation mass depth (wet) was calculated using hyperbolic secant (sech) and hyperbolic cosine (cosh) functions, that is, equation (1) (Matsuda et al., 2015).

$$A_m(\zeta) = A_{m,0} \cosh(\zeta_0/\beta_w) \text{sech}(-(\zeta - \zeta_0)/\beta_w) \quad (1)$$

where ζ is the mass depth (g cm^{-2}), A_m is the concentration at the mass depth ζ (Bq kg^{-1}), $A_{m,0}$ is the concentration at the ground surface (Bq kg^{-1}), ζ_0 is the mass depth from the ground surface to the point of maximum concentration (g cm^{-2}), and β_w is the relaxation mass depth (wet) (g cm^{-2}).

$A_{m,0}$, β_w , and ζ_0 are determined by an iterative approach using the solver function in Excel (Microsoft Office).

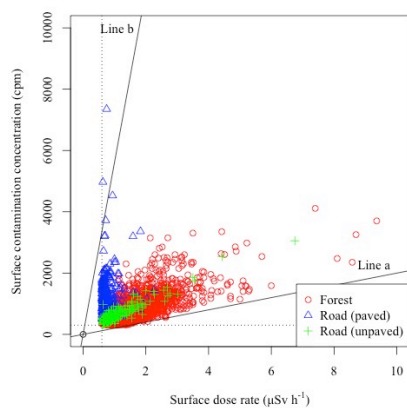
5.3 Results and considerations

5.3.1 Scatter plot analyses of surface dose rates and surface contamination concentrations

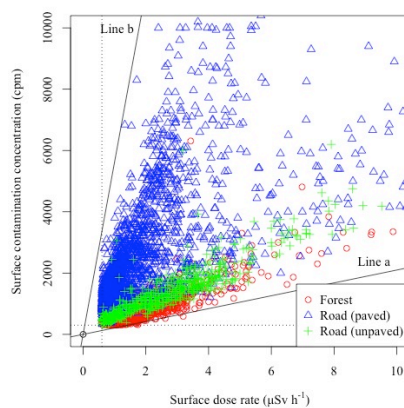
The scatter plot shown in Fig. 5-1 analyzes the relation between the surface dose rate and surface contamination concentration. The number of data points collected each month is shown in Table 5-1 and Fig. 5-2. Data at some of the points were not plotted because the horizontal axis ranged from 0 to 10 $\mu\text{Sv h}^{-1}$ and the vertical axis ranged from 0 to 10,000 cpm. Positive correlations were found for both surface dose rate and surface contamination concentration in all three categories (forests, paved roads, unpaved roads). In addition, low surface contamination concentrations were recorded at monitoring points in forest and on unpaved roads even under conditions with high surface dose rates. Conversely, higher contamination concentrations were observed on paved roads than in forests and on unpaved roads, even under conditions with low surface dose rates.

Based on the results, a line was drawn through the original point and lower limit of points in each scatter diagram (hereinafter referred to as “Line a”). The slope of Line a is assumed to represent the ratio between the surface dose rate and surface contamination concentration under conditions where almost all beta rays are shielded and only gamma rays are detected.

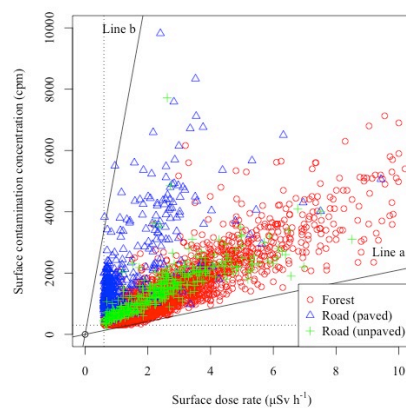
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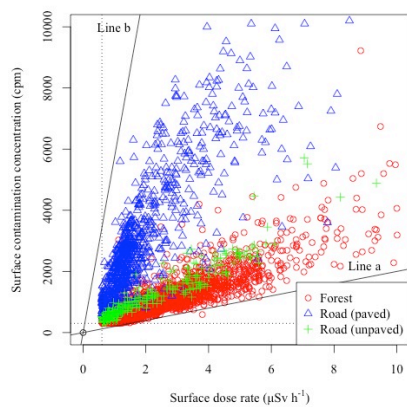
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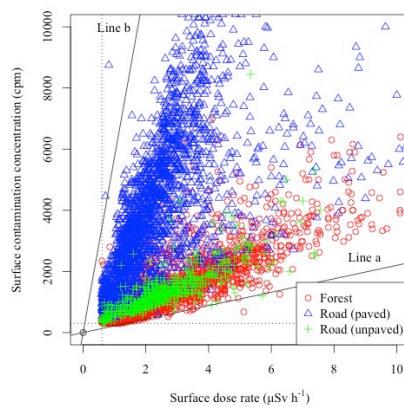
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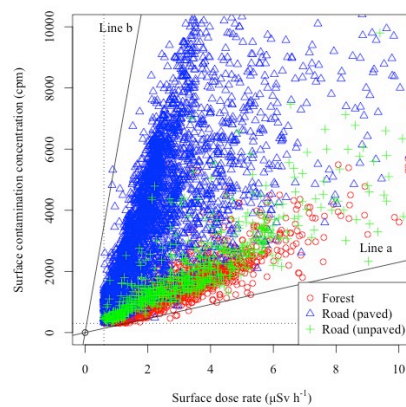
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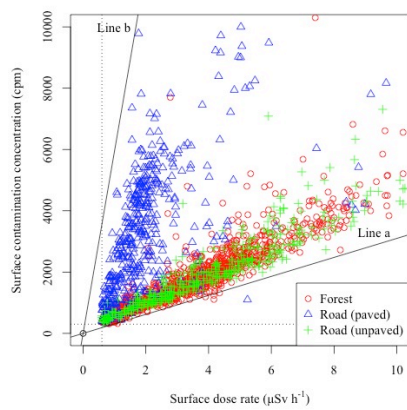
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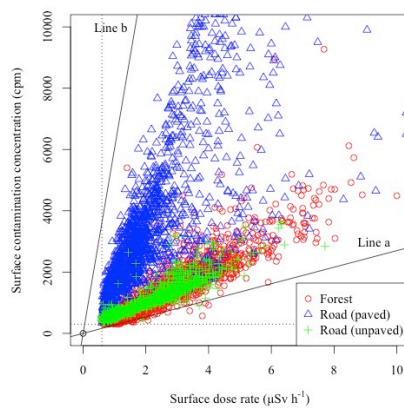
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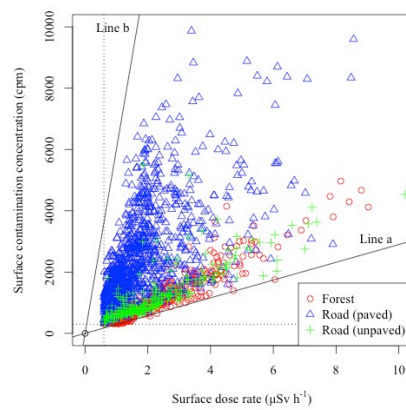
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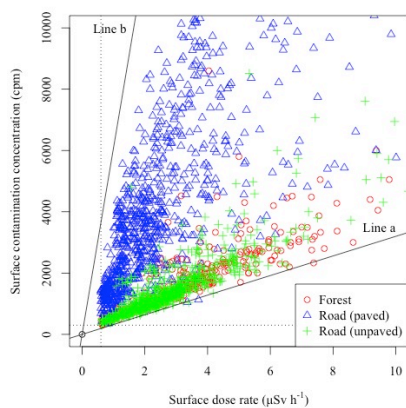
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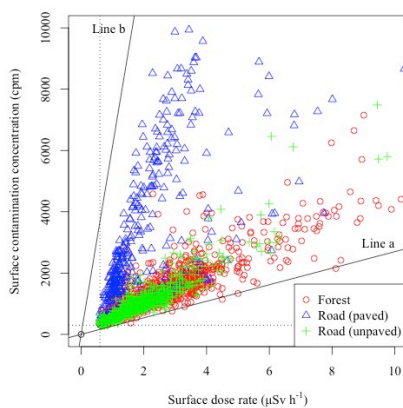
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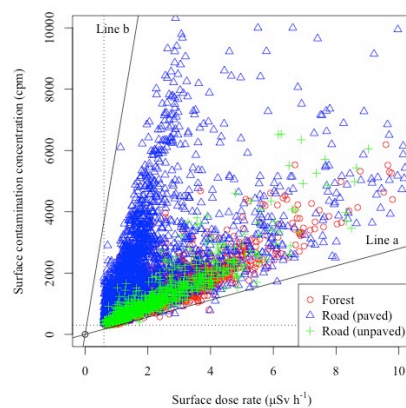
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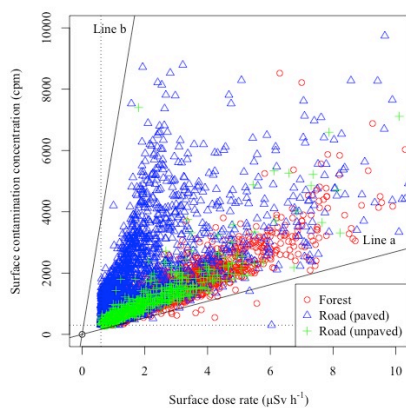
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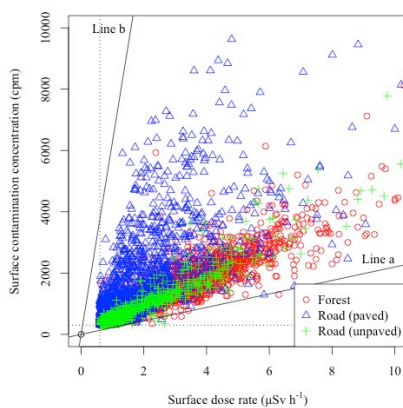
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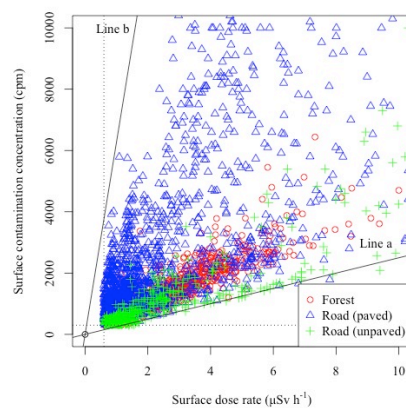
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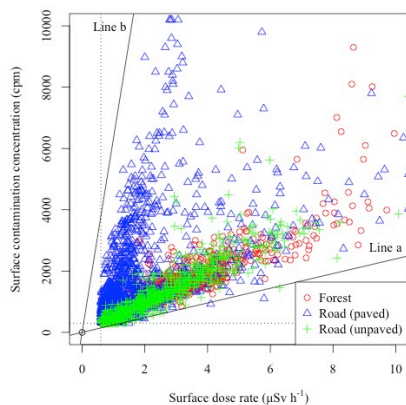
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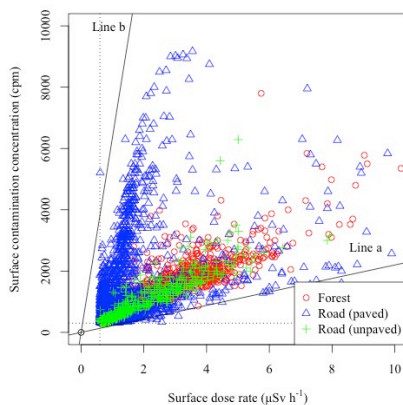
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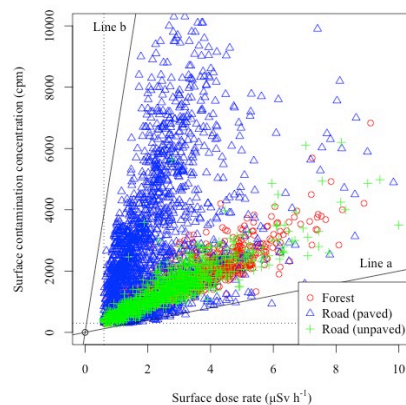
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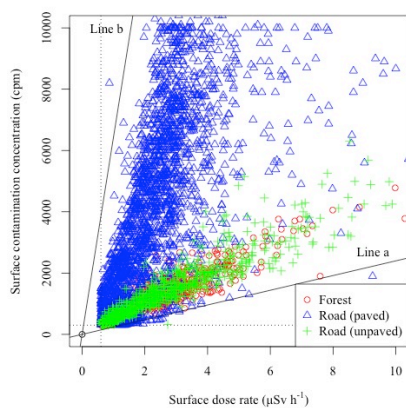
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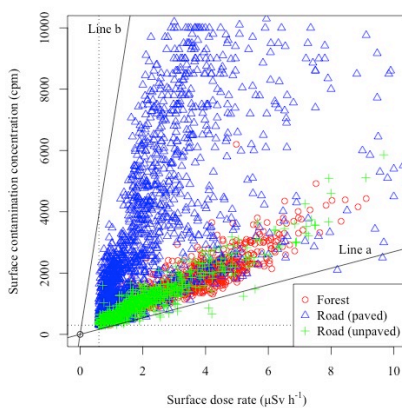
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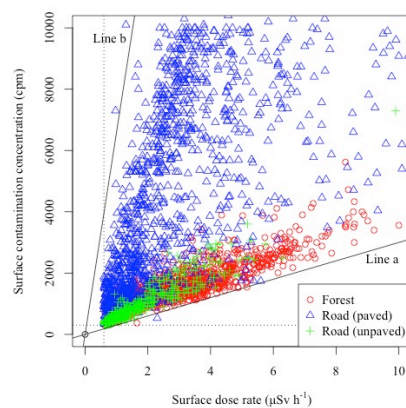
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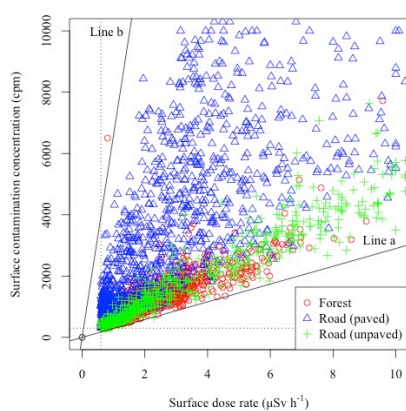
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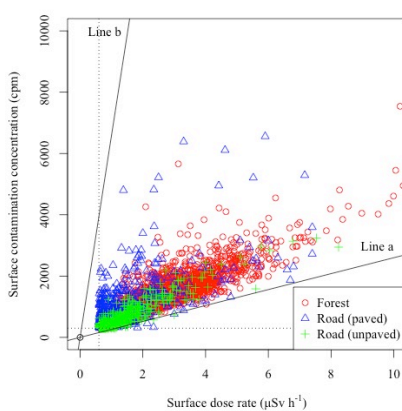
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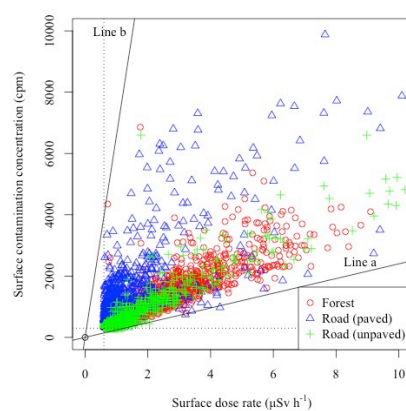
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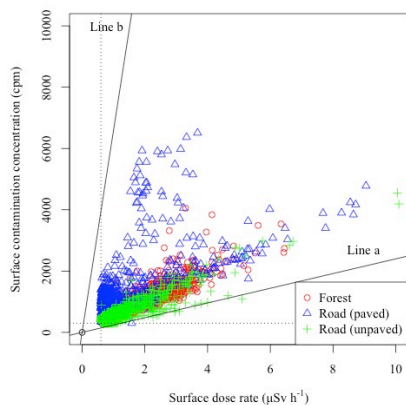
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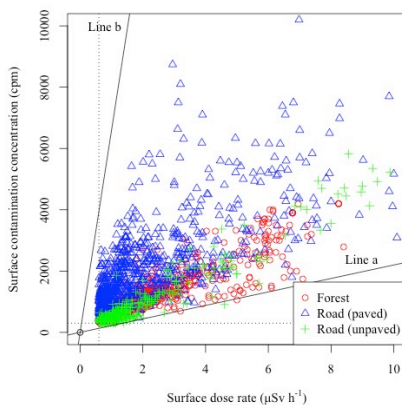
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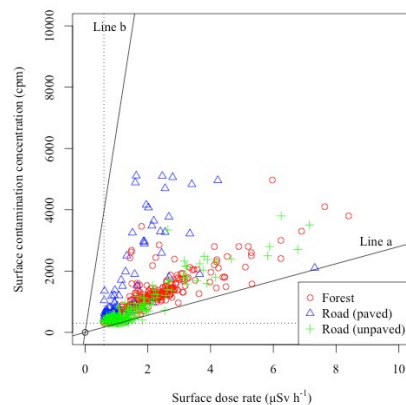
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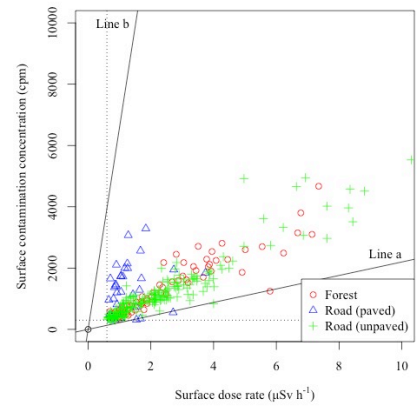
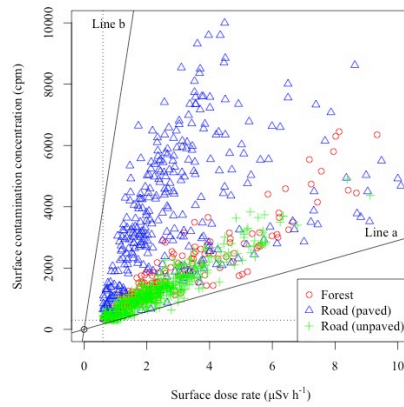
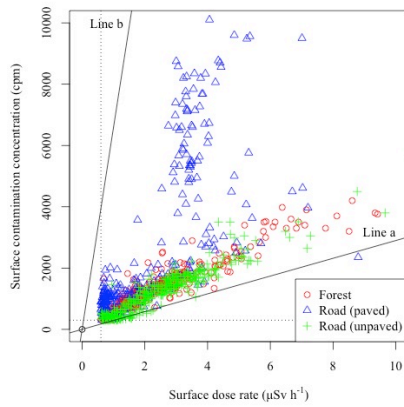
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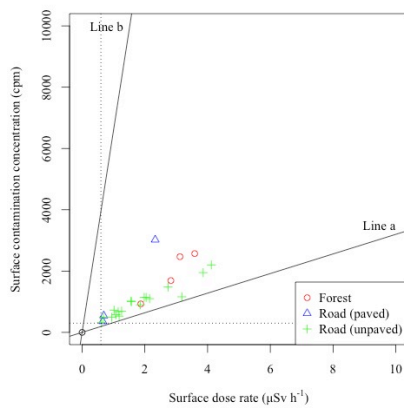


Fig. 5-1 Scatter plots of surface dose rates and surface contamination concentrations (Sep. 2012 - Dec. 2015). Points with surface dose rates of 0 - 10 $\mu\text{Sv h}^{-1}$ and surface contamination concentrations of 0 - 10,000 cpm are plotted.

Table 5-1 The number of data points in each category of each month

	09/201	10/201	11/201	12/201	01/201	02/201	03/201	04/201	05/201
	2	2	2	2	3	3	3	3	3
Forest	556	3,062	1,446	392	273	367	505	829	2,634
Paved road	347	1,529	502	308	116	229	52	269	121
Unpaved road	5	105	86	133	28	17	9	16	66
	06/2013	07/2013	08/2013	09/2013	10/2013	11/2013	12/2013	01/2014	02/2014
Forest	2,875	2,434	3,243	3,897	3,952	3,209	1,445	2,616	534
Paved road	218	1,869	413	814	2,199	3,098	480	1,638	1,031
Unpaved road	205	632	371	244	586	686	433	829	232
	03/201	04/201	05/201	06/201	07/201	08/201	09/201	10/201	11/201
	4	4	4	4	4	4	4	4	4
Forest	333	1,273	2,704	3,150	3,154	1,221	1,572	2,480	2,120
Paved road	820	360	2,120	2,083	2,121	2,031	1,479	1,596	1,779
Unpaved road	799	818	862	952	862	559	831	462	1,196
	12/2014	01/2015	02/2015	03/2015	04/2015	05/2015	06/2015	07/2015	08/2015
Forest	1,486	1,422	1,401	1,576	2,639	1,734	1,103	709	300
Paved road	3,162	2,006	1,428	1,533	503	656	777	872	79
Unpaved road	901	917	477	837	670	861	926	343	208
	09/201	10/201	11/201	12/2015					
	5	5	5						
Forest	408	205	94	4					
Paved road	247	357	36	3					
Unpaved road	357	507	208	18					

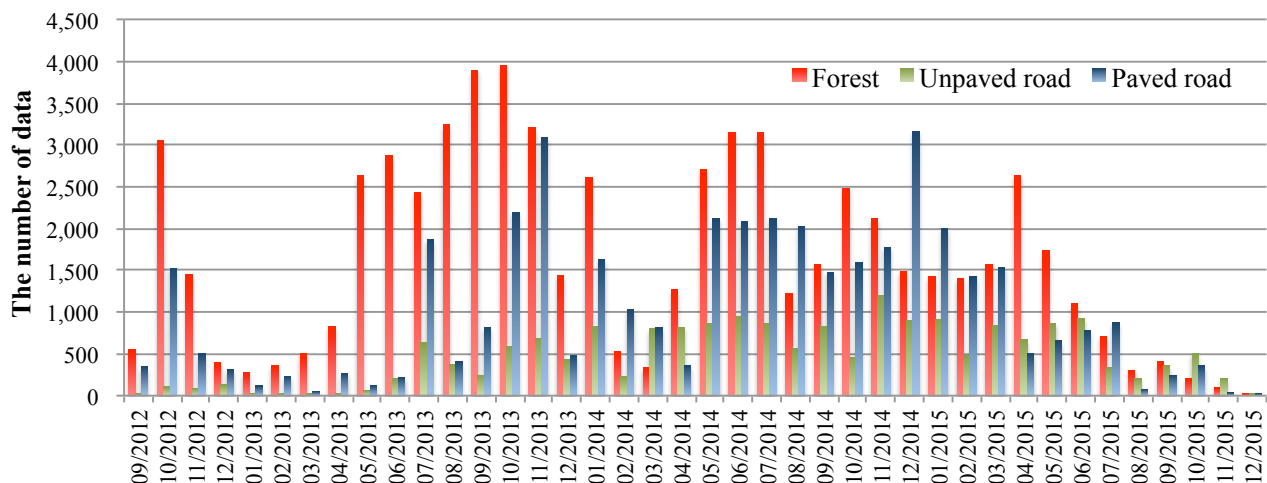


Fig. 5-2 The number of data points in each category of each month.

Line b and Line B were defined as upper limits of the surface contamination concentration, calculated by CDE (Calculation system for Decontamination Effect) as follows:

a) Setup of virtual field

Setup of a virtual field measuring 1,005 m by 1,005 m divided into a mesh of 201 rows and 201 columns measuring 5 m by 5 m, each with a homogeneously distributed radioactivity of 10 Bq cm^{-2} , according to the guideline (JAEA, 2016a).

b) Calculation of the air dose rate (100 cm from the ground) in the virtual field

The air dose rate (100 cm from the ground) in the virtual field was calculated by CDE. The evaluation date was unified as the 16th for every month except in February (15th).

c) Calculation of the surface dose rate corresponding to the air dose rate (100 cm from the ground)

The surface dose rate was calculated by CDE to obtain the closest value to the air dose rate (100 cm from the ground) calculated in b). This surface dose rate was defined as $X (\mu\text{Sv h}^{-1})$.

d) Calculation of the countable number of beta ray values corresponding to 10 Bq cm^{-2}

The surface contamination concentration corresponding to 10 Bq cm^{-2} was calculated under the following assumptions:

- Geometric efficiency of the GM survey meter (TGS-146B, [then-Hitachi-Aloka Medical]) in monitoring the beta rays directly below the radiation source: 0.5
- Window dimension: 19.6 cm^2
- Aperture ratio of the GM survey meter: 85 %

$$10 \text{ Bq cm}^{-2} * 0.5 * 19.6 \text{ cm}^2 * 0.85 * 60 \text{ sec/min} = 5,000 \text{ cpm}$$

e) Definition of lines as upper limit

Under the condition where all radioactive Cs are distributed on the surface of substances, no beta rays or

gamma rays are shielded, and the surface dose rate is X ($\mu\text{Sv h}^{-1}$), the maximum value of the surface contamination concentration is the sum of counts by the GM survey meter for gamma rays and 5,000 cpm, a value corresponding to 10 Bq cm^{-2} . Therefore, when the surface dose rate was X ($\mu\text{Sv h}^{-1}$), the surface contamination concentration calculated according to the function of Line a was defined as Y (cpm). Finally, “Line b” was defined as the line through the original point and (X ($\mu\text{Sv h}^{-1}$), $5,000+Y$ (cpm)). The average slope of Line b through the monitoring term was around 6,100 cpm. Therefore, “Line B” was defined as the line through the original point and ($1 \mu\text{Sv h}^{-1}$, 6,100 cpm).

The slopes of Line a and Line b each month are shown in both Fig. 5-3 and Table 5-2. As a result of analyses, the monitoring points were mostly distributed between Line a and Line b.

The Line a's plotted during the monitoring term had an average slope of 270.

In months with small numbers of monitoring points, Line a was apart from the real low limit. In months with large numbers of monitoring points (e.g., May 2013 – Nov. 2013), the slopes of Line a were smaller than the slope of line A, approximately 200 - 230. According to the display of the GM survey meter (TGS-121, [then-Hitachi-Aloka Medical]) and accompanying descriptions on the relation between the surface dose rate and surface contamination concentration, $1 \mu\text{Sv h}^{-1}$ corresponds to 200 cpm. The diameter of the GM survey meter (TGS-121) used was 2 cm, considerably smaller than the 5 cm diameter of the GM survey meters often used in other decontaminating activities, such as the TGS-146. The monitoring efficiency of the different devices probably differs as a result. Moreover, given the possibility that the survey meters were still influenced by beta rays even in the forests or on the unpaved roads, the average slope of Line a would reasonably be assumed to be around 270 during the monitoring term in this research.

As for Line b, the radioactive substances detected by the GM survey meter can be regarded as mainly ^{134}Cs and ^{137}Cs . Although various kinds of radioactive substances were released into the environment, including ^{133}Xe , ^{134}Cs , ^{137}Cs , ^{89}Sr , and ^{90}Sr (NISA, 2011a; NISA, 2011b), sufficient research has yet to be conducted on the radioactive substances that emit beta rays. Hence, the influences of such substances cannot be analyzed at present. ^{134}Cs emits several kinds of gamma rays with different energies: 0.605 MeV (emission rate: 97.6 %), 0.796 MeV (emission rate: 85.5 %), 0.569 MeV (emission rate: 15.4 %), 0.802 MeV (emission rate: 8.7 %), 0.563 MeV (emission rate: 8.4 %), and 1.365 MeV (emission rate: 3.0 %), with around 3.1 gamma ray photons per beta ray. The same holds for ^{137}Cs : 0.662 MeV (emission rate: 85.1 %), 0.0321 MeV (emission rate: 5.8 %), 0.0365 MeV (emission rate: 1.3 %), with around 1.0 gamma ray photon per beta ray (JRIA, 2011).

The proportion of ^{134}Cs , an isotope with a shorter half-life than ^{137}Cs , therefore decreases as time goes by. In the wake of this phenomenon, the proportion of beta ray for the same count value monitored by GM survey meter will increase. The tendency of the slope of Line b to gradually increase is concordant with this phenomenon (Fig. 5-3).

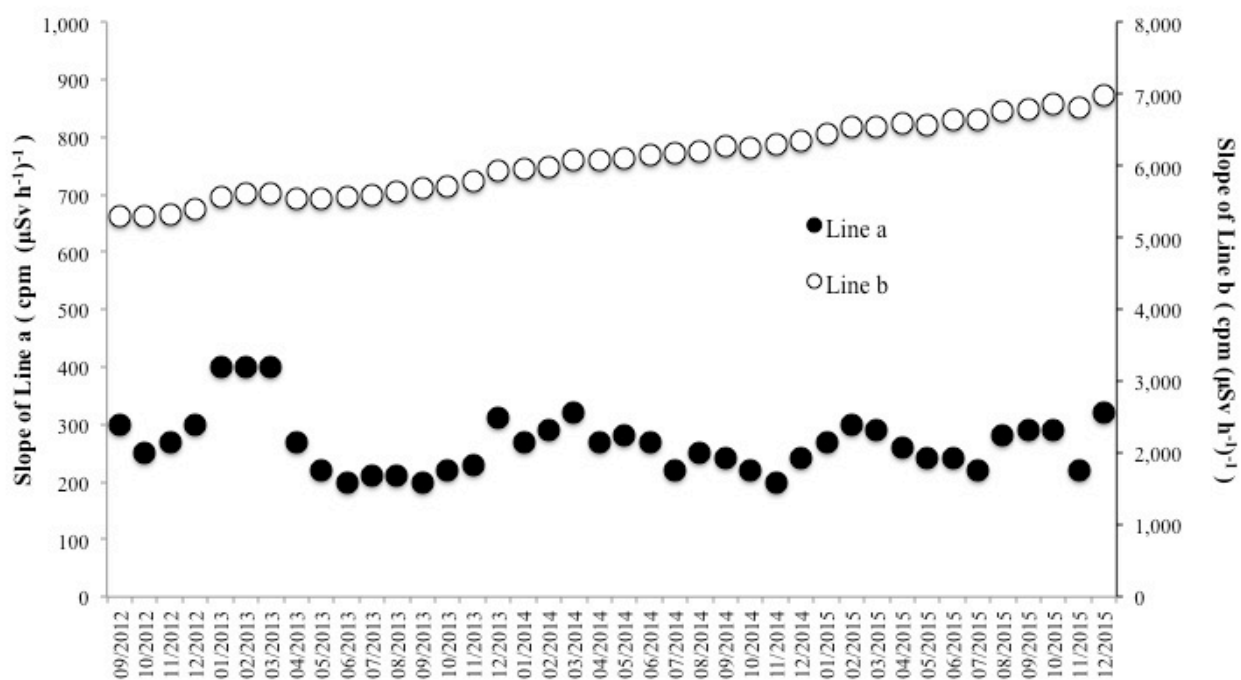


Fig. 5-3 Temporal change of the slopes of Line a and Line b (Sep. 2012 – Dec. 2015).

Table 5-2 Slopes of Line a and Line b in each month

Month/Year	Line a	Line b
09/2012	300	5,300
10/2012	250	5,301
11/2012	270	5,321
12/2012	300	5,402
01/2013	400	5,555
02/2013	400	5,608
03/2013	400	5,608
04/2013	270	5,533
05/2013	220	5,539
06/2013	200	5,576
07/2013	210	5,586
08/2013	210	5,645
09/2013	200	5,695
10/2013	220	5,715
11/2013	230	5,786
12/2013	310	5,928
01/2014	270	5,952
02/2014	290	5,972
03/2014	320	6,067
04/2014	270	6,084

Month/Year	Line a	Line b
05/2014	280	6,094
06/2014	270	6,152
07/2014	220	6,172
08/2014	250	6,202
09/2014	240	6,264
10/2014	220	6,244
11/2014	200	6,298
12/2014	240	6,338
01/2015	270	6,443
02/2015	300	6,550
03/2015	290	6,540
04/2015	260	6,589
05/2015	240	6,569
06/2015	240	6,650
07/2015	220	6,630
08/2015	280	6,774
09/2015	290	6,784
10/2015	290	6,869
11/2015	220	6,799
12/2015	320	6,987

As mentioned above, the GM survey meter detects both beta rays and gamma rays. When the value of the scintillation survey meter is the same, a larger GM survey meter value results in the detection of more beta rays. Given that beta rays have a weaker penetration power than gamma rays and that the count efficiency changes according to the gamma ray energy, Line a describes the count of a GM survey meter detecting only gamma rays, and the count efficiency is the lowest. If the monitoring points are plotted far above Line a, the sources of the beta rays remain near the surface and reach the detector without being shielded by soil, organic matter, or other obstacles.

Because the average slope of Line a was around 270, the line through the original point and (1 $\mu\text{Sv h}^{-1}$, 270 cpm) was defined as “Line A.”

As mentioned above, the difference between the surface contamination concentration at the monitoring point and that on Line A is an index describing the condition of residual radioactive Cs on the surface when the surface dose rate is same. Therefore, the SRI (Surface Residual Index) is defined by equations (2), (3), and (4):

$$SRI = (y_2 - y_1)/y_1 \quad (2)$$

$$SRI = 0 \quad (y_2 - y_1 < 0) \quad (3)$$

$$y_1 = 270x_1 \quad (4)$$

where x_1 ($\mu\text{Sv h}^{-1}$) is the surface dose rate and y_2 (cpm) is the surface contamination concentration at the monitoring point. If “ $y_2 - y_1$ ” is less than zero, the SRI is defined as zero.

The box and whisker charts in Fig. 5-4 - Fig. 5-6 respectively plot the temporal changes of the residual condition on the surfaces of forests, paved roads, and unpaved roads, as expressed by the SRI. The vertical axis represents the SRI value and the horizontal axis represents the month when the surface dose rate and surface contamination concentration were measured in the pre-decontamination monitoring. Note that the scale of the vertical axis on paved roads is different from that on forests and unpaved roads.

The top, bottom, and middle line of each box respectively mark the 75th percentile, 25th percentile, and median. The upper whisker is calculated by adding the 75th percentile to 1.5 IQR (interquartile range). If the actual maximum is smaller than that value, the upper whisker represents the actual maximum value. The bottom whisker is calculated by subtracting 1.5 IQR from the 25th percentile. If the actual minimum value is larger than that value, the bottom whisker represents the actual minimum value.

The SRI values for the forests gradually decreased from the beginning of the monitoring term down to around 0.6 - 0.7 in the middle of 2013, then remained in the range of 0.8 - 1.0 (Fig. 5-4).

The SRI values for unpaved roads fluctuated more widely than those for forests because fewer data points were measured. Overall, however, they showed a similar decreasing trend, reaching around 0.8 in the latter part of 2013 and then stabilizing at around 0.7 -1.0 (Fig. 5-5). Fewer data points were measured in Apr. 2013 than in the other months, possibly due to the large discrepancy in the measurement results from the other months. The difference between forests and unpaved roads might reflect differences in the infiltration velocity and soil density. The much larger SRI values on paved roads compared to those in forests and on unpaved roads could imply that abundant radioactive Cs remained on the paved road surfaces. According to the periodical car-borne survey, the dose rate reduction on roads was larger than that expected by physical attenuation. From the first survey (Jun. 2011) to the 5th survey (Dec. 2012), the surface dose rate reduction was larger than the air dose rate reduction (100 cm from the

ground). After the 5th survey, however, the dose rates decreased to an almost equal degree in all places without natural disturbances (JAEA, 2016b). As such, there was no need to consider the large effluence of radioactive Cs from the road surfaces during the monitoring term in this research.

From a long-term perspective, SRI values ranged from 5 to 8 up to 2013, while those on paved roads decreased to 2 to 5 afterwards (Fig. 5-6). While this can be partly explained by the reduced number of data points collected on roads compared to forests, the radioactive Cs may have infiltrated in the vertical direction even on the paved roads. Bartlett-test was conducted and homoscedasticity was not confirmed ($p < 0.05$). In the wake of Bartlett-test, Kruskal-Wallis test was subsequently conducted and at least the SRI in one of the months stochastically different from that of other months ($p < 0.05$).

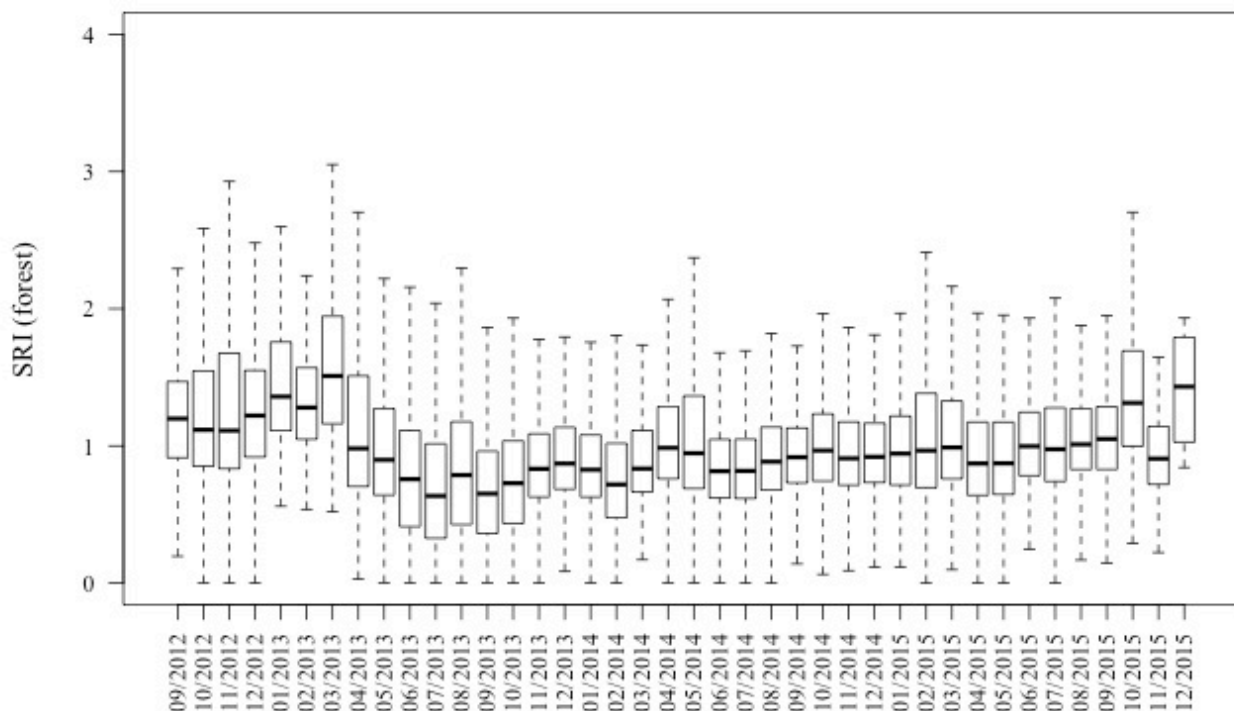


Fig. 5-4 Temporal change of SRI values in forests (Sep. 2012 - Dec. 2015). The top, bottom, and middle line of each box respectively mark the 75th percentile, 25th percentile, and median. The upper whisker is calculated by adding the 75th percentile to 1.5 IQR (interquartile range). If the actual maximum is smaller than that value, the upper whisker represents the actual maximum value. The bottom whisker is calculated by subtracting 1.5 IQR from the 25th percentile. If the actual minimum value is larger than that value, it represents the actual minimum value.

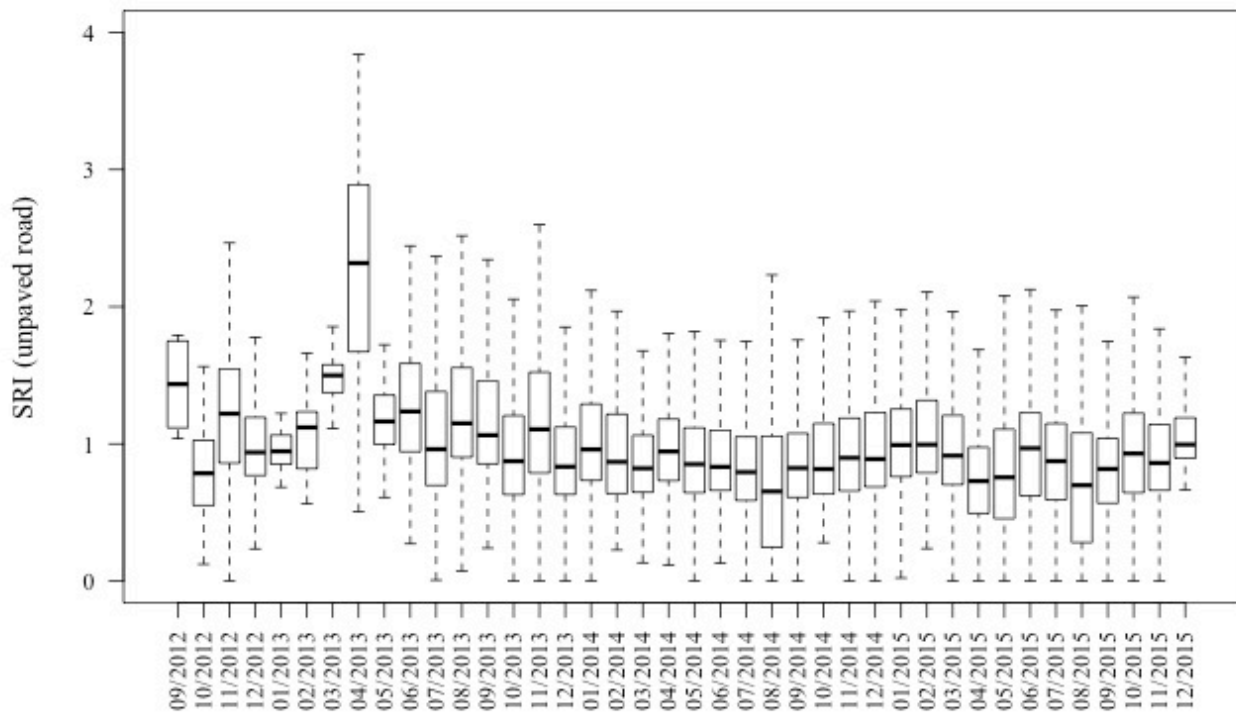


Fig. 5-5 Temporal change of SRI values on unpaved roads (Sep. 2012 - Dec. 2015).

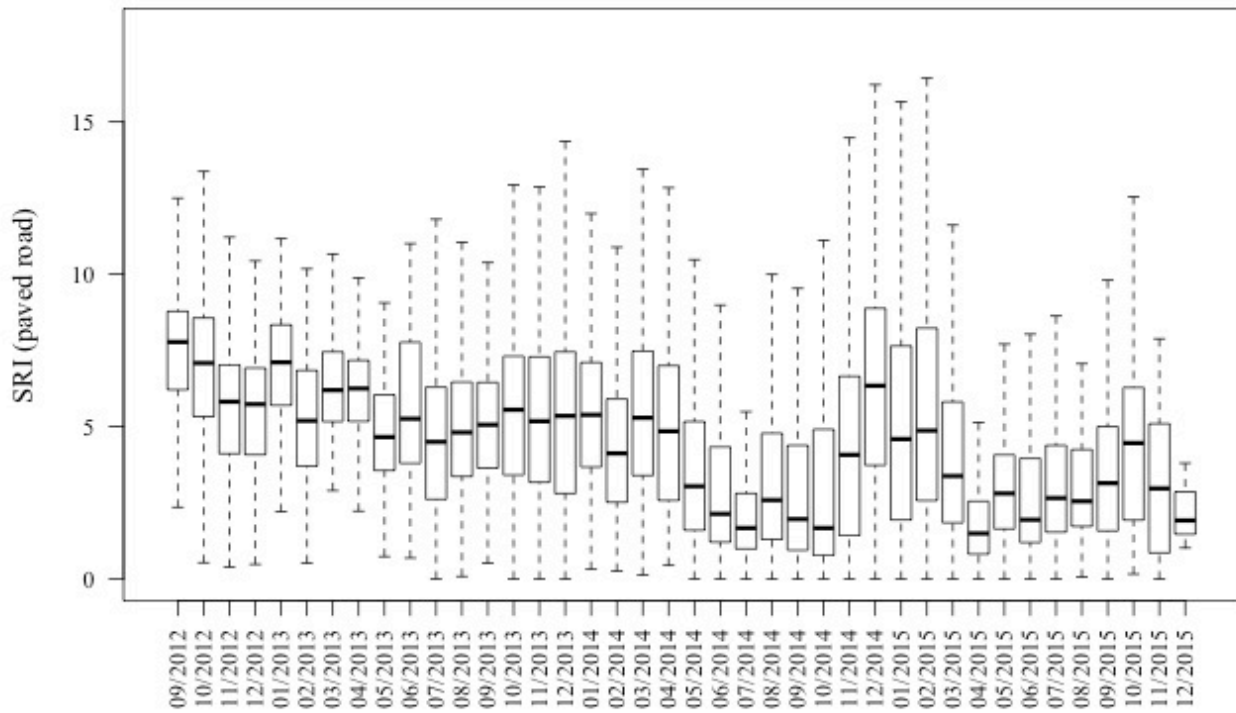


Fig. 5-6 Temporal change of SRI values on paved roads (Sep. 2012 - Dec. 2015).

5.3.2 Infiltration of radioactive Cs in different types of vegetation and evaluation by SRI

In the research already reported (Mori et. al., 2016), the β value in five forests with different vegetation was expressed based on the dried mass depth, or β_d , because of the correlation between the mass depth and decontamination effect evaluated under various weather conditions. In this research, meanwhile, the β value was evaluated on the wet basis, or β_w , because the SRI value was calculated based on the surface dose rate and surface contamination concentration monitored under the natural condition. The β_w value in *Larix kaempferi* is shown in Fig. 5-7 and the β_w values in four other forests with different types of vegetation are shown in Fig. 5-8 - Fig. 5-11.

The fit to the approximate curve based on equation (1) to the monitored value varied widely from vegetation to vegetation. In the *Pinus densiflora* and Deciduous broadleaf, the concentration of radioactive Cs was much lower in the L layer than in the F layer and the discrepancy between the approximate curve and the monitored value was comparatively large. This was because equation (1) assumed that the concentration of radioactive Cs decreased in the vertical direction at an exponential rate, whereas the radioactive Cs actually infiltrated deeper in the soil layer than expected in the equation.

The relaxation mass depth (β_w) was 1.43 g cm^{-2} , 1.61 g cm^{-2} , 1.78 g cm^{-2} , 1.99 g cm^{-2} , and 1.36 g cm^{-2} for *Larix kaempferi*, *Pinus densiflora*, Deciduous broadleaf, *Cyptomeria japonica*, and *Chamaecyparis obtusa*, respectively. Higher β_w values corresponded with deeper infiltration of the radioactive Cs. Hence, the radioactive Cs infiltrated towards the deeper layer in the *Cyptomeria japonica* forest and remained in the shallow layer in *Chamaecyparis obtusa*.

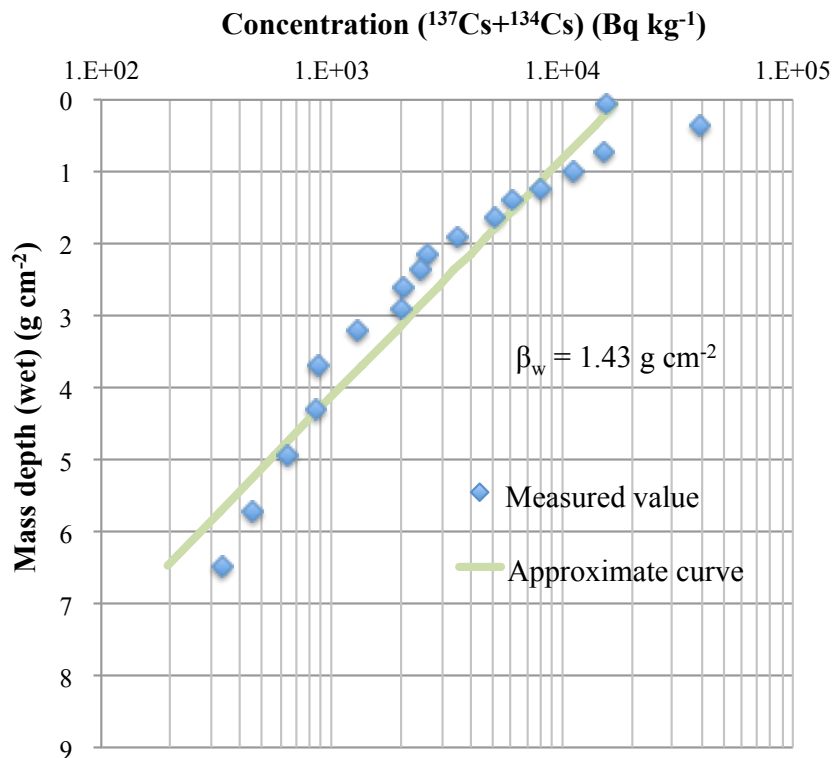


Fig. 5-7 Depth profile of radioactive Cs with mass depth in *Larix kaempferi*.

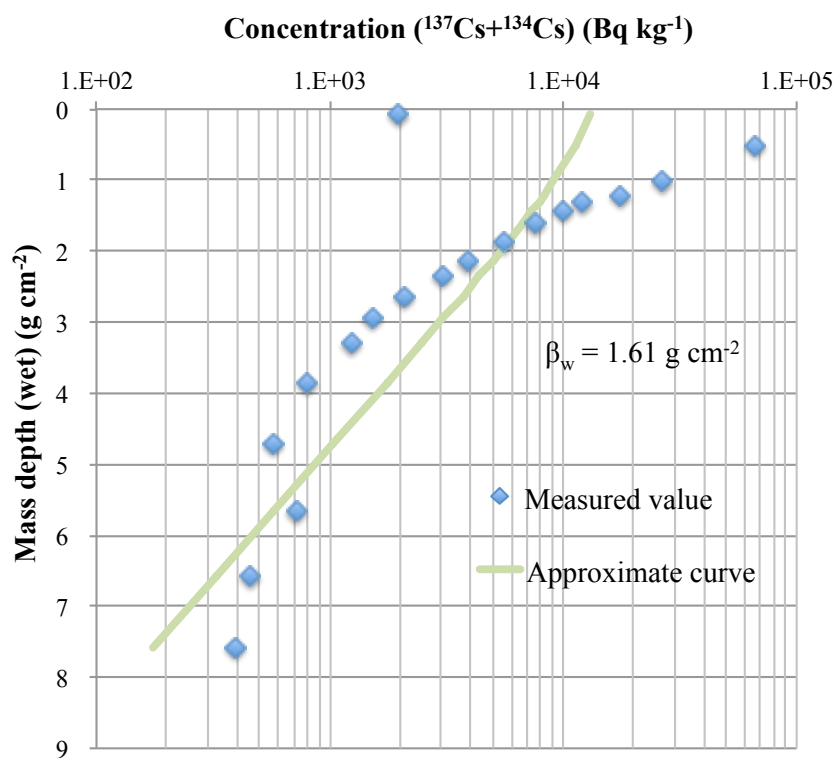


Fig. 5-8 Depth profile of radioactive Cs with mass depth in *Pinus densiflora*.

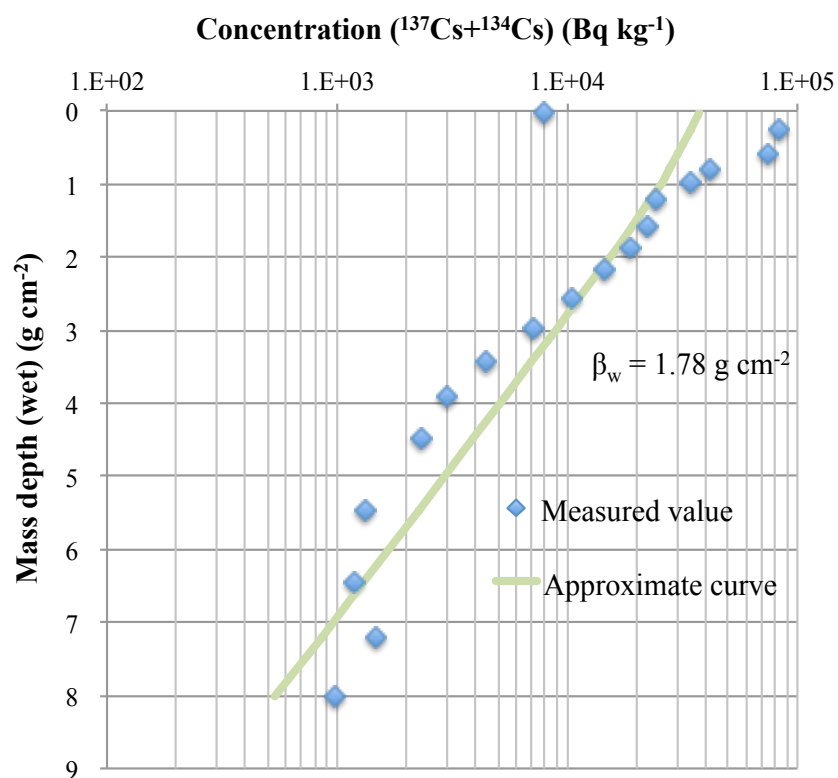


Fig. 5-9 Depth profile of radioactive Cs with mass depth in Deciduous broadleaf trees.

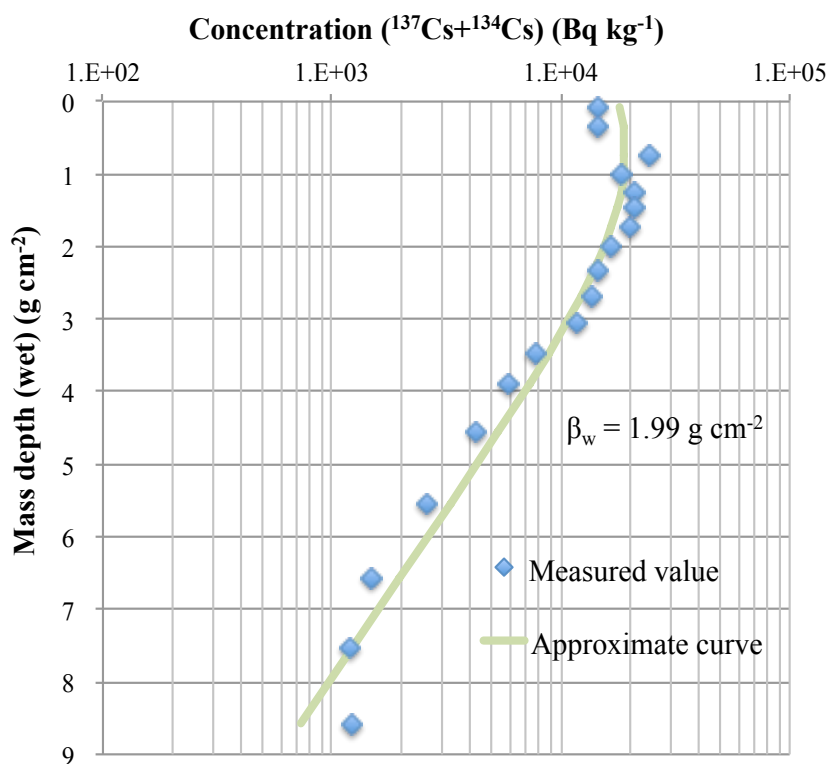


Fig. 5-10 Depth profile of radioactive Cs with mass depth in *Cryptomeria japonica*.

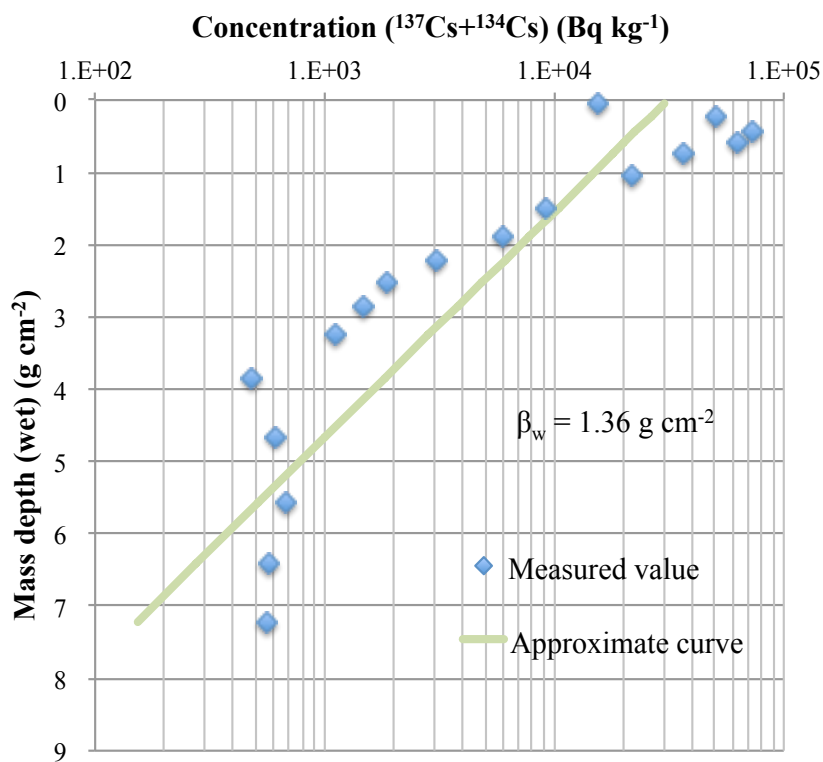


Fig. 5-11 Depth profile of radioactive Cs with mass depth in *Chamaecyparis obtusa*.

We can assume, however, that the infiltration is affected by the characteristics of the organic matter or soil, which make direct physical contact with the radioactive Cs rather than the vegetation. Thus, the relation between the infiltration and the characteristics of the organic matter or soil should be revealed through deeper analyses.

Fig. 5-12 shows the relation between the surface dose rate and the surface contamination concentration monitored before scraping. Every monitoring point was distributed near Line A, through the original point and (1 $\mu\text{Sv h}^{-1}$, 270 cpm), following the same current as the other monitoring points plotted. A great deal of the beta rays monitored in this research might also have been shielded by the organic matter and soil on the infiltrating radioactive Cs. The SRI values were calculated, as mentioned above. The β_w values were negatively correlated, to some extent, with the SRI value (the higher the beta value, the lower the SRI values) (Fig. 5-13). The beta rays had a maximum energy of 0.658 MeV for ^{134}Cs (emission rate: 70.2 %) and 0.514 MeV for ^{137}Cs (emission rate: 94.4 %), and a radiation range of around $0.407\text{E}^{1.38} \text{ mg cm}^{-2}$. The soil, which has an apparent specific gravity of 1 g cm^{-3} and a thickness of 3 mm thickness, can theoretically completely shield the beta rays. Even in the case of beta rays emitted from ^{137}Cs with a maximum energy of 1.176 MeV (emission rate: 5.6 %), the radiation range would be around $542\text{E}-133 \text{ mg cm}^{-2}$. For this reason, soil with an apparent specific gravity of 1 g cm^{-3} and a thickness of 5 mm should completely shield the beta rays in theory.

As soil layers have random voids, beta rays from soil layers deeper than 5 mm from the top were detected. Calculating the SRI values alone can provide a grasp of the rough profile but not an accurate expression of the detailed infiltration condition of the radioactive Cs.

The correlation between the β_w values and SRI value differences was analyzed by comparing the surface contamination concentration measured with and without a 2-mm-wide acrylic plate (Fig. 5-14). Equation (5) describes the difference in the SRI value in measurements with and without the acrylic plate:

$$SRI - SRI_{acryl} = \frac{y_2 - y_1}{y_1} - \frac{y_3 - y_1}{y_1} = \frac{y_2 - y_3}{y_1} \quad (5)$$

$$y_1 = 270x_1 \quad (4)$$

where y_2 (cpm) is the surface contamination concentration without the acrylic plate, y_3 (cpm) is that with the acrylic plate, and x_1 ($\mu\text{Sv h}^{-1}$) is the surface contamination concentration at the monitoring point.

The correlation became stronger when using the SRI value differences, compared with the evaluation using the SRI values themselves. The acrylic plate measured $180 \text{ mm} * 120 \text{ mm} * 2 \text{ mm}$ and weighed 52 g, which translated into a density of $52 / (180 * 120 * 2) * 1000 = 1.2 \text{ g cm}^{-3}$. Taking the maximum beta ray energy emitted from ^{134}Cs and ^{137}Cs as 0.658 MeV and 0.514 MeV, respectively, equation (6) describes the relation between the mass range (R) (mg cm^{-2}), density of the acrylic plate (D) (g cm^{-3}), range (L) (cm), and maximum energy of the beta ray (E) (MeV).

$$R = DL = 0.407\text{E}^{1.38} \quad (6)$$

$$L = 0.407 * 0.658^{1.38} * / 1.20 = 0.19 \text{ cm}$$

The 2-mm-thick acrylic plate will almost completely shield the beta rays.

With the acrylic plate, radiation emitted by radioactive Cs remaining on the surface or from voids located in the

upper layer was shielded. In other words, the plate re-created a situation where beta rays were shielded by soil particles according to the depth from the top. Therefore, the SRI value differences derived from the acrylic plate had a stronger correlation with the β_w values than the SRI values themselves. Acrylic plates have been sometimes used to evaluate the condition of residual radioactive Cs, but only in limited ways and only for a very small portion of the extensive monitoring performed. It would be unrealistic to apply acrylic plate at all points, and impossible to speculate on the residual condition from the data on decontamination activities conducted in the past.

Among the various types of radiation emitted from natural radioactive nuclides, this chapter has only taken radioactive Cs into account. In conditions with low rates of contamination, where the radiation derived from radioactive Cs and natural nuclides is balanced, the influences of natural radiation will require much deeper discussion.

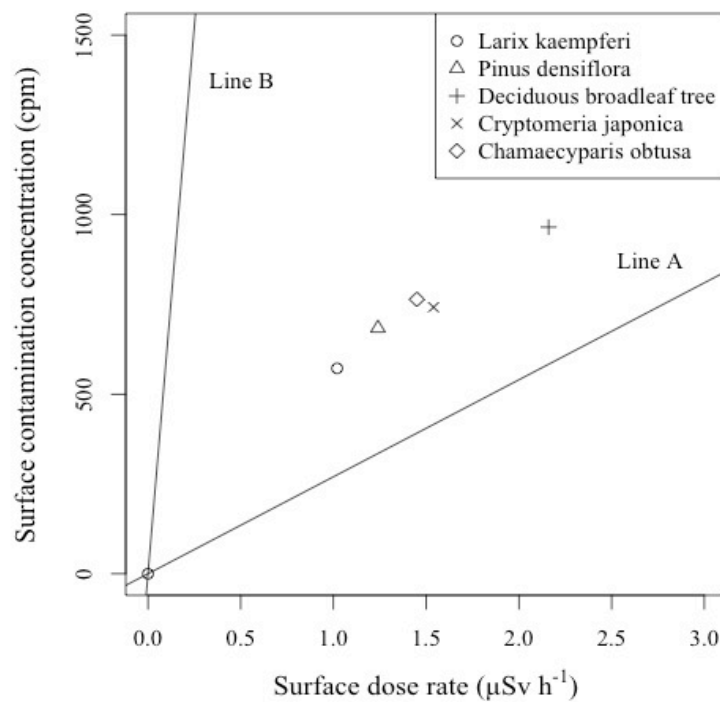


Fig. 5-12 Scatter plot of the surface dose rates and surface contamination concentrations in 5 forests with different types of vegetation. The line on the bottom right passing through the original point and ($1 \mu\text{Sv h}^{-1}$, 270 cpm) is Line A. The line on the top left passing through the original point and ($1 \mu\text{Sv h}^{-1}$, 6,100 cpm) is Line B.

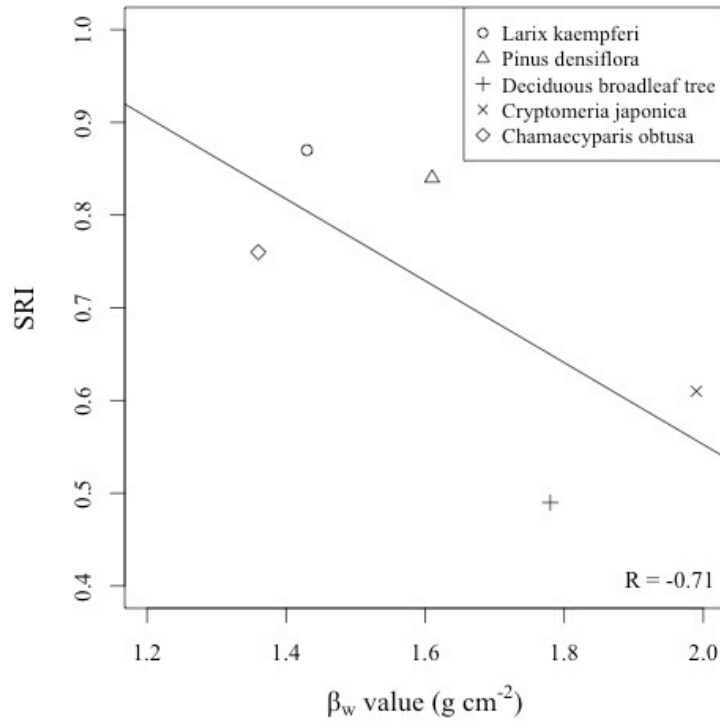


Fig. 5-13 Scatter plot of β_w values and surface contamination concentrations in five forests with different types of vegetation.

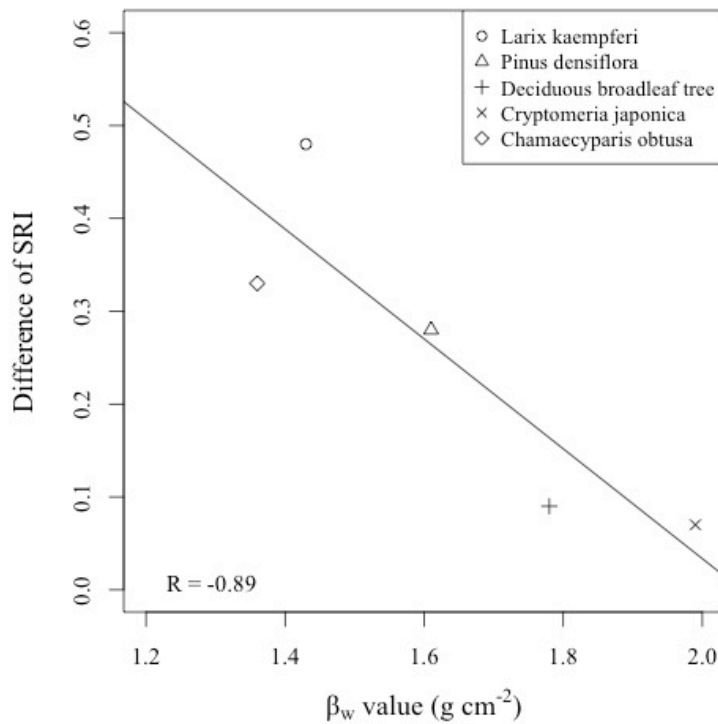


Fig. 5-14 Scatter plot of β_w values and SRI value differences in five forests with different types of vegetation. SRI values were calculated with and without an acrylic plate and the differences between the two values are plotted on the vertical axis.

5.4 Discussion and conclusions

The radioactive substances monitored in this research were mainly ^{134}Cs and ^{137}Cs . In “Results and considerations”, each main energy of beta rays and gamma rays is mentioned. The total attenuation coefficients of gamma rays in water, concrete, and air were $8 - 9 \times 10^{-2} \text{ cm}^2 \text{ g}^{-1}$ at 0.6 MeV and $7 - 8 \times 10^{-2} \text{ cm}^2 \text{ g}^{-1}$ at 0.8 MeV, respectively. If $8 \times 10^{-2} \text{ cm}^2 \text{ g}^{-1}$ was adopted as a representative value for a total attenuation coefficient and 1.5 g cm^{-3} was adopted as the apparent specific gravity (disregarding location-dependent variations), the amount of gamma rays would be cut by almost half for a 5-6-cm-deep layer of soil under the condition where the buildup effect was ignored. The beta rays might have been completely shielded by a soil layer of around 5 mm in width, as mentioned above. Yet allowing for voids randomly distributed within the soil, some of the radiation emitted from radioactive Cs located at depths of greater than 5 mm could be detected on the surface. Taking these points into account, the high surface contamination concentration measured under even low-surface-dose-rate conditions, the condition shown in the scatter plots of the paved roads, could be explained by the existence of remnant radioactive Cs on the paved road surfaces and the detection of counts derived from beta rays. In the forests and unpaved roads, meanwhile, shielding effects might have prevented most of the beta rays from reaching the detector.

Line B, the upper limit of the monitoring points in the scatter plot of each month, was theoretically calculated. Almost all points were distributed under Line B, which implied that Line A represented GM survey counts, that is, counts that were derived from gamma rays and had the lowest count efficiency. This tells us that the monitoring points more distant from Line A were characterized by more radioactive Cs remaining on the surface and higher proportions of beta rays reaching the detector without being blocked by organic matter or soil. Only the geometric efficiency was considered when calculating Line B. If a more accurate upper limit was to be determined, the additional absorption of beta rays at the windows of the detectors and other factors would have to be taken into account.

The SRI value was defined to describe the condition of residual radioactive Cs on the surface. An analysis of the temporal transitions revealed that the SRI values in forests and on unpaved roads tended to decrease gradually and remain constant during late monitoring terms, but were generally low compared with those on paved roads. This implies that by about 18 months after the nuclear accident, the radioactive Cs had already infiltrated vertically to some extent and no longer remained on the surface. This assumption concords with the result from the annual monitoring of radioactive Cs in the Fukushima forests, namely, that the distribution of radioactive substances in the forests had changed and the proportion of radioactive Cs in the soil had risen by as early as 1 year after the accident (FA, 2016). The paved roads, on the other hand, showed fluctuation, and much larger SRI values than were measured in the forests and unpaved roads. This implies that the radioactive Cs remained on the surfaces of paved roads, though it could have also moved gradually downward.

As mentioned above, the proportion of ^{137}Cs , an isotope with a longer half-life than ^{134}Cs , has increased over time, and the proportion of counts derived from beta rays has also increased in the same measurements of surface contamination concentration. The SRI values in nature have thus been assumed to rise with time, whereas actually they have remained on a declining trend. In the wake of these results, the temporal reduction of the SRI could not be attributed to a change in the abundance ratio of ^{134}Cs and ^{137}Cs .

As observed in the forests in the late monitoring term, the SRI value slightly increased over time. This phenomenon might stem from the temporal change in the proportions of ^{134}Cs and ^{137}Cs remaining, as well as the almost complete cessation of the infiltration of radioactive Cs.

The results of this study demonstrate that the surface dose rate and surface contamination concentration, two

conditions routinely recorded during the decontamination works, can potentially be used to estimate the condition of residual radioactive Cs on surfaces.

The relation between the existence proportion of obtained radioactive Cs in organic layer (cm^{-1}) and SRI value were shown in Fig. 5-15. The existence proportion was divided by the thickness of organic layer for compensation, because the thickness is different between the types of soil.

Strong correlation was observed and this result could imply that SRI value might contribute the effective forest decontamination to remove organic layer, as well as reducing the generation of unnecessary waste or soil.

At this stage, however, the accuracy of the proposed approach is still insufficient to evaluate the infiltration condition in forests with different types of vegetation. Additional investigations comparing the depth profiles of radioactive Cs in various types of objects, variations in the monitoring values of scintillation survey meters and GM survey meters, etc. will be necessary. Deep analyses of points such as these will allow us to develop the method to a level sufficient for application to actual decontamination activities.

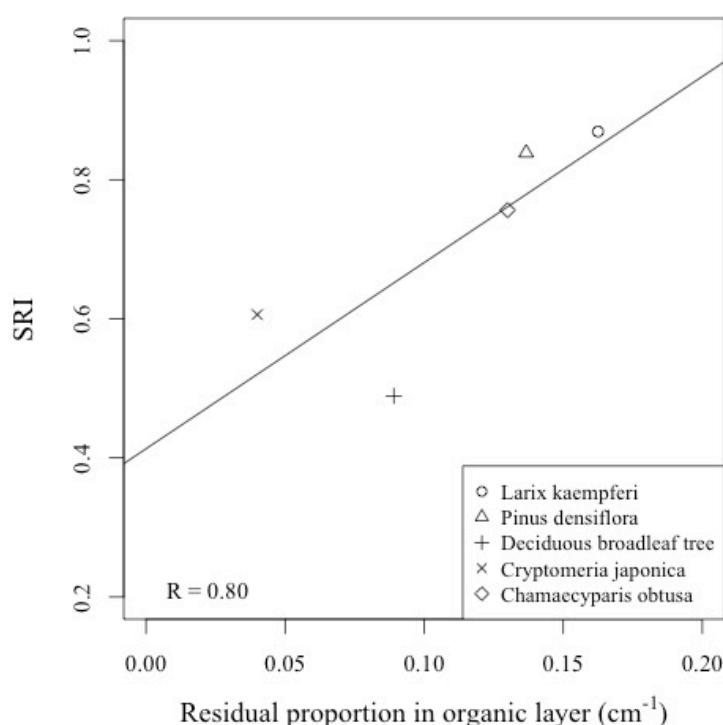


Fig. 5-15 Scatter plot of residual proportion in organic layer and SRI values in five forests with different types of vegetation.

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Chapter 6 Discussion and conclusions

6.1 Conclusions of this research

Extensive area, from northern part of Tohoku to southern part of Kanto was contaminated by radioactive substances released by nuclear accident happened in Mar. 2011. In this research, forests were focused among various kinds of land use, including house, park, school, public building, farmland, grass field and so forth.

There are some reasons for this. First, forests occupy a great deal of proportion of land in Fukushima, as well as other prefectures where decontamination activities have been conducted. Around 70 % of land is forest in Fukushima and forests has been part of life for many of people in Fukushima and this could fit in with whole Japan. People have enjoyed significant benefit from forests, from various kinds of perspectives including forestry, food, education, recreation and so on.

Second, the long-term research and development would be necessary for measures against contamination in forests. It would be unrealistic to remove all organic matter and soil out of mountain in terms of technique, time, finance, waste management as well as prevention of second disaster. In addition to that, taking the fact that half-time of radioactive ^{137}Cs is around 30 years, the continuous monitoring and research for dynamics including mechanism of adsorption of radioactive Cs to soil particles is essential in forests in these area.

There are other areas that full-scale would not be conducted in water-related area, such as bottom of ponds, rivers, lakes, dams and ocean. This is because water shield would be expected to reduce the influence to people minimally in these areas as well as some risk for re-diffusion of radioactive substances to be considered during dredging the soil. There is some exception, however, for reservoirs and fire cisterns in which the water should be withdrawn for use and bottom of them could be exposed to air circumstances for a certain period of time (MOE, 2014).

In these areas, continuous monitoring and risk communication would be some of the main techniques for comprehensive radioactive countermeasures as applicable to forests.

This research was divided into roughly three parts: Factor analyses concerning the effect of forest decontamination using statistic and depth profile investigation (Chapter 3), Analyses of the influence of forest soil characteristics on radioactive Cs infiltration (Chapter 4), and Evaluation of residual radioactive Cs on surfaces by monitoring surface dose rates and surface contamination concentrations (Chapter 5). Summary of these achievements was graphically represented in Fig. 6-1.

In Chapter 3, based on decontamination data regarding the surface dose rate, air dose rate (100 cm from the ground), and surface contamination concentration (Jun. 2012 - Dec. 2015), the relationships of the decontamination effect with the “pre-decontamination radiation dose”, “monitoring term of pre-decontamination” and “types of vegetation” were analyzed. Higher pre-decontamination ranges corresponded to higher rates of radiation dose reduction, but the reduction almost stabilized once the radiation dose reached a certain level. Background radiation was assumed to exert a stronger influence on the decontamination effect in forest areas. The rate of radiation dose reduction decreased as time passed, even under high radiation conditions in the later monitoring term, though some fluctuation in the rate was seen. Finally, the reduction rate varied among different types of vegetation observed through analyses using GIS data. The rate was much higher, for example, in Deciduous conifer plantation compared with other types of vegetation. Additional on-site fieldwork revealed that the variable levels of radioactive Cs

infiltration in vegetation might be linked to differences in the decontamination work performed. Temporal changes of the depth profiles presumably influenced the decontamination effect, given the basic method of decontamination mainly by removing the leaves, branches and other organic matter. Further investigation was necessary to reveal the differences of radioactive Cs infiltration in different types of vegetation, and additional research on the relationship between the depth profile and the soil characteristics was subsequently conducted in Chapter 4.

In Chapter 4, soil core (0-5 cm and 5-10 cm) samplings were conducted in five points with different vegetation in Fukushima Prefecture, the same places with on-site field work mentioned in Chapter 3, in order to explore saturated hydraulic conductivity, field capacity and voidage. Depth profiles of radioactive Cs, ignition loss and CEC (Cation Exchange Capacity) in the five forest soils were also investigated, making use of scraper plate (at 0.5 cm intervals for 0-5 cm and at 1.0 cm intervals for 5-10 cm). Depth profiles in soil layers were totally different between forests and explicit relation could be confirmed neither for field capacity, voidage nor ignition loss. On the other hand, CEC correlated weakly and saturated hydraulic conductivity did strongly with infiltration of radioactive Cs. Compartment modeling was conducted, to try to simulate the monitored depth profile, taking ignition loss as a parameter, based on the experiment result that ignition loss had positive correlation with CEC, which might influence the adsorption process on radioactive Cs in soil layer. Though some discrepancy was observed in the middle parts of soil layer, simulated values were generally consistent with monitored values. In the wake of these results as well as the fact that saturated hydraulic conductivity might have explicit relation with infiltration of radioactive Cs, factors related with precipitation or water flow in early stage after the accident could influence the depth profile, before adsorbed with negative charge in soil particles. In addition, future predictions were conducted for 10, 20 and 30 years after the accident using compartment model. When comparing the simulated concentration of radioactive Cs with the calculated concentration considering only the physical attenuation, in 10 years after the accident, the simulated concentrations became larger than those of calculated concentrations in organic layer or upper parts of soil layer. In 20 and 30 years, the simulated concentrations got smaller than those of calculated values in almost all of the layers. These results imply that transition values were overestimated when seeing them as constant from the beginning of the accident toward future and continuous monitoring or analysis will be necessary. Relation between the infiltration of radioactive Cs and the characteristics of soil could be guessed according to the results of this Chapter 4, though additional research must be conducted to grasp the phenomena especially in early stage after the fallout of radioactive Cs.

In Chapter 5, specific measure tried to be developed, which could be applicable in all types of land use and easy-to-do on site to evaluate the residual condition of radioactive Cs on the targeted surface of decontamination. Concretely, scatter plots based on the monitoring data (Sep. 2012- Dec. 2015) showed that at the surfaces of paved roads, surface contamination concentration indicated high values even in the low surface dose rate circumstances. On the other hand, at the surfaces of forests and unpaved roads, surface contamination concentration indicated low values even in the high surface dose rate circumstances. “SRI value”, which was defined to represent the residual radioactive Cs at surfaces, referred that in the forests and unpaved roads, SRI values tended to gradually decrease and much smaller than those of paved roads. It has been assumed that radioactive Cs had already penetrated toward the underground to some extent and continuously moved downward, after 1.5 years have passed since the nuclear power plant accident occurred. On the paved roads, SRI values set up the possibility that radioactive Cs still remained on the surfaces, but has infiltrated slowly towards the end of monitoring term. SRI values possibly evaluate the depth profile of

radioactive Cs in forest soils with different types of vegetation, because β_w value, which indicates the degrees of penetration of radioactive Cs, and residual condition of radioactive Cs in organic layer, showed correlation with SRI values. They are thought to be effective to grasp the rough residual condition of radioactive Cs quickly on the site of decontamination activities. Some improvement, however, is necessary, including the increase of monitoring points for more accurate estimation.

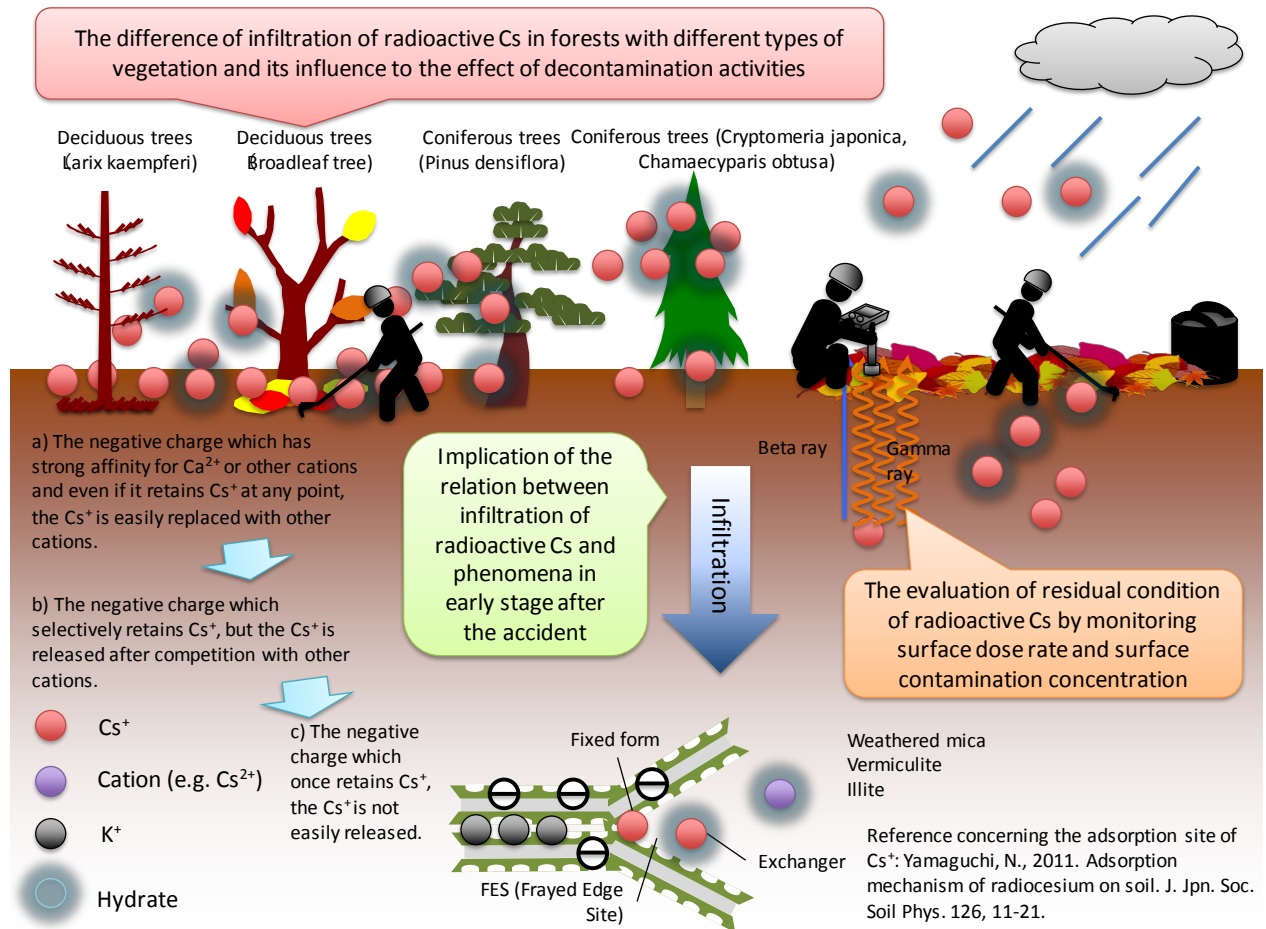


Fig. 6-1 The summary of the achievements of this research.

6.2 Future tasks and prospects

Regarding the results in Chapter 3, more detailed investigation is necessary. In this research, there was no choice but to adopt the same reduction rate for *Cryptomeria japonica* and *Chamaecyparis obtusa*, as there were no sub-categories in the vegetation map more detailed than “evergreen conifer plantation.” As a consequence of these analyses, *Chamaecyparis obtusa* represented a lower value relative to the tendency of the other types of vegetation. Additional research, especially the decontamination effect in forests with *Cryptomeria japonica* and *Chamaecyparis obtusa* might provide additional measurements to clarify the mechanism of the relation.

The continuous field study could contribute to improve the understanding of the relation between vegetation and infiltration of radioactive Cs. Field works could be performed as one-shot sampling in one forest with different types of vegetation, and more data would make these results more persuasive by analyzing average or dispersion.

In light of the results of characteristics of soil and infiltration of radioactive Cs mentioned in Chapter 4, it was implied that natural phenomena in the early time after the accident, when radioactive Cs was still in soluble form might be dominant to determine the depth profile, before adsorbed in negative charge in soil particle. Therefore, in order to prove this hypothesis, the acceleration experiment to reproduce the circumstances in forests at that time would be effective to see the events in early term after the accident.

Finally, in Chapter 5, the simple calculation function to evaluate the residual condition of radioactive Cs on surfaces was proposed, taking the difference of penetration force of beta ray and gamma ray, though there are some points to be improved. As mentioned in Chapter 5, enough accuracy could not be secured, to estimate the detailed residual condition on the surface of forests with different types of vegetation. The residual condition in different types of surface, that is, paved road and forest could be fully understandable and timeline alteration of the condition was also compassable.

This has possibility to be applied on site at this moment, without bringing the sample to laboratory for a long distance or taking time for analyses. More examples to describe the relation between the depth profile and SRI value in various types of surface should be collected, to consider the relation and modify this method.

Finally, in my personal opinion, there are a lot of measures to tackle the radioactive pollution in forests (Fig. 6-2). Not only the removal of radioactive substances, but also revitalization of forestry, continuous monitoring, risk communication, research and development are important.

The full-scale decontamination activities would be finished at the end of Mar. 2017 followed by supplementary process. Therefore, the comprehensive and integrated measures should be focused, for sustainable reconstruction in forest environment.

With regards to the continuous monitoring, in addition to the monitoring the air dose rate by aircraft, continuous ground monitoring at fixed points, radioactivity examination of cultivated foods or freshwater from forests would also lead to the safety and security of people living there.

Risk communication would also one of the keys to foster the science-based knowledge to people. “To fear appropriately”, that is, to be neither too pessimistic nor too optimistic, is significant when facing to this invisible radiation risk. The evaluation of exposed dose during recreation, for example, hiking, fishing and camping could be effective information to people.

Long-term research and development would be essential in this field of study. Dynamics and behavior of radioactive Cs in forest environment should be revealed in more detailed level, though great progresses can be seen even at this point of time.

It has been well-known that radioactive Cs must have fallen from tree canopy to the ground in the early stage after the accident, followed by adsorption in FES (Sawhney, 1972) with negative charge in soil particle and not easily released once being caught at this site.

However, detailed mechanism for radioactive Cs to infiltrate to deeper layer or to circulate in forest ecosystem, in difference types of vegetation or soil is still unknown and in-depth investigation is needed.

Finally, revitalization of sustainable forestry, which had been run before the accident, was essential and effective for both forest management and control of radioactive substance.

Bottom weed or young tree grown after tree thinning has positive effect to prevent the organic matter or soil from flowing out of forest by stabilizing the surface.

The wooden chips or boards made from thinned trees could be utilized as workpiece to cover the road for strolling or business as well as to prevent the soil runoff. In some area, power generation plant has tried to be constructed, using these biomass materials as heat source.

Integration of these measures must have been the indispensable package for revitalization of forest in Fukushima or other contaminated area.

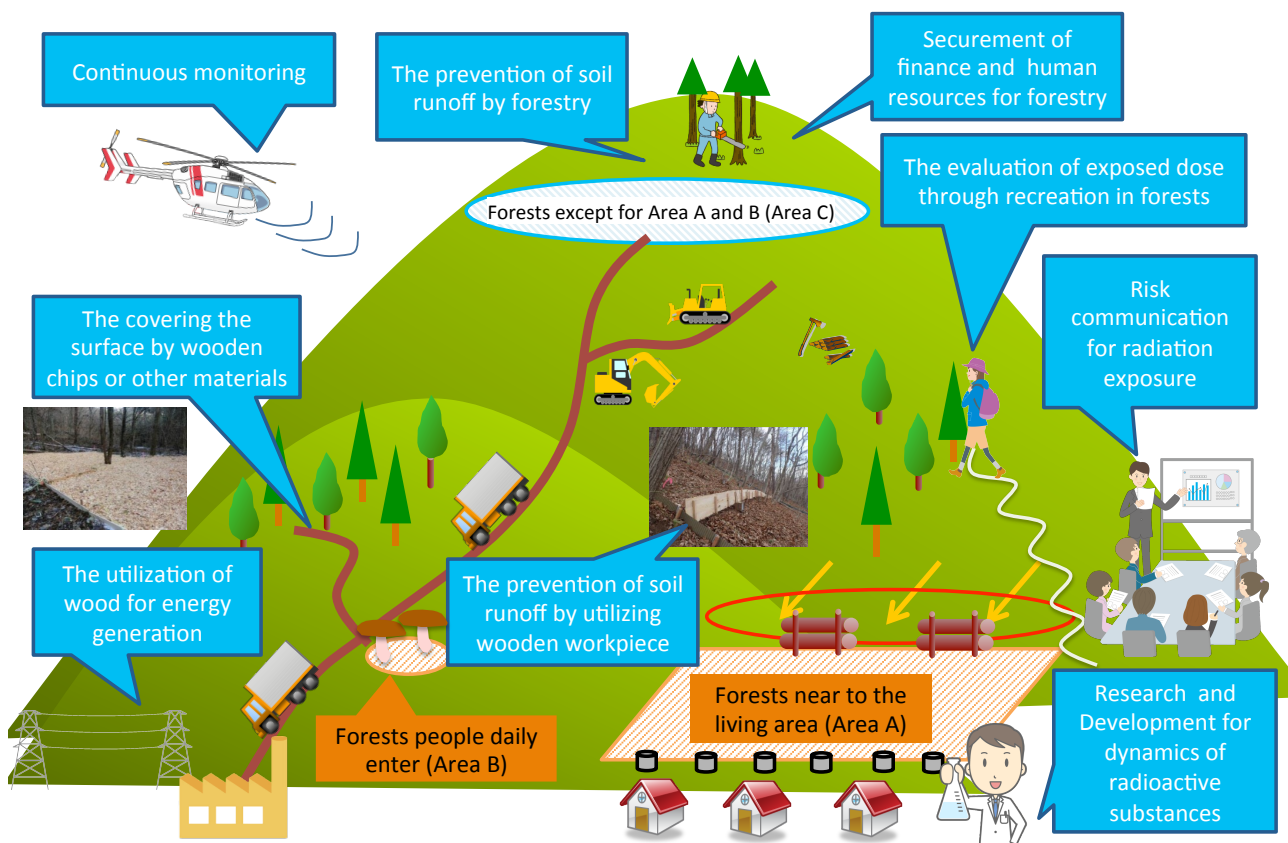


Fig. 6-2 The concept of comprehensive measures against radioactive contamination in forests.

Reference: Edited version based on the 9th Panel for Environment Recovery (MOE)

References (Chapter 6)

Ministry of the Environment, 2014. The 12th Panel for the Environment Recovery. Available at: <http://josen.env.go.jp/material/session/012.html> (in Japanese).

Sawhney B. L., 1972. Selective sorption and fixation of cations by clay minerals: a review. *Clays Clay Miner*, 20, 93–100.

Published papers and presentations related to this research

Chapter 3 Factor analyses concerning the effect of forest decontamination using statistic and depth profile investigation

- Published papers with peer review

Mori Y., Yoneda M., Shimada Y., Fukutani S., Ikegami M., 2016, Factor analyses concerning the effect of decontamination by utilizing statistic and depth profile investigation. J. Soc. Remed. Radioact. Contam. Environ., 4, No.4, pp.313-324.

- Presentations

Mori Y., 2015, The effect of decontamination activities. International Symposium on Radiological Issues for Fukushima's Revitalized Future. S1-3.

Mori Y., Yoneda M., 2015, The factor analyses for effect of decontamination activities. The 4th Annual Meeting of the Society for Remediation of Radioactive Contamination in Environment, pp.45.

Chapter 4 Analyses of the influence of forest soil characteristics on radioactive Cs infiltration

- Published papers with peer review

Mori Y., Yoneda M., Shimada Y., Fukutani S., Ikegami M., Shimomura R., 2017, Influence analyses of radioactive Cs infiltration caused by characteristics of forest soils. J. Soc. Remed. Radioact. Contam. Environ., 5, No.2, pp.95-107.

Chapter 5 Evaluation of residual radioactive Cs on surfaces by monitoring surface dose rates and surface contamination concentrations

- Published papers with peer review

Mori Y., Yoneda M., Shimada Y., Fukutani S., Ikegami M., 2017, Evaluation of residual radioactive Cs at surfaces by monitoring 1cm air dose rate and surface contamination concentration. J. Soc. Remed. Radioact. Contam. Environ., 5, No.1, pp.3-15.

- Presentations

Mori Y., Yoneda M., Shimada Y., Fukutani S., Ikegami M., 2016, Evaluation of residual radioactive Cs on surfaces by monitoring 1cm air dose rates and surface contamination concentrations. The 5th Annual Meeting of the Society for Remediation of Radioactive Contamination in Environment, pp.28.

Appendix 1 VBA program for compartment model

(Example of *Larix kaempferi*; $P=aQ^{-1}+b$)

Option Explicit

Option Base 1

Sub transport()

“The definition of the form of transition coefficient”

Dim i As Integer

Dim ia As Integer, ib As Integer

Dim a As Double, b As Double

Dim n As Integer

Dim na As Integer, nb As Integer

“The definition of the form of transition coefficient in each layer”

Dim Pl As Double, Pf As Double, Ph As Double, P0005 As Double, P0510 As Double, P1015 As Double, P1520 As Double, P2025 As Double, P2530 As Double

Dim P3035 As Double, P3540 As Double, P4045 As Double, P4550 As Double, P5060 As Double, P6070 As Double, P7080 As Double, P8090 As Double, P90100 As Double

Dim Pln As Double, Pfn As Double, Phn As Double, P0005n As Double, P0510n As Double, P1015n As Double, P1520n As Double, P2025n As Double, P2530n As Double

Dim P3035n As Double, P3540n As Double, P4045n As Double, P4550n As Double, P5060n As Double, P6070n As Double, P7080n As Double, P8090n As Double, P90100n As Double

“The definition of the form of radioactivity concentration in each layer”

Dim Ml As Double, Mf As Double, Mh As Double, M0005 As Double, M0510 As Double, M1015 As Double, M1520 As Double, M2025 As Double, M2530 As Double

Dim M3035 As Double, M3540 As Double, M4045 As Double, M4550 As Double, M5060 As Double, M6070 As Double, M7080 As Double, M8090 As Double, M90100 As Double

Dim Mln As Double, Mfn As Double, Mhn As Double, M0005n As Double, M0510n As Double, M1015n As Double, M1520n As Double, M2025n As Double, M2530n As Double

Dim M3035n As Double, M3540n As Double, M4045n As Double, M4550n As Double, M5060n As Double, M6070n As Double, M7080n As Double, M8090n As Double, M90100n As Double

“The definition of the form of subtract between monitored value and calculated value in each layer”

Dim Rl As Double, Rf As Double, Rh As Double, R0005 As Double, R0510 As Double, R1015 As Double, R1520 As Double, R2025 As Double, R2530 As Double

Dim R3035 As Double, R3540 As Double, R4045 As Double, R4550 As Double, R5060 As Double, R6070 As Double, R7080 As Double, R8090 As Double, R90100 As Double

“The definition of the form of sum of error in each layer”

Dim SE As Double, SEM As Double

“The number of the months (Mar. 2011 – Oct. 2015)”

n = 56

“Deletion of the number of cells (Cells (4,10) – Cells (44, 50))”

na = 10

nb = 4

Range(Cells(4, 10), Cells(44, 50)).Select

Selection.ClearContents

For ia = 10 To 50

For ib = 4 To 44

a = Cells(3, ia)

b = Cells(ib, 9)

Cells(ib, ia).Select

With Selection.Interior

.ColorIndex = 0

End With

“The initial concentration of radioactive Cs”

Ml = Cells(20, 7)

Mf = 0

Mh = 0

M0005 = 0

M0510 = 0

M1015 = 0

M1520 = 0

M2025 = 0

M2530 = 0

M3035 = 0

M3540 = 0

M4045 = 0

M4550 = 0

M5060 = 0

M6070 = 0

M7080 = 0

M8090 = 0

M90100 = 0

For i = 1 To n

“The definition of the transition coefficient based on the ignition loss”

Pl = a / 0.9 + b

Pf = a / 0.76 + b

Ph = a / 0.54 + b

$$\begin{aligned}
P0005 &= a / 0.5 + b \\
P0510 &= a / 0.49 + b \\
P1015 &= a / 0.48 + b \\
P1520 &= a / 0.46 + b \\
P2025 &= a / 0.45 + b \\
P2530 &= a / 0.44 + b \\
P3035 &= a / 0.43 + b \\
P3540 &= a / 0.43 + b \\
P4045 &= a / 0.43 + b \\
P4550 &= a / 0.43 + b \\
P5060 &= a / 0.43 + b \\
P6070 &= a / 0.42 + b \\
P7080 &= a / 0.41 + b \\
P8090 &= a / 0.39 + b \\
P90100 &= a / 0.38 + b
\end{aligned}$$

“The concentration of radioactive Cs in each layer”

$$\begin{aligned}
M_{ln} &= M_l * (1 - P_l / 0.8) * 0.5^{(1 / (30.17 * 12))} \\
M_{fn} &= (M_f + M_l * P_l / 0.8 - M_f * P_f / 2.5) * 0.5^{(1 / (30.17 * 12))} \\
M_{hn} &= (M_h + M_f * P_f / 2.5 - M_h * P_h / 0.8) * 0.5^{(1 / (30.17 * 12))} \\
M0005n &= (M0005 + M_h * P_h / 0.8 - M0005 * P0005 / 0.5) * 0.5^{(1 / (30.17 * 12))} \\
M0510n &= (M0510 + M0005 * P0005 / 0.5 - M0510 * P0510 / 0.5) * 0.5^{(1 / (30.17 * 12))} \\
M1015n &= (M1015 + M0510 * P0510 / 0.5 - M1015 * P1015 / 0.5) * 0.5^{(1 / (30.17 * 12))} \\
M1520n &= (M1520 + M1015 * P1015 / 0.5 - M1520 * P1520 / 0.5) * 0.5^{(1 / (30.17 * 12))} \\
M2025n &= (M2025 + M1520 * P1520 / 0.5 - M2025 * P2025 / 0.5) * 0.5^{(1 / (30.17 * 12))} \\
M2530n &= (M2530 + M2025 * P2025 / 0.5 - M2530 * P2530 / 0.5) * 0.5^{(1 / (30.17 * 12))} \\
M3035n &= (M3035 + M2530 * P2530 / 0.5 - M3035 * P3035 / 0.5) * 0.5^{(1 / (30.17 * 12))} \\
M3540n &= (M3540 + M3035 * P3035 / 0.5 - M3540 * P3540 / 0.5) * 0.5^{(1 / (30.17 * 12))} \\
M4045n &= (M4045 + M3540 * P3540 / 0.5 - M4045 * P4045 / 0.5) * 0.5^{(1 / (30.17 * 12))} \\
M4550n &= (M4550 + M4045 * P4045 / 0.5 - M4550 * P4550 / 0.5) * 0.5^{(1 / (30.17 * 12))} \\
M5060n &= (M5060 + M4550 * P4550 / 0.5 - M5060 * P5060 / 1\#) * 0.5^{(1 / (30.17 * 12))} \\
M6070n &= (M6070 + M5060 * P5060 / 1\# - M6070 * P6070 / 1\#) * 0.5^{(1 / (30.17 * 12))} \\
M7080n &= (M7080 + M6070 * P6070 / 1\# - M7080 * P7080 / 1\#) * 0.5^{(1 / (30.17 * 12))} \\
M8090n &= (M8090 + M7080 * P7080 / 1\# - M8090 * P8090 / 1\#) * 0.5^{(1 / (30.17 * 12))} \\
M90100n &= (M90100 + M8090 * P8090 / 1\# - M90100 * P90100 / 1\#) * 0.5^{(1 / (30.17 * 12))}
\end{aligned}$$

$$M_l = M_{ln}$$

$$M_f = M_{fn}$$

$$M_h = M_{hn}$$

$$M0005 = M0005n$$

$$M0510 = M0510n$$

$$M1015 = M1015n$$

M1520 = M1520n
 M2025 = M2025n
 M2530 = M2530n
 M3035 = M3035n
 M3540 = M3540n
 M4045 = M4045n
 M4550 = M4550n
 M5060 = M5060n
 M6070 = M6070n
 M7080 = M7080n
 M8090 = M8090n
 M90100 = M90100n
 Next i

“The error between the monitored concentration and calculated concentration”

$$Rl = \text{Log}(\text{Cells}(2, 4)) / \text{Log}(10) - \text{Log}(Ml) / \text{Log}(10)$$

$$Rf = \text{Log}(\text{Cells}(3, 4)) / \text{Log}(10) - \text{Log}(Mf) / \text{Log}(10)$$

$$Rh = \text{Log}(\text{Cells}(4, 4)) / \text{Log}(10) - \text{Log}(Mh) / \text{Log}(10)$$

$$R0005 = \text{Log}(\text{Cells}(5, 4)) / \text{Log}(10) - \text{Log}(M0005) / \text{Log}(10)$$

$$R0510 = \text{Log}(\text{Cells}(6, 4)) / \text{Log}(10) - \text{Log}(M0510) / \text{Log}(10)$$

$$R1015 = \text{Log}(\text{Cells}(7, 4)) / \text{Log}(10) - \text{Log}(M1015) / \text{Log}(10)$$

$$R1520 = \text{Log}(\text{Cells}(8, 4)) / \text{Log}(10) - \text{Log}(M1520) / \text{Log}(10)$$

$$R2025 = \text{Log}(\text{Cells}(9, 4)) / \text{Log}(10) - \text{Log}(M2025) / \text{Log}(10)$$

$$R2530 = \text{Log}(\text{Cells}(10, 4)) / \text{Log}(10) - \text{Log}(M2530) / \text{Log}(10)$$

$$R3035 = \text{Log}(\text{Cells}(11, 4)) / \text{Log}(10) - \text{Log}(M3035) / \text{Log}(10)$$

$$R3540 = \text{Log}(\text{Cells}(12, 4)) / \text{Log}(10) - \text{Log}(M3540) / \text{Log}(10)$$

$$R4045 = \text{Log}(\text{Cells}(13, 4)) / \text{Log}(10) - \text{Log}(M4045) / \text{Log}(10)$$

$$R4550 = \text{Log}(\text{Cells}(14, 4)) / \text{Log}(10) - \text{Log}(M4550) / \text{Log}(10)$$

$$R5060 = \text{Log}(\text{Cells}(15, 4)) / \text{Log}(10) - \text{Log}(M5060) / \text{Log}(10)$$

$$R6070 = \text{Log}(\text{Cells}(16, 4)) / \text{Log}(10) - \text{Log}(M6070) / \text{Log}(10)$$

$$R7080 = \text{Log}(\text{Cells}(17, 4)) / \text{Log}(10) - \text{Log}(M7080) / \text{Log}(10)$$

$$R8090 = \text{Log}(\text{Cells}(18, 4)) / \text{Log}(10) - \text{Log}(M8090) / \text{Log}(10)$$

$$R90100 = \text{Log}(\text{Cells}(19, 4)) / \text{Log}(10) - \text{Log}(M90100) / \text{Log}(10)$$

$$SE = Rl^2 + Rf^2 + Rh^2 + R0005^2 + R0510^2 + R1015^2 + R1520^2 + R2025^2 + R2530^2 + R3035^2 + R3540^2 + R4045^2 + R4550^2 + R5060^2 + R6070^2 + R7080^2 + R8090^2 + R90100^2$$

“Calculation by method of least squares”

$$\text{Cells}(ib, ia) = SE^{0.5}$$

If ia = 10 And ib = 4 Then SEM = SE

If SE < SEM Then

$$SEM = SE$$


```

na = ia
nb = ib
End If

Next ib
Next ia

Cells(nb, na).Select
    With Selection.Interior
        .ColorIndex = 6
    End With

“The selection of the most appropriate transition coefficient”
a = Cells(3, na)
b = Cells(nb, 9)
Cells(22, 6) = a
Cells(23, 6) = b

“The calculation using the most appropriate transition coefficient”
Ml = Cells(20, 7)
Mf = 0
Mh = 0
M0005 = 0
M0510 = 0
M1015 = 0
M1520 = 0
M2025 = 0
M2530 = 0
M3035 = 0
M3540 = 0
M4045 = 0
M4550 = 0
M5060 = 0
M6070 = 0
M7080 = 0
M8090 = 0
M90100 = 0
For i = 1 To n

Mln = Ml * (1 - Pl / 0.8) * 0.5 ^ (1 / (30.17 * 12))
Mfn = (Mf + Ml * Pl / 0.8 - Mf * Pf / 2.5) * 0.5 ^ (1 / (30.17 * 12))
Mhn = (Mh + Mf * Pf / 2.5 - Mh * Ph / 0.8) * 0.5 ^ (1 / (30.17 * 12))

```

$$M0005n = (M0005 + Mh * Ph / 0.8 - M0005 * P0005 / 0.5) * 0.5 ^ (1 / (30.17 * 12))$$

$$M0510n = (M0510 + M0005 * P0005 / 0.5 - M0510 * P0510 / 0.5) * 0.5 ^ (1 / (30.17 * 12))$$

$$M1015n = (M1015 + M0510 * P0510 / 0.5 - M1015 * P1015 / 0.5) * 0.5 ^ (1 / (30.17 * 12))$$

$$M1520n = (M1520 + M1015 * P1015 / 0.5 - M1520 * P1520 / 0.5) * 0.5 ^ (1 / (30.17 * 12))$$

$$M2025n = (M2025 + M1520 * P1520 / 0.5 - M2025 * P2025 / 0.5) * 0.5 ^ (1 / (30.17 * 12))$$

$$M2530n = (M2530 + M2025 * P2025 / 0.5 - M2530 * P2530 / 0.5) * 0.5 ^ (1 / (30.17 * 12))$$

$$M3035n = (M3035 + M2530 * P2530 / 0.5 - M3035 * P3035 / 0.5) * 0.5 ^ (1 / (30.17 * 12))$$

$$M3540n = (M3540 + M3035 * P3035 / 0.5 - M3540 * P3540 / 0.5) * 0.5 ^ (1 / (30.17 * 12))$$

$$M4045n = (M4045 + M3540 * P3540 / 0.5 - M4045 * P4045 / 0.5) * 0.5 ^ (1 / (30.17 * 12))$$

$$M4550n = (M4550 + M4045 * P4045 / 0.5 - M4550 * P4550 / 0.5) * 0.5 ^ (1 / (30.17 * 12))$$

$$M5060n = (M5060 + M4550 * P4550 / 0.5 - M5060 * P5060 / 1\#) * 0.5 ^ (1 / (30.17 * 12))$$

$$M6070n = (M6070 + M5060 * P5060 / 1\# - M6070 * P6070 / 1\#) * 0.5 ^ (1 / (30.17 * 12))$$

$$M7080n = (M7080 + M6070 * P6070 / 1\# - M7080 * P7080 / 1\#) * 0.5 ^ (1 / (30.17 * 12))$$

$$M8090n = (M8090 + M7080 * P7080 / 1\# - M8090 * P8090 / 1\#) * 0.5 ^ (1 / (30.17 * 12))$$

$$M90100n = (M90100 + M8090 * P8090 / 1\# - M90100 * P90100 / 1\#) * 0.5 ^ (1 / (30.17 * 12))$$

Ml = Mln

Mf = Mfn

Mh = Mhn

M0005 = M0005n

M0510 = M0510n

M1015 = M1015n

M1520 = M1520n

M2025 = M2025n

M2530 = M2530n

M3035 = M3035n

M3540 = M3540n

M4045 = M4045n

M4550 = M4550n

M5060 = M5060n

M6070 = M6070n

M7080 = M7080n

M8090 = M8090n

M90100 = M90100n

Next i

Rl = Cells(2, 4) - Ml

Rf = Cells(3, 4) - Mf

Rh = Cells(4, 4) - Mh

R0005 = Cells(5, 4) - M0005

R0510 = Cells(6, 4) - M0510

R1015 = Cells(7, 4) - M1015

R1520 = Cells(8, 4) - M1520

R2025 = Cells(9, 4) - M2025

R2530 = Cells(10, 4) - M2530

R3035 = Cells(11, 4) - M3035

R3540 = Cells(12, 4) - M3540

R4045 = Cells(13, 4) - M4045

R4550 = Cells(14, 4) - M4550

R5060 = Cells(15, 4) - M5060

R6070 = Cells(16, 4) - M6070

R7080 = Cells(17, 4) - M7080

R8090 = Cells(18, 4) - M8090

R90100 = Cells(19, 4) - M90100

$$SE = R1^2 + Rf^2 + Rh^2 + R0005^2 + R0510^2 + R1015^2 + R1520^2 + R2025^2 + R2530^2 + R3035^2 + R3540^2 + R4045^2 + R4550^2 + R5060^2 + R6070^2 + R7080^2 + R8090^2 + R90100^2$$

Cells(2, 5) = Ml

Cells(3, 5) = Mf

Cells(4, 5) = Mh

Cells(5, 5) = M0005

Cells(6, 5) = M0510

Cells(7, 5) = M1015

Cells(8, 5) = M1520

Cells(9, 5) = M2025

Cells(10, 5) = M2530

Cells(11, 5) = M3035

Cells(12, 5) = M3540

Cells(13, 5) = M4045

Cells(14, 5) = M4550

Cells(15, 5) = M5060

Cells(16, 5) = M6070

Cells(17, 5) = M7080

Cells(18, 5) = M8090

Cells(19, 5) = M90100

Cells(2, 6) = Abs(Rl)

Cells(3, 6) = Abs(Rf)

Cells(4, 6) = Abs(Rh)

Cells(5, 6) = Abs(R0005)

Cells(6, 6) = Abs(R0510)

Cells(7, 6) = Abs(R1015)

Cells(8, 6) = Abs(R1520)

```
Cells(9, 6) = Abs(R2025)
Cells(10, 6) = Abs(R2530)
Cells(11, 6) = Abs(R3035)
Cells(12, 6) = Abs(R3540)
Cells(13, 6) = Abs(R4045)
Cells(14, 6) = Abs(R4550)
Cells(15, 6) = Abs(R5060)
Cells(16, 6) = Abs(R6070)
Cells(17, 6) = Abs(R7080)
Cells(18, 6) = Abs(R8090)
Cells(19, 6) = Abs(R90100)
Cells(21, 6) = Sqr(SE)
```

```
End Sub
```

Appendix 2 VBA program for compartment model

(Example of *Larix kaempferi*, $P=aQ^{-1}+b$, Mar. 2021)

Option Explicit

Option Base 1

Sub transport()

“The definition of the form of transition coefficient”

Dim i As Integer

Dim ia As Integer, ib As Integer

Dim a As Double, b As Double

Dim n As Integer

Dim na As Integer, nb As Integer

“The definition of the form of transition coefficient in each layer”

Dim Pl As Double, Pf As Double, Ph As Double, P0005 As Double, P0510 As Double, P1015 As Double, P1520 As Double, P2025 As Double, P2530 As Double

Dim P3035 As Double, P3540 As Double, P4045 As Double, P4550 As Double, P5060 As Double, P6070 As Double, P7080 As Double, P8090 As Double, P90100 As Double

Dim Pln As Double, Pfn As Double, Phn As Double, P0005n As Double, P0510n As Double, P1015n As Double, P1520n As Double, P2025n As Double, P2530n As Double

Dim P3035n As Double, P3540n As Double, P4045n As Double, P4550n As Double, P5060n As Double, P6070n As Double, P7080n As Double, P8090n As Double, P90100n As Double

“The definition of the form of radioactivity concentration in each layer”

Dim Ml As Double, Mf As Double, Mh As Double, M0005 As Double, M0510 As Double, M1015 As Double, M1520 As Double, M2025 As Double, M2530 As Double

Dim M3035 As Double, M3540 As Double, M4045 As Double, M4550 As Double, M5060 As Double, M6070 As Double, M7080 As Double, M8090 As Double, M90100 As Double

Dim Mln As Double, Mfn As Double, Mhn As Double, M0005n As Double, M0510n As Double, M1015n As Double, M1520n As Double, M2025n As Double, M2530n As Double

Dim M3035n As Double, M3540n As Double, M4045n As Double, M4550n As Double, M5060n As Double, M6070n As Double, M7080n As Double, M8090n As Double, M90100n As Double

“The definition of the form of subtract between monitored value and calculated value in each layer”

Dim Rl As Double, Rf As Double, Rh As Double, R0005 As Double, R0510 As Double, R1015 As Double, R1520 As Double, R2025 As Double, R2530 As Double

Dim R3035 As Double, R3540 As Double, R4045 As Double, R4550 As Double, R5060 As Double, R6070 As Double, R7080 As Double, R8090 As Double, R90100 As Double

“The definition of the form of sum of error in each layer”

Dim SE As Double, SEM As Double

“The number of the months (Mar. 2011 – Mar. 2021)*100”

$n = 6600$

“The definition of the transition coefficient based on the ignition loss”

$PI = (Cells(22, 6) / 0.9 + Cells(23, 6)) * 0.01$

$Pf = (Cells(22, 6) / 0.76 + Cells(23, 6)) * 0.01$

$Ph = (Cells(22, 6) / 0.54 + Cells(23, 6)) * 0.01$

$P0005 = (Cells(22, 6) / 0.5 + Cells(23, 6)) * 0.01$

$P0510 = (Cells(22, 6) / 0.49 + Cells(23, 6)) * 0.01$

$P1015 = (Cells(22, 6) / 0.48 + Cells(23, 6)) * 0.01$

$P1520 = (Cells(22, 6) / 0.46 + Cells(23, 6)) * 0.01$

$P2025 = (Cells(22, 6) / 0.45 + Cells(23, 6)) * 0.01$

$P2530 = (Cells(22, 6) / 0.44 + Cells(23, 6)) * 0.01$

$P3035 = (Cells(22, 6) / 0.43 + Cells(23, 6)) * 0.01$

$P3540 = (Cells(22, 6) / 0.43 + Cells(23, 6)) * 0.01$

$P4045 = (Cells(22, 6) / 0.43 + Cells(23, 6)) * 0.01$

$P4550 = (Cells(22, 6) / 0.43 + Cells(23, 6)) * 0.01$

$P5060 = (Cells(22, 6) / 0.43 + Cells(23, 6)) * 0.01$

$P6070 = (Cells(22, 6) / 0.42 + Cells(23, 6)) * 0.01$

$P7080 = (Cells(22, 6) / 0.41 + Cells(23, 6)) * 0.01$

$P8090 = (Cells(22, 6) / 0.39 + Cells(23, 6)) * 0.01$

$P90100 = (Cells(22, 6) / 0.38 + Cells(23, 6)) * 0.01$

“The initial concentration of radioactive Cs”

$Ml = Cells(2, 4)$

$Mf = Cells(3, 4)$

$Mh = Cells(4, 4)$

$M0005 = Cells(5, 4)$

$M0510 = Cells(6, 4)$

$M1015 = Cells(7, 4)$

$M1520 = Cells(8, 4)$

$M2025 = Cells(9, 4)$

$M2530 = Cells(10, 4)$

$M3035 = Cells(11, 4)$

$M3540 = Cells(12, 4)$

$M4045 = Cells(13, 4)$

$M4550 = Cells(14, 4)$

$M5060 = Cells(15, 4)$

$M6070 = Cells(16, 4)$

$M7080 = Cells(17, 4)$

$M8090 = Cells(18, 4)$

$M90100 = Cells(19, 4)$

“Simulation based on the compartment model”

For i = 1 To n

$$M_{ln} = M_l * (1 - P_l / 0.8) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{fn} = (M_f + M_l * P_l / 0.8 - M_f * P_f / 2.5) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{hn} = (M_h + M_f * P_f / 2.5 - M_h * P_h / 0.8) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{0005n} = (M_{0005} + M_h * P_h / 0.8 - M_{0005} * P_{0005} / 0.5) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{0510n} = (M_{0510} + M_{0005} * P_{0005} / 0.5 - M_{0510} * P_{0510} / 0.5) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{1015n} = (M_{1015} + M_{0510} * P_{0510} / 0.5 - M_{1015} * P_{1015} / 0.5) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{1520n} = (M_{1520} + M_{1015} * P_{1015} / 0.5 - M_{1520} * P_{1520} / 0.5) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{2025n} = (M_{2025} + M_{1520} * P_{1520} / 0.5 - M_{2025} * P_{2025} / 0.5) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{2530n} = (M_{2530} + M_{2025} * P_{2025} / 0.5 - M_{2530} * P_{2530} / 0.5) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{3035n} = (M_{3035} + M_{2530} * P_{2530} / 0.5 - M_{3035} * P_{3035} / 0.5) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{3540n} = (M_{3540} + M_{3035} * P_{3035} / 0.5 - M_{3540} * P_{3540} / 0.5) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{4045n} = (M_{4045} + M_{3540} * P_{3540} / 0.5 - M_{4045} * P_{4045} / 0.5) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{4550n} = (M_{4550} + M_{4045} * P_{4045} / 0.5 - M_{4550} * P_{4550} / 0.5) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{5060n} = (M_{5060} + M_{4550} * P_{4550} / 0.5 - M_{5060} * P_{5060} / 1\#) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{6070n} = (M_{6070} + M_{5060} * P_{5060} / 1\# - M_{6070} * P_{6070} / 1\#) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{7080n} = (M_{7080} + M_{6070} * P_{6070} / 1\# - M_{7080} * P_{7080} / 1\#) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{8090n} = (M_{8090} + M_{7080} * P_{7080} / 1\# - M_{8090} * P_{8090} / 1\#) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_{90100n} = (M_{90100} + M_{8090} * P_{8090} / 1\# - M_{90100} * P_{90100} / 1\#) * 0.5 ^ {(0.01 / (30.17 * 12))}$$

$$M_l = M_{ln}$$

$$M_f = M_{fn}$$

$$M_h = M_{hn}$$

$$M_{0005} = M_{0005n}$$

$$M_{0510} = M_{0510n}$$

$$M_{1015} = M_{1015n}$$

$$M_{1520} = M_{1520n}$$

$$M_{2025} = M_{2025n}$$

$$M_{2530} = M_{2530n}$$

$$M_{3035} = M_{3035n}$$

$$M_{3540} = M_{3540n}$$

$$M_{4045} = M_{4045n}$$

$$M_{4550} = M_{4550n}$$

$$M_{5060} = M_{5060n}$$

$$M_{6070} = M_{6070n}$$

$$M_{7080} = M_{7080n}$$

$$M_{8090} = M_{8090n}$$

$$M_{90100} = M_{90100n}$$

Next i

,

```
Cells(2, 5) = Ml  
Cells(3, 5) = Mf  
Cells(4, 5) = Mh  
Cells(5, 5) = M0005  
Cells(6, 5) = M0510  
Cells(7, 5) = M1015  
Cells(8, 5) = M1520  
Cells(9, 5) = M2025  
Cells(10, 5) = M2530  
Cells(11, 5) = M3035  
Cells(12, 5) = M3540  
Cells(13, 5) = M4045  
Cells(14, 5) = M4550  
Cells(15, 5) = M5060  
Cells(16, 5) = M6070  
Cells(17, 5) = M7080  
Cells(18, 5) = M8090  
Cells(19, 5) = M90100  
,  
End Sub
```


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みずきが平成 26 年 4 月に誕生し、子育ての大変さや喜びも噛み締める中で、妻の真由子には、ずいぶんと負担をかけたかと思います。平成 26 年度は業務と並行して、入学の準備をすることができ、先生とのディスカッションや、研究も開始しました。平成 27 年度は学業専念の機会を得て、ずいぶんと、みずきと一緒に過ごす時間も増えましたが、原子炉実験所での実験や、福島でのフィールド調査のために長期間家を留守にすることもありました。平成 28～29 年度は福島に転勤になって、月 2 回ほど週末に自宅に戻ることはありましたが、やはり一緒にいられる機会も減りました。ときどき体調を崩すみずきの看病や保育園の送り迎えなど、真由子に家事等で負担をかけたこともあったかと思います。準備期間も含め、研究に打ち込むことができ、この博士論文を取りまとめるにいたったのも、ひとえに真由子のおかげだと感謝しています。今後、福島、日本、世界にどう貢献したいか、自分の将来も見据え、明確な問題意識を持って、研究に取り組めたのではないかと思います。みずきにも、進学等のためだけに学ぶのではなく、「何故学ぶのか」「学んだことをどういかしていくのか」ということを常に考え、悩み、誰かに相談しながら、自分の答えを見つけられるようになって欲しいと思います。今回頂いた貴重な経験も踏まえ、できる限りの手助けができるよう、私も努力していきたいと思います。

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