Shoji Hashimoto
Masabumi Komatsu
Satoru Miura

Forest Radioecology in Fukushima

Radiocesium Dynamics, Impact, and Future

OPEN ACCESS

Springer

Forest Radioecology in Fukushima

Shoji Hashimoto • Masabumi Komatsu •
Satoru Miura

Forest Radioecology in Fukushima

Radiocesium Dynamics, Impact, and Future

Springer

Shoji Hashimoto
Department of Forest Soils
Forestry and Forest Products Research Institute
Tsukuba, Ibaraki, Japan

Masabumi Komatsu
Department of Mushroom Science and Forest Microbiology
Forestry and Forest Products Research Institute
Tsukuba, Ibaraki, Japan

Satoru Miura
Center for Forest Restoration and Radioecology
Forestry and Forest Products Research Institute
Tsukuba, Ibaraki, Japan

ISBN 978-981-16-9403-5 ISBN 978-981-16-9404-2 (eBook)
https://doi.org/10.1007/978-981-16-9404-2

Translation from the Japanese language edition: Radiation Ecology of Forests by Shoji Hashimoto, Masabumi Komatsu and Satoru Miura © Shoji Hashimoto, Masabumi Komatsu, Satoru Miura 2021. Published by Maruzen Publishing Co., Ltd. All Rights Reserved.

Funding Information: Forestry and Forest Products Research Institute

© The Editor(s) (if applicable) and The Author(s) 2022.
The translation of this work was done with the help of artificial intelligence (machine translation by the service DeepL.com). Intensive improvements were subsequently made by the authors throughout the text to ensure accuracy of expression and contents and to enhance the clarity.
Open Access This book is licensed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (http://creativecommons.org/licenses/by-nc-nd/4.0/), which permits any noncommercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if you modified the licensed material. You do not have permission under this license to share adapted material derived from this book or parts of it.
The images or other third party material in this book are included in the book's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the book's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.
This work is subject to copyright. All commercial rights are reserved by the author(s), whether the whole or part of the material is concerned, specifically the rights of reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Regarding these commercial rights a non-exclusive license has been granted to the publisher.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

The essential role that forests play in our global environment has become ever clearer in recent decades. With our increasing realization of the ecological importance of forests, so the value that we place on forests has grown, especially since we have lost an estimated 420 million hectares of forest cover globally since 1990 (FAO/UNEP, 2020). Increasingly, we recognize the essential role that forests play in capturing and recycling carbon, in protecting biodiversity, in conserving and moderating water flows, and even in controlling climate at local and regional scales. In addition to providing these essential ecosystem services, forests also play a critical role as interceptors of atmospheric pollutants; in some regions of the world forests have been damaged because they are so efficient in scavenging atmospheric particles resulting from industrial processes such as coal burning. In regions subject to so-called acid rain, where emissions from coal burning are often unregulated, there have been substantial reductions in normally functioning forest cover. This has led to the loss of the natural services which forests provide, including the downstream impacts of increased water runoff and reduced water quality. Unfortunately, it is often not until we lose such precious resources that we realize their full value.

Globally, forests cover approximately 30% of the land surface. Japan is a highly industrialized nation so it is perhaps surprising that forests cover approximately 70% of the country, amounting to 25 million hectares. In the Fukushima Prefecture this figure is even higher at approximately 74%, or 1.02 million hectares in absolute terms (Global Forest Watch, 2021). In contrast with many other countries where deforestation has been evident, these high levels of forest cover have been maintained in Japan for the past 30 years or more, indicating the value which the Japanese people place on their forests as a key natural resource.

In 2011, the unthinkable happened: in the space of a few days the extensive forests of Fukushima were contaminated by radioactive fallout from the accident at the Fukushima Daiichi Nuclear Power Plant. Faced with this sudden catastrophe the Japanese people had to make rapid and rational decisions about how to respond. Understandably, this completely unforeseen event shook the public's confidence not only in the technology which had released such large quantities of radioactivity into the environment but also in the environment itself as a safe and trusted place to turn to for refuge and many basic resources. Since forests represent such a large proportion of the environment in the Fukushima Prefecture they suddenly became areas of suspicion, where normal practices such as the gathering of wood and wild foods were curtailed or even prevented completely.

Sadly, this was not the first time that this tragic situation had arisen. Twenty-five years previously, in 1986, the Chernobyl accident contaminated the extensive forests surrounding the power plant itself and much further beyond. A zone of 30 km radius around the Chernobyl Power Plant was quickly established from which the general public, including people whose homes were within the zone, were evacuated and excluded. In fact, it was a forest within the exclusion zone which came to symbolize the tragedy of the Chernobyl accident in the minds of the Soviet people. This was the so-called Red Forest, a relatively small area of pine trees which were so heavily exposed to radiation that they died within weeks of the accident, turning a characteristic red color. One of the ironic consequences of the exclusion of human activity around Chernobyl has been the growth of forest cover in the exclusion zone which increased from an estimated 41% in 1986 to almost 60% in 2020 (Matsala et al., 2021). Along with this increase in tree cover, biodiversity has flourished and the forests of Chernobyl have become an unexpected symbol of recovery from the ecological destruction of 1986.

From studies carried out since the Chernobyl accident we know that forests are highly susceptible to contamination from radionuclides released by nuclear accidents, just as they are prone to the impacts of other non-radioactive air pollutants. We have also learned that they are resilient to most radioactive contamination; in all but the most severely affected areas such as the Red Forest, ecological functioning proceeds normally despite the presence of abnormally elevated radioactivity. The greatest impact of radioactive contamination is the reduction in the utility of forests to people whose lives and livelihoods are negatively impacted by the need to control radiation exposures through contaminated forest products and by simply being in the forest environment. Interventions to reduce the radiological impacts of forest contamination have proved to be impracticable except on a small scale where localized clean-up is preferable to evacuation.

Since all radionuclides are subject to predictable radioactive decay, it is a certainty that time will reduce the problem, no matter how severe the initial contamination may be. Ecological processes will also help mitigate radiation exposures, by redistributing radionuclides from tree canopies and vegetation surfaces to deeper soil layers where natural shielding will reduce ambient dose rates. Understanding these processes and the timescales over which they operate is a key part of the research undertaken by the numerous scientists who have intensively studied Fukushima's forests since 2011. The authors of this book have drawn together an extremely large, and growing, body of knowledge concerning the radioecology of the forests affected by the Fukushima accident. But they have also addressed the wider issues of the human impacts of the accident, especially viewed from the perspective of those whose lives were directly affected when the forests on which they rely were suddenly made radioactive. The authors make it clear that this is a complex and long-lived problem and that there is much work to be done to ensure we continue to understand and manage the impacts of the accident in 2011. This excellent book is a key milestone in that journey.

References

FAO and UNEP (2020) The State of the World's Forests 2020. Forests, biodiversity and people. Rome. https://doi.org/10.4060/ca8642en

Global Forest Watch (2021) https://www.globalforestwatch.org/

Matsala M, Bilous A, Myroniuk V, Holiaka D, Schepaschenko D, See L, and Kraxner F (2021) The return of nature to the Chernobyl Exclusion Zone: increases in forest cover of 1.5 times since the 1986 disaster. Forests 12: 1024. https://doi.org/10.3390/f12081024

Nottingham, UK George Shaw

Preface

The images of the massive tsunami that hit the Pacific coast of the Tohoku region of Japan on March 11, 2011, shocked people around the world. The subsequent nuclear accident may have had an even greater impact on people in the world. Do you remember the chaos at that time?

This book was first published in Japanese in March 2021; it was exactly 10 years since the Great East Japan Earthquake of 2011. The magnitude 9.0 earthquake caused a large number of casualties due to the tsunami and also triggered the accident at the Fukushima Daiichi Nuclear Power Plant of Tokyo Electric Power Company (TEPCO), resulting in radioactive contamination of a large area of land and water. Forests, in particular, account for about 70% of Japan's land area, and much of the contaminated land is forests.

After the accident, evacuation orders were issued for a 20 km radius around the nuclear plant and for the highly contaminated northwestern direction. The government has implemented decontamination and other measures against the contamination over a wide area, and as a result of the decrease in air dose rates around residential areas, the evacuation orders have been gradually lifted. Although the rate of return to the affected areas is not sufficient, at less than 30%, the recovery of the affected areas seems to be progressing. However, if we look at the forests that are the subject of this book, we can say that contamination by radiocesium is still continuing.

In Fukushima Prefecture, which is blessed with nature, many residents have benefited from living surrounded by forests before the accident. Even now, after the accident, decontamination has been carried out and the evacuation order has been lifted, many of the residents are still struggling with how to deal with the forests. At the same time, we found that there are no books explaining radioactive contamination in Fukushima forests, which should help people overcome these problems. Before the accident, we were forest researchers who knew little about radioactivity, but after the accident, we became involved in investigating radioactive materials in forests, and since then, each of us has been trying to clarify the dynamics of radioactive materials in the areas related to our fields of expertise. On the occasion of the tenth anniversary of the disaster, we have written this book because we believe it is worthwhile to record and share our experiences and findings with the people of Japan and the world.

In writing this book, our goal was to inform people who use forests contaminated by radioactive materials about the current situation of radioactively contaminated forests, and to provide a resource that should serve as a basis for how to deal with the situation. In addition, to educate the younger generation about the radioactive contamination of forests, which is expected to continue for a long time, we aimed to create a book that could be used as a textbook for university students studying forests and the environment. Therefore, we have tried to make the explanations as plain as possible, while at the same time covering information related to forests based on the results of research we have been involved in. In addition to the behavior of radioactive materials in forests, we have also included background information on the effects of radioactive contamination on forest industries and people's lives, as well as countermeasures. It is not an exaggeration to say that the issue of radioactive contamination in forests is related to everything related to forests. For example, a wide range of research fields are involved, including biogeochemistry, forest hydrology, wood anatomy, forest management, forest ecology, tree physiology, forest soil science, forest sociology, etc. In fact, experts from a variety of fields are working on Fukushima research, and this book contains interdisciplinary content that crosses these fields.

In the year 2020, when the writing of this book in Japanese began in earnest, there was a situation that was unimaginable when the book was planned. The coronavirus pandemic. There is a difference in the geographical scale of the event, from the perspective of Japan and Fukushima as a local event on a global scale (although radioactive materials actually ran around the entire globe, albeit in small amounts), to a global event involving all of humanity. However, in the sense that people's lives and society are greatly affected by some kind of event (radioactive materials, viruses), and that they are greatly concerned about unknown situations, we feel that the fundamental structure is similar. More importantly, each individual has to evaluate the risks and make decisions to change their lifestyle based on the information flying around in the media, on the Internet, and from the national and local governments. The 2011 earthquake, tsunami, and radioactive contamination issues also revealed the limitations of science and the problem of scientists not being able to adequately communicate with people and provide them with appropriate information.

It is still in the midst of this confusion that we are writing this English version. In this book, we have asked Japanese researchers and European researchers who experienced Chernobyl to write memoirs about what they felt and what happened immediately after the Fukushima accident. Memoirs may be unusual for a textbook, but we wanted to leave clear records of what the researchers thought and how they acted. In writing this book, we, the authors, have not only looked back at the scientific knowledge we have gained over the past 10 years, but we have also occasionally looked back at the tension and confusion at the time of the Fukushima accident, and remembered the feelings we had at that time that still make us shudder, which has been the driving force behind the writing of this book.

As mentioned earlier, we have been writing this book with the goal of comprehensively compiling information on the forests of Fukushima in an easy-to-understand manner on the occasion of the 10-year anniversary. We also wanted to summarize what we had learned and experienced while there was still a lot of enthusiasm from many researchers, and to keep that enthusiasm alive, though not at the same level as in the past 10 years.

We hope that this book will help to solve more and more problems in the forests of Fukushima and promote understanding not only among those directly involved in the forests of Fukushima, but also among many others. There will always be situations in your life when something happens that affects your life, and you will have to understand and judge the scientific findings of that event. As authors, we would be happy if this book could be a reference for your scientific literacy (how to understand and accept scientific information, and how to deal with complex issues in a balanced manner). On the other hand, as some things have been clarified after 10 years of observation, but others are still unanswered, there is always a limit to how science can deliver the right situation to people at the right time. In such situations, it will be important to be careful not to fall into panicky thinking, but to be on the safe side and deal with the situation.

The book is organized as follows. Chapter 1 gives an overview of the release of radioactive material caused by the Fukushima nuclear power plant accident and the general situation of the forests in Fukushima, Chap. 2 describes the basic concept of radioactive contamination, and Chap. 3 summarizes the dynamics of radiocesium in the forests as revealed by 10 years of research. In Chap. 4, the relationship between forest ecosystems and radioactive contamination is comprehensively considered, and in Chap. 5, radiation protection and various criteria are explained from the point of view of how to protect people from radiation damage. Chap. 6 outlines the effects of radioactive contamination of forests on people's lives and industries from various perspectives, and Chap. 7 concludes with a discussion of the future of forests.

In this English edition, we have made some changes to the original book so that people all over the world can understand the geography, culture, and situation of Japan. We have also included a "Fact sheet" and a topographical map of Fukushima at the beginning of the book, as well as more explanations about the location and its unique cultures in Japan in the text. The reference list was also improved to list the original Japanese source as well as English sources. We also listed key review papers and reports from international agencies and Japan's government. We sincerely hope that this book will comprehensively convey the reality of Fukushima's forests and our thoughts on the current situation to readers around the world.

Finally, we have a small request: radioactive contamination is a problem that will continue for a long time to come. We hope that everyone who has picked up this book will continue to occasionally pay attention to this issue, even if only for a little while, and that you will get as much reliable information as possible when doing so. Also, if more students major in radioecology after reading this book, we will be more than happy.

This book is based on a vast amount of research and survey results. We would like to express our gratitude and respect to all the researchers who have worked on the forest research in Fukushima. In particular, we would like to express our gratitude to the members of the Forestry and Forest Products Research Institute; Isotope Agriculture Education and Research Facility and Laboratory of Silviculture, Graduate School of Agricultural and Life Sciences, the University of Tokyo, for their great support in various ways. We are grateful to the Forestry Agency, Fukushima Prefecture, municipalities in Fukushima Prefecture, and forestry cooperatives for their cooperation in providing data and surveys. The authors also participated in a project of the International Atomic Energy Agency. We met the European researchers there, and worked together to analyze the data. They had experienced Chernobyl, were concerned with the Fukushima nuclear accident, and helped us and encouraged us. We are especially indebted to Professor Emeritus Brenda Jane Howard (Centre for Ecology and Hydrology, UK) for her help in the project. We are also indebted to Dr. Keiko Tagami, Dr. Yves Thiry, Professor Emeritus George Shaw (all three of whom participated in the aforementioned project), and Dr. Masamichi Takahashi, who was at the forefront of the project during its most turbulent period, for contributing their memoirs to the column. We would also like to thank Dr. Michio Aoyama for his advice on the terminology and usage of radioactivity and radiation, and thank Mike Williams for his English check for this English edition. We are also indebted to Maruzen Co., Ltd for generous agreement to publish the English version.

Tsukuba, Japan
November 2021

Shoji Hashimoto
Masabumi Komatsu
Satoru Miura

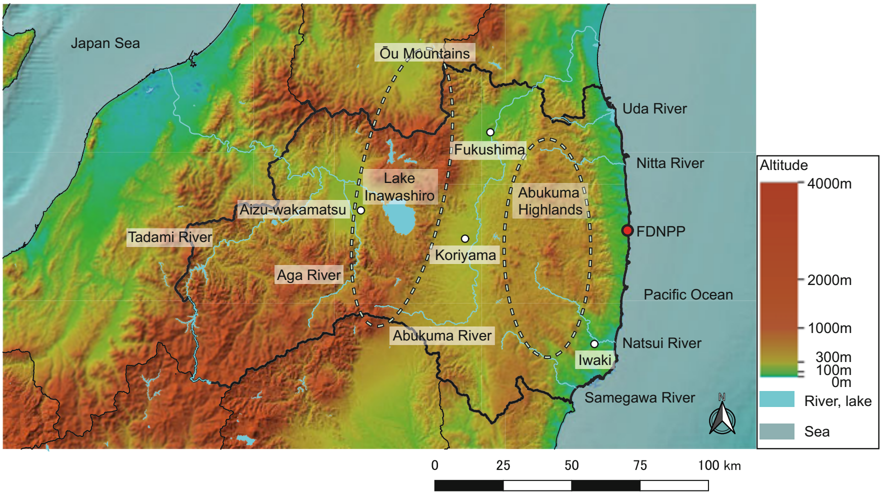
Fact Sheet—15 Points to Understand the Radioactive Contamination of Forest in Fukushima

Abstract This *Fact Sheet* will provide general information helpful to understand the Fukushima accident and forest through 15 Q&As.

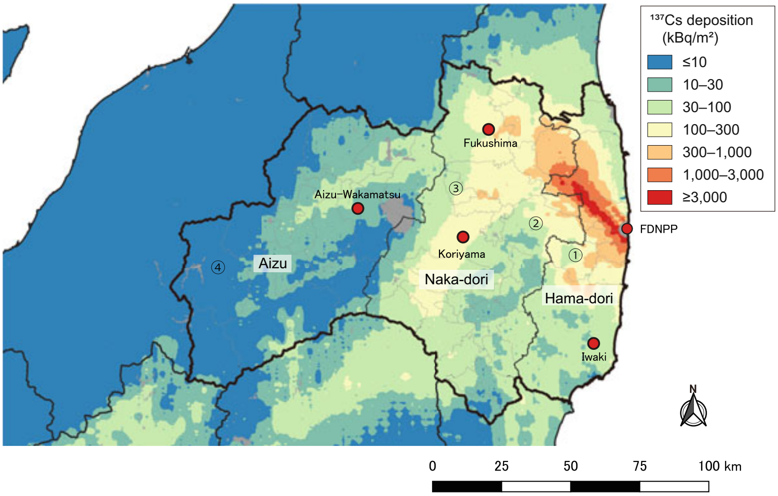
Keywords Fukushima accident; Fukushima forest; Impact; Future

Aerial view of the Fukushima Daiichi Nuclear Power Plant and Fukushima Prefecture, looking west. The Fukushima Daiichi Nuclear Power Plant can be seen along the coast in the lower center, the white area (Source: Prepared based on Geospatial Information Authority of Japan, Digital globe)

Geography of Fukushima



Geography of Fukushima Prefecture and surrounding areas. FDNPP is shown in red. The border of Fukushima Prefecture is indicated by a thick black line. Abukuma Highlands are the area circled by a dashed line (Source: Geospatial Information Authority of Japan, "GSI Tiles (Color elevation map including marine area data provided from Hydrographic and Oceanographic Department, Japan Coast Guard)" and Ministry of Land, Infrastructure, Transport and Tourism, "Administrative Boundary Data, Digital National Land Information")



Spatial distribution of contamination of Fukushima Prefecture and surrounding areas, and key place names in this book. FDNPP and major cities are shown with red dots. The border of Fukushima Prefecture is indicated by a thick black line. Fukushima Prefecture consists of Hama-dori (east), Naka-dori (middle), and Aizu (west) regions. ①: Kawauchi Village, ②: Tamura City, ③: Otama Village, ④: Tadami Town. Also see Fig. 6.6 for difficult-to-return areas (Source: Nuclear Regulation Authority, "(1) Results of Airborne Monitoring Survey in Hokkaido and (2) Revision to the Results of Airborne Monitoring Survey over the Eastern Part of Japan with Detailed Consideration of the Influence of Natural Radionuclides", decay corrected as of May 31, 2012)

Overview of the Fukushima Accident

Q1: When and why did the Fukushima accident happen?

A: On March 11, 2011, a massive earthquake struck the northeastern part of Japan. The earthquake triggered a massive tsunami that flooded the emergency diesel generators of the Fukushima Daiichi Nuclear Power Plant. Due to the loss of power, the reactors could not be cooled, resulting in hydrogen explosions and a subsequent radioactive leak. Radioactive materials were released intermittently, mainly between March 12 and 21.

Q2: How much and what kind of radioactive material was released?

A: There were many different kinds of radioactive nuclides released, but the ones that were released in particularly large quantities were xenon-133, iodine-131, cesium-134, and cesium-137. Xenon was released at twice the level of Chernobyl, but cesium-134 and cesium-137 were released at a fraction of the level of Chernobyl. Strontium 90 was also released, although not in as large a quantity.

Q3: How many people were evacuated from the contaminated area?

A: Approximately 154,000 people were evacuated from their homes and work areas, of which 109,000 were from the "Evacuation Order Zone" (or no-go area). In 2021, approximately 40,000 people have not yet returned to their homes.

Fukushima Forest

Q4: What is the percentage of forested land in the contaminated areas?

A: Fukushima Prefecture is one of the most forested areas in Japan, with about 71% of its area covered by forest.

Q5: What trees are in the forests?

A: Evergreen coniferous trees such as Japanese cedar, Japanese cypress, and red pine account for about 40%, and deciduous trees such as konara oak account for about 60%.

Forest in Fukushima, Japanese cedar and understory vegetations (Photo taken by the author)

Q6: How were the forests used?

A: About 35% of the forest is man-made. Evergreen coniferous trees were mainly grown for construction timber usage, while deciduous broadleaf konara oak was used for papermaking materials and mushroom cultivation. Many people living in mountain villages enjoyed the blessings of the forest by gathering edible wild mushrooms and wild plants, hiking, etc. Some of them obtained their livelihood from the forest.

Q7: What are forests and people (*satoyama*) in Fukushima?

A: In Japan's mountainous regions, such as the forests of Fukushima, a small amount of farmland is surrounded by forests, and the people who live there have lived in harmony with the forests, making use of their blessings. Such a forest is called satoyama (Sato: village, Yama: mountain/forest) in Japanese, and furthermore the term "satoyama" often refers to the entire zone including such forests, villages, and farmlands.

Four seasons of a satoyama landscape (Courtesy of Masami Tajima, stills from the movie "Fukushima's lost spring, seen though Shiitake mushrooms (Vol.1)")

Impact

Q8: How did the radiocesium behave in the forest?

A: When radiocesium fell into the forest from the air, most of it adhered to the tree leaves and branches. Over the next few years, the radiocesium from the trees migrated to the soil, and now most of the radiocesium in the forest is in the soil. Currently, only a small amount is thought to be cycling between the tree and the soil through absorption by the trees and returning to the soil by falling old leaves.

Q9: What are the radiation levels?

A: Cesium-134, which has a half-life of 2 years, decreases rapidly by decay, so there was a large decrease below half in the radiation levels in the first few years after the accident. The radiocesium remaining today is mostly cesium-137, which has a half-life of 30 years, so the radiation level is decreasing very slowly.

Q10: Are the effects of radiation exposure confirmed in the forest?

A: There have been some reports of morphological abnormalities of trees due to radiation exposure effects, but these are rare and minor.

Q11: What measures has the government taken to protect people from possibly contaminated forests?

A: The government has set criteria for forest products and created a guideline that people can use with confidence. The government has also banned access to areas with high levels of contamination. Forests that border residential and agricultural areas have been decontaminated (the soil surface organic layer was removed) within 20 m of the forest edge.

Q12: What impact did the accident have on people's lives?

A: Currently, there are still areas where people cannot enter and live based on criteria. Furthermore, even if people are able to return to their homes in the decontaminated residential areas, there are areas where people cannot use the surrounding forests because they are still highly contaminated. Mushroom log production has stopped in Fukushima and surrounding prefectures, and mushroom production using logs has yet to recover.

Forest decontamination (Courtesy of Yoshikazu Ohtani, the Forestry and Forest Products Research Institute)

To the Future

Q13: How long does it take for radiocesium and radiation levels to drop sufficiently?

A: The half-life of cesium-137 is 30 years, so it will take 30 years and 100 years for the amount of cesium-137 to decrease to half and one-tenth of the amount at the time of the accident, respectively. Forests tend not to release radiocesium out, so it is expected to decrease in the same way as the radioactive decay of cesium-137. In less contaminated areas, radiation levels will decrease sufficiently in a few years to a few decades, but in severely contaminated areas, it will take several decades to a hundred years or more.

Q14: What should we do about contaminated forests? Can people's livelihoods be restored?

A: We think it is necessary to divide the issue according to the level of contamination. In areas where the level of contamination is not so high, it is considered possible to continue living with forests while avoiding exposure to radiation by taking various measures and precautions. On the other hand, for highly contaminated forests, it is necessary to think of other ways to use the forest and to wait for a long time until the amount of contamination decreases sufficiently, while maintaining the health of the forest.

Q15: Was Japan well prepared for the nuclear accident?

A: We have to say that this is not the case. We experienced the Chernobyl accident as did the Europeans, but when the Fukushima accident happened, most Japanese people did not have much knowledge about radioactive contamination and its risks. We sincerely encourage everyone to understand radioactive contamination and prepare for any future nuclear accident. We hope that this book will help you learn about radioactivity in the environment and prepare for the unexpected accident.

Contents

Chapter 1
Radioactive Materials Released by the Fukushima Nuclear Accident

Abstract In this chapter, the release of radioactive materials and the characteristics of the forest ecosystem will be described to get an overall picture of the radioactive contamination of forests caused by the Fukushima Daiichi Nuclear Power Plant accident.

Keywords Fukushima accident · Tsunami · Released radionuclides · Forest ecosystem · Chernobyl accident

1.1 How Were the Radioactive Materials Dispersed from the Power Plant?

The fate of radioactive materials released into the atmosphere as a result of the Fukushima nuclear accident was affected by meteorological conditions such as precipitation and wind direction, and the amount deposited on the ground surface varied by more than 1000 times depending on the location.

The release of radioactive materials from the Fukushima Daiichi Nuclear Power Plant occurred as a result of the massive tsunami triggered by the March 11, 2011 earthquake, which caused the plant to lose power and the ability to cool its reactors. The release of radioactive materials occurred from several reactors, and the major releases and depositions are believed to have occurred between March 12 and 21. The main radioactive materials (nuclides) released were xenon-133 (^{133}Xe), iodine-131 (^{131}I), cesium-134 (^{134}Cs) and cesium-137 (^{137}Cs). Among these, iodine-131, cesium-134, and cesium-137 are the most dominant nuclides, and although there is still some room for discussion about the exact value, the emitted amount of each nuclide is estimated to be 160, 18, and 15 PBq ($P = \text{peta} = 10^{15}$ = thousand trillion, and Bq = becquerel; becquerel is explained in Sect. 2.3) according to the data compiled by the Ministry of the Environment of Japan (Table 1.1). The half-lives

S. Hashimoto et al., *Forest Radioecology in Fukushima*,
https://doi.org/10.1007/978-981-16-9404-2_1

Table 1.1 Half-lives of dominant radionuclides and amount released to the environment by the Fukushima Daiichi Nuclear Power Plant accident and Chernobyl Nuclear Power Plant accident

		Released amount to the environment (PBq: peta becquerel)	
Nuclide	Half-life	Fukushima accident	Chernobyl accident
Xenon-133 (^{133}Xe)	5 days	11,000	6500
Iodine-131 (^{131}I)	8 days	160	~ 1760
Cesium-134 (^{134}Cs)	2 years	18	~ 47
Cesium-137 (^{137}Cs)	30 years	15	~ 85
Strontium-90 (^{90}Sr)	29 years	0.14	~ 10
Plutonium-238 (^{238}Pu)	88 years	1.9×10^{-5}	1.5×10^{-2}
Plutonium-239 (^{239}Pu)	24,100 years	3.2×10^{-6}	1.3×10^{-2}
Plutonium-240 (^{240}Pu)	6540 years	3.2×10^{-6}	1.8×10^{-2}

Note: A peta is 10^{15}, or a thousand trillion

Source: Data from Ministry of the Environment, BOOKLET to Provide Basic Information Regarding Health Effects of Radiation (First Edition), “Chap. 2 Radiation Exposure, 2.2 Nuclear Disaster, Comparison of Estimated Amounts of Released Radionuclides between Chernobyl and Fukushima Daiichi NPS Accidents” [1]

(the time it takes for a radionuclide to decay to half of its original amount, see Sect. 2.1) of these radionuclides are very different: 8 days (^{131}I), 2 years (^{134}Cs), and 30 years (^{137}Cs), respectively. A short half-life means that the radionuclide decreases quickly through decay. Therefore, the amount of iodine-131 was high immediately after the accident, but rapidly decreased, and radiocesium contamination became a major problem several months after the accident. According to Table 1.1, which is an estimate for the first few months after the accident, the ratio of cesium-134 to cesium-137 was 1.2:1, but according to many subsequent studies it was considered that the emitted ratio was approximately 1:1 at the time of the accident. In addition, 7 years after the accident, the amount of cesium-134 decreases to less than one tenth of the initial amount. After that, contamination with cesium-137, which has a longer half-life, becomes a long-lasting problem. Since cesium-134 and cesium-137 have the boiling point of 671 °C and become gases when nuclear fuel is melted, and then become particles when the temperature drops below the melting point of 28 °C, most of the radiocesium in the air was considered to be in the form of small particles and was diffused by the wind. In the case of the Fukushima accident, radioactive plutonium (^{238}Pu, ^{239}Pu, ^{240}Pu) and strontium (^{90}Sr) were released in very small amounts, so they were not a major problem. Although xenon-133 was released in much larger quantities than cesium-134 and 137, it has a very short half-life of 5 days and is an inert gas, so it is considered to have little impact on the human body or the environment.

The Fukushima nuclear accident is often compared to the Chernobyl Nuclear Power Plant accident that occurred in 1986. According to the scale of an international organization, both accidents were serious accidents of level 7, but if we compare the amount of radionuclides released, we can see that the amount of radioactive iodine and cesium released by the Fukushima nuclear accident was less than a fraction of the amount released from the Chernobyl nuclear accident, and the amount of strontium

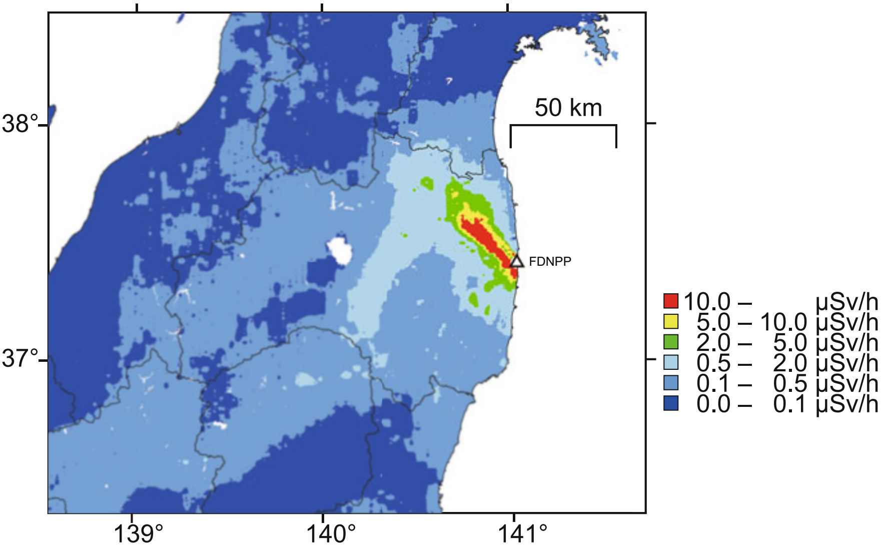


Fig. 1.1 Map of air dose rate in and around Fukushima Prefecture prepared by airborne monitoring. Decay corrected as of May 31, 2012 (Source: Data from Nuclear Regulation Authority of Japan, "(i) Results of Airborne Monitoring Survey in Hokkaido and (ii) Revision to the Results of Airborne Monitoring Survey over the Eastern Part of Japan with Detailed Consideration of the Influence of Natural Radionuclides" [3])

and plutonium was less than 1/100 to 1/1000 of the amount released by the Chernobyl nuclear accident (Table 1.1). Furthermore, the area contaminated by the Fukushima accident was much smaller than that of the Chernobyl nuclear accident, which contaminated a large part of Europe (Figs. 1.1 and 1.2).

The released radioactive materials drifted in the air as a plume according to the wind at that time. Although the amount of radioactive materials released changed from moment to moment, and the flow was greatly affected by weather and wind direction at the time of release, most (about 80% in the case of cesium-137) flowed out to sea [2]. However, land areas, mainly in eastern Japan, were also widely contaminated. The contamination was particularly pronounced in the area extending in a northwestern direction from the Fukushima Daiichi Nuclear Power Plant, which was considered to have been mainly contaminated by the wind and rain in the afternoon of March 15 (Fig. 1.1).

Contamination of land is mainly caused by deposition, a phenomenon in which radioactive materials fall from the atmosphere to the land surface and adhere to objects on the surface. The higher the amount deposited, the more heavily the land is contaminated with radioactive materials. Deposition can be divided into two main processes. Wet deposition occurs when precipitation such as rain falls, and dry deposition occurs when fine particles of radioactive aerosols drifting in the air hit and adhere to the plant leaves and the ground surface (Fig. 1.3). In addition, there is

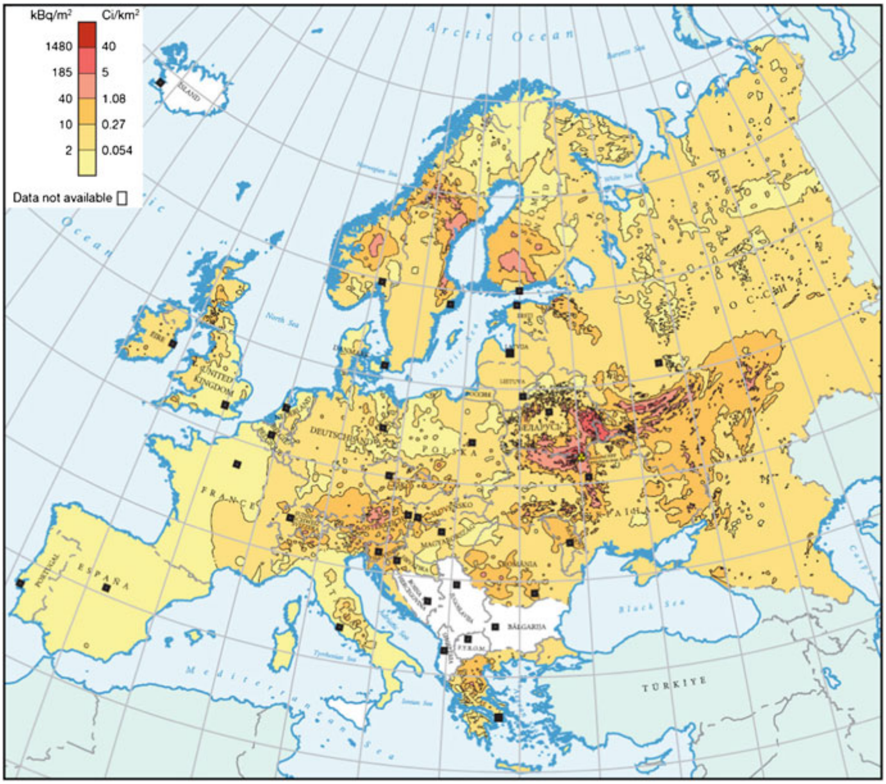


Fig. 1.2 Map of radiocesium (cesium-137) distribution in Europe after the Chernobyl Nuclear Power Plant accident. Including not only cesium-137 emitted from the Chernobyl nuclear accident but also derived from the past nuclear tests (global fallout: see Sect. 4.4) (Source: Reprinted from Saenko et al. [4], original map: De Cort M, Dubois G, Fridman ShD, et al. (1998) Atlas of Caesium Deposition on Europe After the Chernobyl Accident. EUR Report no.16733. Luxembourg: Office for Official Publications of the European Communities. https://op.europa.eu/en/publication-detail/-/publication/110b15f7-4df8-49a0-856f-be8f681ae9fd)

fog water deposition caused by fog. In areas where the amount of deposition was high, it is thought that most of the deposition was caused by wet deposition [5, 6].

To understand a wide area of contamination, regional surveys using aircraft were conducted, which is commonly called airborne monitoring. In airborne monitoring, gamma (γ) radiation from the ground is measured and corrected using ground-based observations to create a map. The airborne monitoring revealed the extremely uneven spatial distribution of the contamination: even within a distance of 10–80 km from the plant, the air dose rate was around 0.1 μSv/h in the less contaminated areas, while in the highly contaminated areas northwest of the plant, there were points where the air dose rate exceeded 50 μSv/h. In addition, it has become clear that the amount of radiocesium deposited immediately after the accident ranged from less than 10 kBq/m^2 (k = kilo = 10^3) to 10 MBq/m^2 (M = mega = 10^6) at high-dose points, a difference of more than 1000 times. The

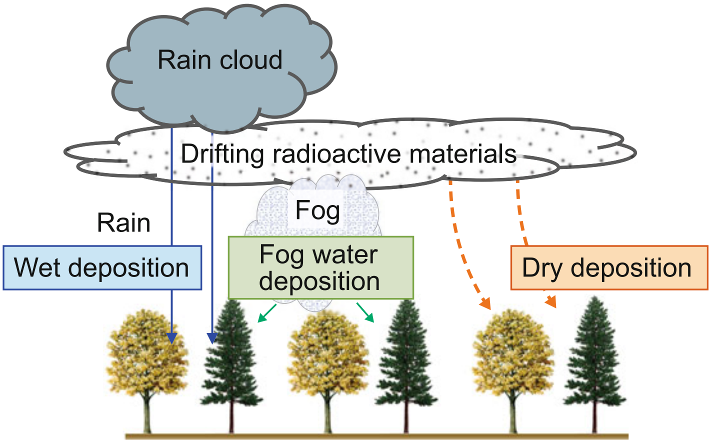


Fig. 1.3 Various deposition processes of radioactive materials

airborne monitoring was not only used to provide the public with a visualization of the spatial extent of contamination, but was also widely used by researchers as a rough indicator of the contamination level at the study sites.

1.2 Characteristics of Forests in Fukushima

Fukushima is one of the areas in Japan where forests are widely distributed.

Approximately 67% of Japan's land area is covered by forests (Fig. 1.4). The forest coverage in Fukushima Prefecture is 71%, which is higher than the average for Japan, and the forest area is 970,000 hectares [7]. Artificial forests (forests that have been planted and managed) cover 380,000 hectares, and natural forests (forests that have sprouted and grown by nature, or forests that have been unmanaged by humans for a long time) covers 580,000 hectares [7]. By type of ownership, national forests cover 410,000 hectares and privately owned forests cover 570,000 hectares. There are a wide variety of tree species, but the main ones are evergreen coniferous trees such as Japanese cedar (*Cryptomeria japonica*), cypress (*Chamaecyparis obtusa*), and red pine (*Pinus densiflora*), and deciduous broadleaf trees such as konara oak (*Quercus serrata*) (Fig. 1.5). Evergreen trees have leaves throughout the year, while deciduous trees drop all their leaves in autumn and spend the winter without leaves on their branches, and then sprout new leaves in spring.

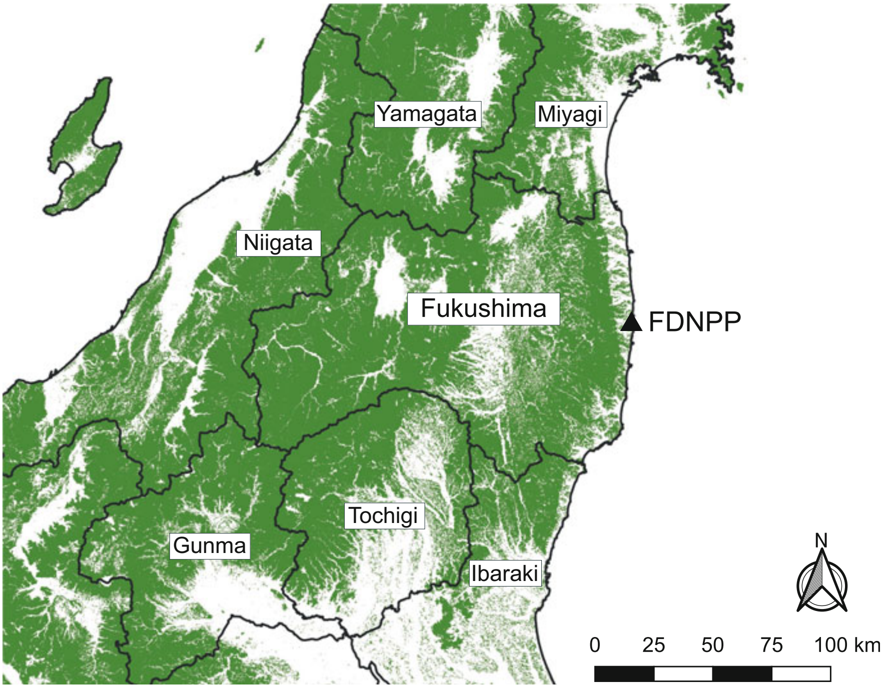


Fig. 1.4 Distribution of forests in and around Fukushima Prefecture. Forests are shown in green areas, and prefectural borders are indicated by black lines (Source: Data from Ministry of Land, Infrastructure, Transport and Tourism, based on Land-use Maps from "Digital National Land Information" [8])

Fig. 1.5 Forests in Fukushima Prefecture (Left: Japanese cedar forest; Right: konara oak forest in winter, which has no leaves because konara oak is a deciduous tree) (Source: Reprinted from IAEA, TECDOC-1927 [9], courtesy of Shinta Ohashi, the Forestry and Forest Products Research Institute)

In particular, the forests in the Abukuma Highlands (Abukuma Mountains, see Fact Sheet), which stretch to the east of Fukushima Prefecture, have been actively cultivating trees for mushroom logs, mainly konara oak, but they have been greatly affected by the contamination caused by the accident (Sect. 6.5).

1.3 Forest Ecosystems Are Unique and Different from Cropland

Time scales of forests range from a few decades to 100 years.

Forests are similar to cropland in the sense that plants grow on top of the soil. In reality, however, forests are different from cropland in many ways, causing significantly different behavior of radiocesium (Fig. 1.6). First of all, compared to cropland, where most plants (crops) are annuals, trees in forests have a long life span (perennial), ranging from several decades to more than 100 years. Over time, trees can grow to heights of 10 to 30 meters above the ground, spreading their branches and leaves to form a multi-layered structure that covers the ground surface. If you look at the surface of the ground, you will find layers of mineral soil, which are made up of minerals that have been weathered and mixed with decomposed humic organic matter, and a soil surface organic layer (also known as a litter layer), which is made up of organic matter such as fallen leaves and branches (Fig. 1.7). In cropland, there is no natural organic layer, although grass clippings may be used to mulch the cropland. In cropland soils, the plow layer (the soil near the surface that is

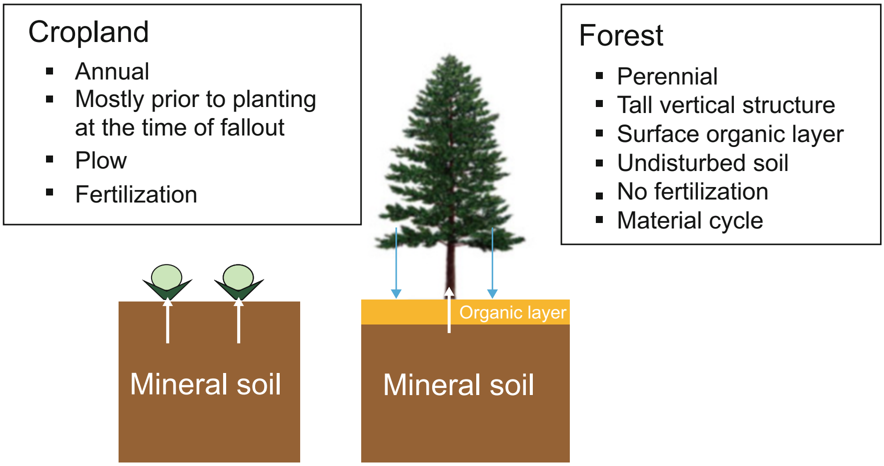


Fig. 1.6 Schematic diagram of structural differences between forest and cropland

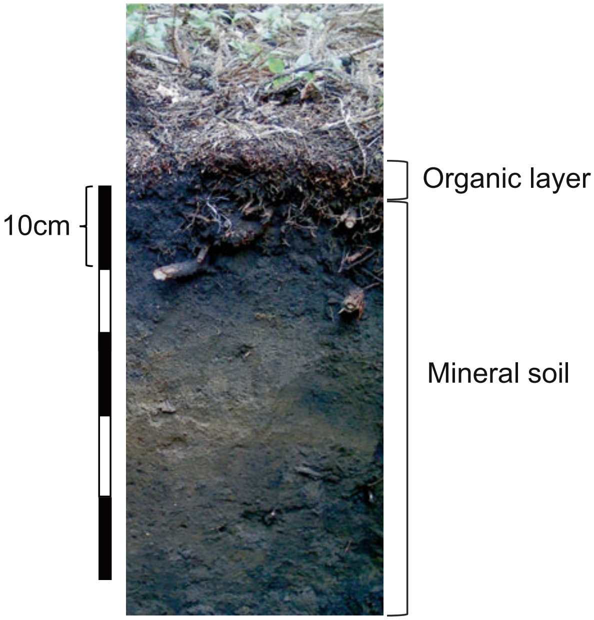


Fig. 1.7 Cross-sectional view of a forest soil. An organic layer consists of leaves or twigs at the soil surface decomposed slightly or strongly, and the darker materials below are mineral soil. Roots can be seen at the top of the mineral soil layer (Courtesy of Shinji Kaneko, the Forestry and Forest Products Research Institute)

used to grow crops) is created artificially by adding compost every year or by tilling and furrowing the soil with a tiller. On the other hand, in forest soils, the soil surface is sometimes disturbed by soil erosion and shallow landslides, but there is no artificial soil disturbance like in cropland. Therefore, the concentrations of various substances in the soil are uniform within the plow layer of cropland, but in forest soils, the concentration of substances and the soil quality vary with depth. In general, the concentration of nutrients tends to decrease with depth in forest soils.

In a forest, major nutrients such as nitrogen, phosphorus, and potassium, as well as trace elements (minor nutrients) necessary for plant growth, are circulating within the system mentioned above. For example, when it rains in a forest, some of the rain adheres to the trees, while the rest goes directly into the soil. Some of the rain on the trees will evaporate, but the rest will fall to the ground immediately or take a little time to travel through the trees and enter the soil. Some of the water that enters the soil penetrates deeply, while some water is absorbed by the trees. Trees are perennial, but as they grow, they renew their foliage by cutting off old leaves and branches and dropping them to the ground. The organic matter that falls to the ground, such as leaves and branches, becomes a source of nutrients for microorganisms and soil animals, and is decomposed by their biological activities. Some of the organic matter accumulates in the soil as humus that does not decompose quickly. Humus also decomposes little by little each year, and some of the nutrients released from it are absorbed by the trees again. The function of forests to circulate and utilize nutrients through litterfall is called self-fertilization, and is a major characteristic of forests.

The degree of human involvement is also very different. In the case of cropland, humans are heavily involved throughout the year in planting, fertilizing, harvesting, and tilling. Forests are also cut down, planted, and thinned, but on a time scale of decades, and human intervention is not as frequent as in cropland. Normally, there is no fertilization or tilling, and the cycling of materials of the ecosystem is left to nature. In addition, while cropland is mostly a place to produce food, the main product of forests is wood. It takes a long time to grow and harvest wood, usually 40 to 50 years, but in some cases harvesting can take over 100 years. In addition to the main product of wood, which is used for building materials, furniture, chips, and logs for mushroom production, various by-products are collected depending on the region, such as mushrooms, wild vegetables, lacquer, Japanese paper, dyes, and honey.

1.4 Column: Looking Back on that Time (1)

I'm proud that I've been a researcher in the field of environmental radioactivity

Keiko Tagami
Group Leader, Quantum Science and Technology Research Organization

The day after the 11th annual "Environmental Radioactivity" workshop in Tsukuba City, Japan, the Tohoku-Pacific Ocean Earthquake struck while I was working at my laboratory in Chiba City, which was also affected by the strong quake. Soon after the earthquake, after I finished checking that everyone was safe, I heard the TV program (no time to watch it at that time) reporting about the huge tsunami that was going to hit the Pacific coast of Tohoku near the epicenter. However, because I heard that the nuclear power plants in operation on the coastal areas had been shut down properly, I had no doubt that the safety devices in these plants were working properly; and I never imagined that it would become such a big nuclear accident.

On the next day, Units No. 1–3 of the Fukushima Daiichi Nuclear Power Plant were not cooled down enough and the situation became critical and started to release large amounts of radionuclides into the environment. By March 15th, relatively high air dose rates were recorded even in the Kanto area (Tokyo metropolitan and adjacent prefectures including Chiba). Because I and my colleagues are radioecologists, even in such conditions, we started to collect environmental samples. In particular, we wanted to know, "What sort of radionuclides were deposited on the ground and in what amounts?". This information would give us the severity of the nuclear accident. Together with this sampling activity, because we were a limited number of environmental radioecologists at that time, we had to take care of many things. Since there were concerns about internal radiation exposure through food and drink, we conducted research on the removal of ^{131}I detected in tap water, reduction of

(continued)

radioactive materials by food processing, absorption of radionuclides on plant surfaces, translocation of radiocesium in plants, etc. At the same time, we exchanged information with overseas countries and provided information to government agencies to reduce exposure doses.

Unfortunately, it was not an easy situation for us to open our research results to the public. At that time in the media, every day, I found unfamiliar faces speaking as environmental radioecologists (are they really experts?) and listened to their comments exaggerating how harmful the radiation exposure was, I felt sad every time. Yet, I measured environmental samples to understand the present situation, and thought about how to obtain data that would be useful in the future; for that purpose I've just kept working with nature. When I measured radioactivity in plants regularly, I noticed that plants simply responded as we had learned before the accident. Thus I thought, "This means that Japan is still safe, and we can reduce radiation exposure". Later, however, I recognized that this is true but only in places where the contamination level is limited (not harmful to human beings).

Particularly in the area northwest of the Fukushima Daiichi Nuclear Power Plant as a highly radioactive plume passed through the area. No matter how beautiful nature is now, there is still high radiation there that can threaten people's lives. When I think about it, I feel sorry because although I am an expert in environmental radioactivity, I can't do anything about it. At least, I would like to know and inform the people how much radiation we are exposed to (or have been exposed to) from our living environments. To do so, we need to provide environmental parameters that can be used in mathematical model assessments, not just lists of raw data. I am glad that I've been a researcher in the field of environmental radioactivity who can do this.

It has been 10 years since the accident. We still have to tackle radiation. I would like to provide the people with useful information so that they can live with some peace of mind.

Chapter 2
Basic Knowledge to Understand Radioactive Contamination

Abstract This chapter will explain the basic characteristics of radioactive materials (radionuclides), which are necessary to understand the entire book, including the behavior of radiocesium in forests in Chap. 3 and countermeasures against radioactive contamination for exposure protection handled in Chap. 5 and later.

Keywords Radioactive contamination · Radiation · Radioactivity · Radioactive materials · Radionuclides · Half-life · Radiation exposure

2.1 Radiation, Radioactivity, and Radioactive Materials (Radionuclides)

A material that has the ability to emit radiation (radioactivity) is called a radioactive material (radionuclide). There are different types of radiation, each with different characteristics.

A radioactive material (radionuclide) is a general term for a substance that has the ability to emit radiation (radioactivity). Since the nucleus of the atom is unstable, it changes into a different substance (nuclide) over time by decay while emitting ionizing radiation. There are various types of radiation, and each type has different properties. The types of radiation emitted by each radionuclide is different.

There are three main types of radiation that are closely related to the nuclear accident: alpha (α), beta (β), and gamma (γ). Alpha and beta rays are helium atoms and electrons emitted from the nuclei of radioactive elements, respectively, and are also called particle radiation. Gamma rays are not material, but electromagnetic waves, the same as X-rays used in X-ray examination. One of the characteristics of each type of radiation is its ability to penetrate objects (Fig. 2.1). Alpha rays have the lowest penetrating ability and can be stopped by a sheet of paper, beta rays can be stopped by a thin sheet of plastic or aluminum. However, gamma rays have a high penetrating ability and can pass through the human body, requiring lead or iron

S. Hashimoto et al., *Forest Radioecology in Fukushima*,
https://doi.org/10.1007/978-981-16-9404-2_2

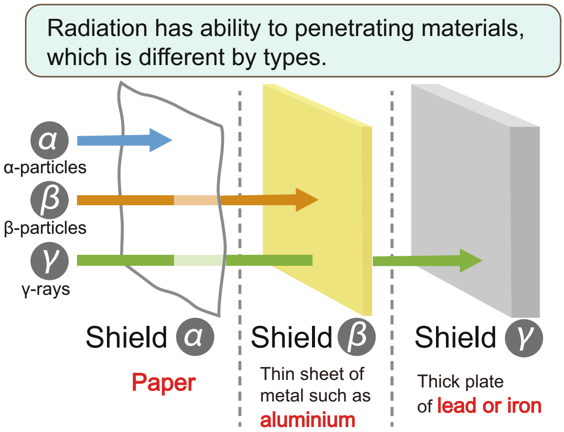


Fig. 2.1 Types of radiation and their penetrating ability (Source: Adapted from Ministry of the Environment, Radioactive Waste Management Information Website "What is Radioactive Waste, Basic Knowledge of Radiation, Types and Characteristics of Radiation" [10])

plates or thick concrete to stop them. Different types of radiation have different penetrating ability, and thus have different impact (exposure) on the human body. Since alpha and beta rays have low penetrating ability, they affect the tissues near the radioactive materials. On the other hand, gamma rays having a high penetrating ability affect the tissues inside the body while passing through the human body. Among radionuclides, cesium-134 and cesium-137 emit beta and gamma rays during decay.

Another important characteristic of radioactive materials is that their nuclei decay (change into other nuclides) over time, resulting in a decrease in the amount of radiation emitted. This phenomenon is called radioactive decay (or physical decay). The probability (or rate) that a radionuclide will decay in a certain amount of time is constant for each nuclide, and the decrease can be expressed as an exponential function. The time it takes for a radionuclide to decrease by half from its original amount due to radioactive decay is called its half-life (physical half-life), and the half-life of cesium-137, which was released in large quantities during the Fukushima nuclear accident, is about 30 years. For example, if there were 100,000 atoms of cesium-137, the number of atoms that would decay per day at that point would be about six, and it will take about 30 years for the number of decayed atoms to be halved to 50,000 (Fig. 2.2). After another 30 years, the number of cesium-137 decays to 25,000, half the number of cesium-137. It will take about 100 years for the radioactivity to decrease by a factor of 10, and 200 years for it to decrease by a factor of 100. The physical half-lives vary greatly depending on the nuclides (Table 1.1). Cesium-134, which, like cesium-137, was released in the nuclear accident, has a short half-life of about 2 years, so its radioactivity will decrease by a factor of 100 in 14 years. The physical half-life of iodine-131, which was released in the Fukushima nuclear accident in a quantity 10 times larger than cesium-137 and 134, is 8 days. Within 2 months after the accident, the radioactivity of iodine-131 was reduced to less than one-hundredth, and after 6 months, its effect was almost undetectable.

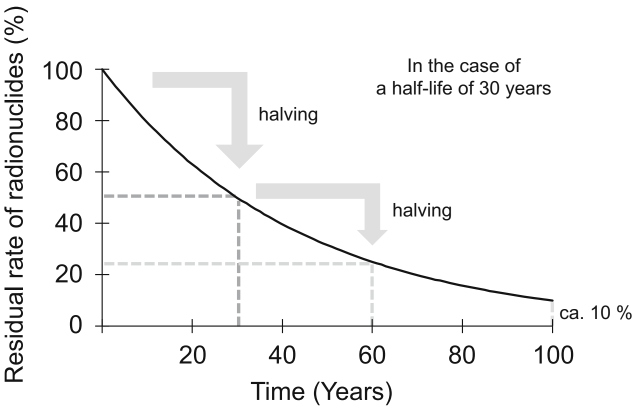


Fig. 2.2 Concept of physical half-life (In the case of a half-life of 30 years, 50% in 30 years and about 10% in 100 years)

In addition to the physical half-life, radioactive materials have various other half-lives, such as biological half-life, effective half-life, and ecological half-life:

- Biological half-life: This refers to the time it takes for radioactive materials taken into an organism through food, etc., to be discharged from the body (outside the tissues) through excretion and other metabolic processes, and to be reduced by half.
- Effective half-life: The half-life that takes into account both radioactive decay and biological half-life.
- Ecological half-life: The time it takes for radioactive materials within an ecosystem to be reduced by half due to changes in the environment such as material cycling and runoff via water.

In addition to the physical half-lives of different types of radionuclides, other half-lives vary greatly among radionuclides, organisms, and ecosystems. Understanding the various half-lives is important from the perspective of radiation protection, which will be discussed later, because it will help us understand how the amount of radioactive materials around us changes (Chap. 5). From now on, when we refer to "half-life", we mean the physical half-life.

2.2 External Exposure and Internal Exposure

There are two main routes of radiation exposure.

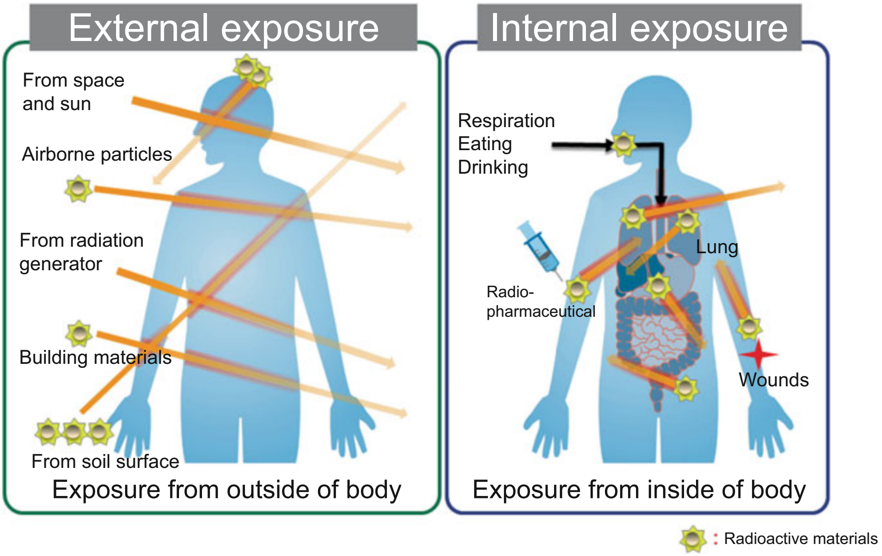


Fig. 2.3 Schematic diagram of external exposure and internal exposure (Source: Adapted from Ministry of the Environment, BOOKLET to Provide Basic Information Regarding Health Effects of Radiation, "Chap. 2 Radiation Exposure, 2.1 Exposure Routes, Internal and External Exposure" [1])

Since the discovery of radiation at the end of the nineteenth century, mankind has explored and utilized the usefulness of radiation, while at the same time, research has been conducted to clarify the dangers of radiation, as the adverse effects of radiation on the human body became a problem. As a result, the concept of "radiological protection" was established to protect people from radiation. Depending on the degree of exposure, either immediate damage to the body's tissues will affect the functioning of the body (deterministic effects), or there will be no immediate effects, but the probability of developing some form of cancer later on will increase (stochastic effects). The routes of exposure can be broadly divided into two categories: from outside and inside the body. Exposure to radiation emitted from radiation sources outside the body is called "external exposure", while exposure to radiation emitted from radiation sources inside the body is called "internal exposure" (Fig. 2.3).

In more detail, radioactive materials emitted into the environment cause exposure to the human body through a variety of routes, but apart from the exposure during the passage of the plume immediately after the accident, the exposure routes from the environment after radioactive materials have fallen that require attention are:

- External exposure from radioactive materials contained in the surrounding environment (soil, etc.).

- Internal exposure due to ingestion of food and drinking water contaminated with radioactive materials.

Internal exposure from inhaling dust containing radioactive materials has also attracted attention, but it is considered to have less impact than the above two exposure routes.

2.3 Becquerel (Bq) and Sievert (Sv): Units for Radioactivity and Radiation Exposure Dose

Each of these units expresses the amount of radioactive material and the strength of the radiation effect on the human body.

We often hear the words "becquerel" and "sievert" used to describe radioactivity. What is the difference between them?

We explained in Sect. 2.1 that a radioactive material is a substance that has the ability to emit radiation (radioactivity). The becquerel (Bq) is used as a unit to express the intensity (amount) of radioactivity. When the nucleus of a radionuclide decays at a rate of one nucleus per second, the activity of the decay is defined as one becquerel. The becquerel is a physical quantity and can be measured with a high purity germanium (HPGe) semiconductor detector or a thallium-doped sodium iodide (NaI(Tl)) scintillation detector, by counting the gamma rays emitted from a sample placed in a shielded container (Fig. 2.4). Since the rate at which a radionuclide decays in a unit of time is constant, the becquerel can be regarded as the amount of radioactive material. Since the Fukushima nuclear accident, we have been measuring the number of becquerels of samples, which is the amount of radioactive material, to understand the dynamics of radiocesium in forests and other ecosystems.

In contrast, the sievert (Sv) is used as a unit of intensity of damage (exposure) to the human body by radiation emitted from radioactive materials. The intensity of exposure varies depending on the type and amount of radioactive material, the distance from the radioactive material and the presence of shielding in between, as well as the age of the person exposed to the radiation and the part of the body. The sievert is a unit of measurement designed to evaluate the health effects of radiation from the perspective of radiation protection to protect humans from exposure. If the radiation dose evaluated in sievert is the same, the effect on human health is also considered to be the same, even if the type of radioactive material and the route of exposure are different.

When assessing the effects of radiation exposure on the human body, there are two ways to look at the exposure dose for each organ (equivalent dose) and the exposure dose for the entire human body (effective dose). Since the unit for both is the sievert, it is easy to confuse the two, but when considering exposure to

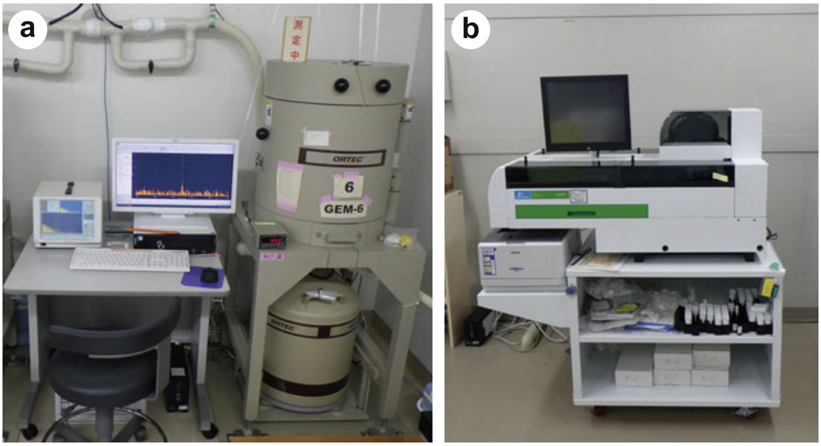


Fig. 2.4 Instruments to measure the amount of radionuclides such as radiocesium. (**a**) High purity Germanium (HPGe) semiconductor detector, (**b**) sodium iodide (NaI(Tl)) scintillation detector (Photo taken by the author)

radiocesium in the environment due to the Fukushima nuclear accident, the effective dose is often used because the human body is considered to be exposed uniformly to some extent regardless of the part or organ[1]. The effective dose is calculated from the equivalent dose of each organ as weighted using tissue weighting factor. However, since it is not possible to measure the effective dose directly, other measurements such as those described below are used instead, or known coefficients are used. More detailed explanations can be found on the websites of the Reconstruction Agency of Japan (Basic Information Regarding Health Effects on Radiation) [11] and the Ministry of the Environment of Japan (BOOKLET to Provide Basic Information Regarding Health Effects of Radiation) [1].

To practically evaluate the effective dose due to external exposure, the air dose rate measured with a survey meter (ambient dose equivalent) and the personal dose equivalent measured with a personal dosimeter are used (Fig. 2.5). Both of these values are higher on the safe side than the effective dose. It should be noted that the external exposure is also affected by the time spent in the place where radiation is emitted (Sects. 5.4 and 6.1). The basic unit of the air dose rate is the sievert per hour (Sv/h), but in the environment in which people in Japan lived before the nuclear accident, it never exceeded 1 microsievert per hour (1 μSv/h, micro = 10^{-6}), which

---

[1] Equivalent doses are used to examine the effects on specific tissues, but since radiation exposure due to radiocesium, whether external or internal, does not have a strong effect on specific tissues, the effective dose is generally used as the whole-body exposure dose. On the other hand, since radioactive iodine (iodine-131) tends to collect in the thyroid gland, it is important to determine the equivalent dose.

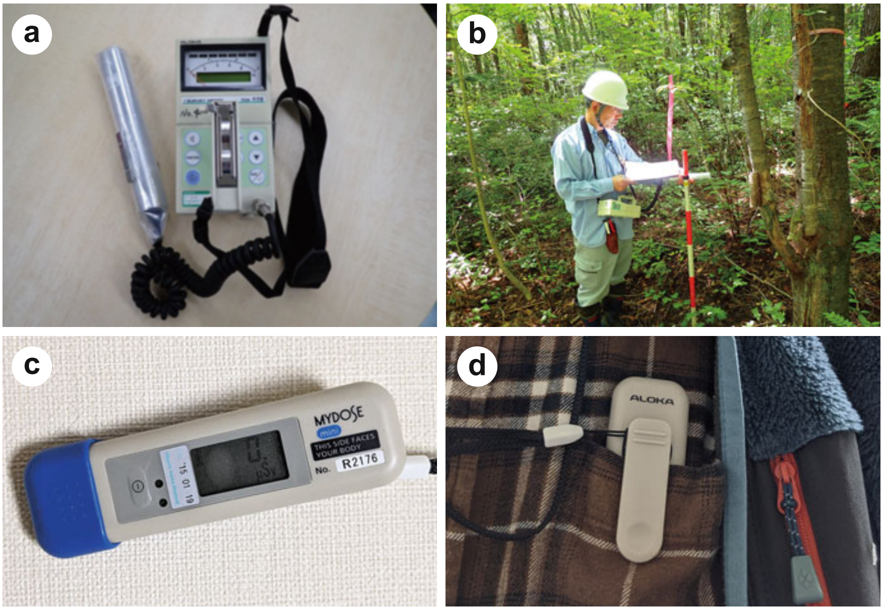


Fig. 2.5 Various dosimeters and examples of their use. (**a**) a survey meter (air dose rate meter), (**b**) measurement of air dose rates in forests, using a pole with scale to measure at a fixed height, (**c**) personal dosimeters, and (**d**) personal dosimeters worn with the clip side facing outward from the body (Courtesy of Wataru Sakashita, the Forestry and Forest Products Research Institute (**a**, **b**), and photos taken by the author (**c**, **d**))

is 1/1,000,000 of 1 sievert per hour (1 Sv/h). For this reason, the unit of microsievert (μSv/h) is used for the air dose rate in daily life, including in forests. As for internal exposure, the latest coefficients (effective dose coefficients, unit: Sv/Bq) for estimating exposure doses according to the type of radionuclides in food ingested and the amount of radiocesium (Bq) have been proposed by the International Commission on Radiological Protection (ICRP, Sect. 5.1) [12]. As a source of more detailed information, booklets and texts are prepared by ministries and public organizations of Japan. Please see the links at the end of this book.

In this chapter, we explained what radioactive materials are, what radiation is, and how to measure it and their units. In the next chapter we will look at the behavior of radiocesium in the forest.

2.4 Column: Looking Back on that Time (2)

Relationship between research and society

Masamichi Takahashi
Technical Advisor, Japan International Forestry Promotion and Cooperation Center
Fellow, Forestry and Forest Products Research Institute

Following the Great East Japan Earthquake of March 11, 2011, the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Plant suffered a hydrogen explosion, and residents in the surrounding areas were evacuated during the tense days that followed. The actual situation in mountain villages was gradually coming out, and there were anxious concerns about the effects of radioactive materials deposited in forests. At the time, I was working at the Forestry and Forest Products Research Institute (FFPRI), where I was in charge of liaising with the Forestry Agency of Japan and other external organizations, and coordinating research within the institute. I was answering inquiries from the Forestry Agency, referring to papers on the Chernobyl nuclear accident. However, the institute had no equipment for measuring radioactivity. The only instrument we had was a Geiger counter, which we lent out to the Fukushima National Forest District Office. Apparently the forests were seriously contaminated. The Forestry Agency provided us with a supplementary budget for equipment such as germanium semiconductor detectors and for the renovation of the laboratory building, so with the cooperation of the administrative staff of the FFPRI, we hurried to design and construct the facility and install the equipment.

There were no experts on radioactive materials at the FFPRI. For this reason, we often exchanged information with organizations specializing in radiation and nuclear energy, but they did not know about nature, such as forests, mountains, and ecosystems. When I looked around the institute again, I found that we had many experts on forest structure, biomass estimation, material cycle, wood structure, soil, hydrology, mushrooms, and so on. Standing tree surveys and felling and sampling surveys in forests are routine tasks for us. A multi-disciplinary survey team was organized within the FFPRI. We were given special permission to cut down trees and we were dispatched to conduct the field survey in August 2011. In cooperation with Fukushima Prefecture, we also conducted a forest decontamination test. Due to concerns about the health effects of radiation, the survey was initially conducted by senior staff, including managers.

Most of the breaking data of forests that had already been published were only based on surveys in which only small parts of the leaves and branches of trees were cut off. The FFPRI aimed for a comprehensive survey that

(continued)

compares the distribution of radioactive materials in the entire forest ecosystem based on the difference between evergreen coniferous trees and deciduous broadleaf trees, as well as the contamination inside wood and this would be conducted at three locations in Fukushima Prefecture. Because of the urgency of the situation, the researchers acted behind the scenes, and the report was published as a press release by the Forestry Agency within the year. Our understanding of forest contamination has improved dramatically. Contamination inside wood could not be understood with the conventional academic common sense and was criticized by some experts. On the other hand, the comprehensive study of forest and wood was highly evaluated by nuclear experts.

After the press release, we received more requests to participate in public committees and review meetings. Interviews and lectures gave us more opportunities to communicate directly with newspaper reporters, citizens, and company executives. Scientific facts predicted the severity and prolonged duration of the effects, which further pushed the people affected by the accident to the edge. The reputation of the safety of nuclear power plants collapsed, and distrust of the government and science increased. Residents and local government offices, who were initially cooperative with the research, became frustrated because of the lack of progress in countermeasures. As a research administrator, I tried to be as sincere as possible, but it was always heartbreaking to talk with the people who suffered. I tried to encourage the use of the research results, but it took a long time due to conflicting opinions and adjustments among the related stakeholders. I was keenly aware that problem solving, which is the mission of researchers, cannot be realized without the understanding by society and politicians.

After a stormy few years, I think we are now able to write our papers calmly. The contents of this book show the world-class achievements in the field of environmental radioactivity. On the other hand, there are still many unresolved issues in Fukushima. I hope that the continuous efforts of researchers will lead to solutions step by step and brighten the future of Fukushima steadily.

(continued)

Sampling cedar wood (Kawauchi Village in 2012)

Sampling cedar bark (Kawauchi Village in 2012)

Sampling soil (Iitate Village in 2014)

Survey of aquatic insects (Nikko City, Tochigi in 2012)

Scenes of forest survey (Courtesy of Masamichi Takahashi)

Chapter 3
Behavior of Radiocesium in the Forest

Abstract This chapter gives the whole picture of how the radiocesium that fell into the forest has been moving in the forest, based on the results of a decade-long survey. The radiocesium entered the forest from the atmosphere as "fallout" immediately after the accident. Most of the radiocesium was initially trapped on the leaves and branches, and then the radiocesium transferred to the forest floor through litterfall and rain within a few years. A small percentage of the total amount of radiocesium in the forest is absorbed from soil by trees, and eventually returns to the ground surface as litterfall; in other words, it is cycling in the forest. Forests have the ability to retain radiocesium. At present, most of the radiocesium transferred to mineral soil, the circulation of radiocesium in the forest is slow, and the behavior of radiocesium in the Fukushima forests is about to enter the phase of quasi-equilibrium and equilibrium. To understand the behavior of the radiocesium and predict the future status, modeling approaches are being carried out in conjunction with field observations.

Keywords Radiocesium · Radiocaesium · Behaviour · Forest · Transfer · Migration · Tree · Soil · Model prediction

3.1 Overview of Behavior

The radiocesium in the forest entered the forest from the atmosphere as "fallout" immediately after the accident. After that, radiocesium moves in the forest through the movement of water, fallen leaves, absorption by trees, etc. Such a large movement and cycling of radiocesium in the ecosystem can be said to be a characteristic of forest ecosystems that is not found in agricultural land (Fig. 3.1). The distribution of radiocesium in the forest changed significantly from the time when the fallout occurred immediately after the accident to the early phase (Fig. 3.2), but the amount of transfer gradually decreased in the transition phase of about 10 years after the accident. Soon, within a few decades, a period of stability (equilibrium) will be reached in which radiocesium appears to be almost unchanged on an annual basis (Fig. 3.2). This does not mean that the movement of radiocesium has completely stopped, but the amount of movement is small, and for example the amount absorbed

S. Hashimoto et al., *Forest Radioecology in Fukushima*,
https://doi.org/10.1007/978-981-16-9404-2_3

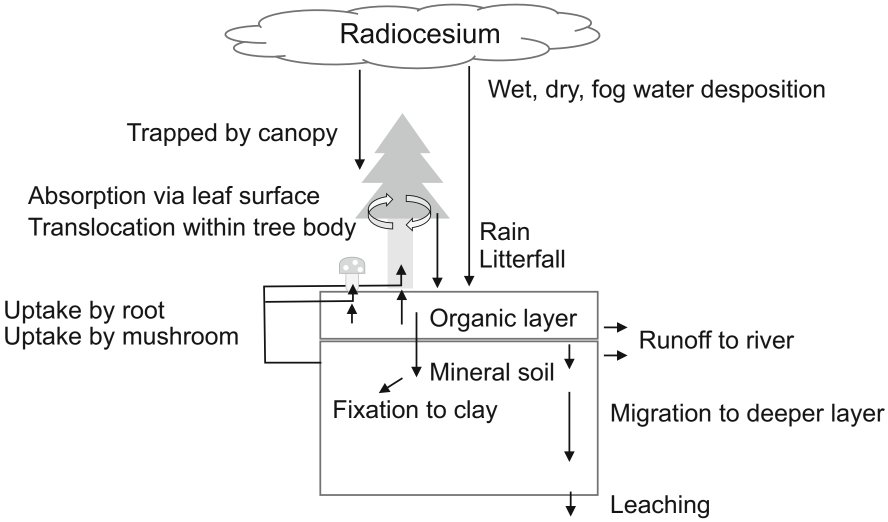


Fig. 3.1 Major movements of radiocesium in the forest (Arrows show the movement of radiocesium)

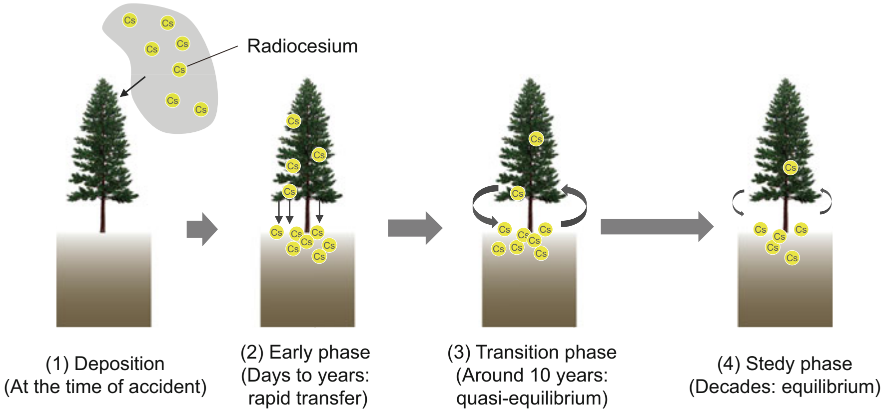


Fig. 3.2 Schematic diagram of the behavior of radiocesium in the forest and its change with time

by trees from the soil and the amount released from trees to the soil are balanced, which is called a steady state (equilibrium). Based on our monitoring results, we think that the behavior of radiocesium in forest is currently (around 2021, 10 years since the accident) in a transition phase. The transition phase is sometimes referred to as the quasi-equilibrium state because it is approaching equilibrium (Sect. 3.5). We would like to take a closer look at what exactly was happening during each of these phases.

3.2 Introduction: Two Types of Radiocesiums: Cesium-134 and Cesium-137

Before we look at the behavior of radiocesium in the forest, let’s talk about two different radioactive cesiums (radiocesiums): cesium-134 and cesium-137. As we saw in the previous chapter, the types of radiocesium released by the Fukushima nuclear accident have a short physical half-life of 2 years (cesium-134) and a long physical half-life of 30 years (cesium-137), and they are considered to have been released in an approximate 1:1 ratio during the accident. Cesium-134 has a short half-life; the radiation dose is accordingly greatly reduced in the early phase (see Chaps. 2 and 6 for details). In general, the term “radiocesium” is sometimes used to refer to these two radionuclides together, and sometimes to cesium-137 alone. Since cesium-134 has a short half-life, the behavior of radiocesium in the forest on an annual basis is focused on cesium-137. This is because cesium-137 remains in the forest in the long term and should be watched more closely, and the mechanism of movement of cesium-134 and cesium-137 in the forest is exactly the same. In this chapter we will refer to cesium-137 as “radiocesium” and look at its behavior in the forest to discuss its dynamics in the forest on an annual basis.

3.3 Large Changes in the Distribution of Radiocesium in the Early Post-Accident Phase

The radiocesium that falls on forests moves the most in the years following the accident.

3.3.1 Most of the Radiocesium that Fell on the Forest Was Initially Trapped onto the Leaves and Branches

The trees in a forest reach a height of 10–30 m and have leaves and branches that extend out from the trunk of the tree to form a layer (canopy) that catches the light and rain. The leaves spread out and cover the ground surface to efficiently capture the energy of sunlight. In particular, cedar and cypress trees, which are the dominant tree species in artificial forests in Japan, spread their branches and leaves in layers, which makes it easy for them to trap radiocesium falling from the sky. For example, Kato et al. [13] reported that even 5 months after the accident, over 60% of the radiocesium in coniferous cedar and cypress forests was still attached to the canopy of the trees. In addition, Gonze and Calmon [14] collected the results of studies on cedar and cypress forests and estimated that about 90% of the fallen radiocesium was attached to the trees in the period from a few days to a few weeks after the accident. Thus, it can be considered that 60–90% of the radiocesium that fell on cedar and cypress forests was first trapped by leaves and branches.

However, the rate of radiocesium trapped by trees is considered to vary depending on the tree species. Since the accident at the Fukushima Daiichi Nuclear Power Plant occurred in March, the leaves of deciduous broadleaf trees such as konara oak had not yet opened when radiocesium fell out. Therefore, the trap rate of deciduous broadleaf trees by the canopy is considered to be lower than that of the evergreen coniferous trees that had leaves. In addition, although pine is an evergreen conifer, the surface area of its leaves is smaller than that of cedar and cypress, so it is thought that its trap rate was lower. According to observations made by the Forestry and Forest Products Research Institute in the summer of 2011, the ratio of radiocesium retained in the canopy of cedar forests as a percentage of the total forest ranged from 22% to 44%, while the ratio was around 18% in mixed forests of red pine and konara oak [15].

Radioactive materials released into the environment as a result of a nuclear power plant accident become very small liquid or solid particles (aerosols) and are transported through the atmosphere according to the wind at that time. When it rains, a lot of radioactive materials fall out and are deposited on the ground. This is how the highly contaminated area stretching northwest from the Fukushima Daiichi Nuclear Power Plant was created. In the case of forests, in addition to weather conditions, different types of forests, such as different leafiness and density of the trees at the time of the accident, affected the behavior of radiocesium as described above.

3.3.2 Then Radiocesium Transferred to the Forest Floor Through Litterfall and Rain

Radiocesium trapped in the canopy is transported to the forest floor through litterfall, throughfall (rainfall from/through the canopy), and stem flow (flow of intercepted water down the trunk). In the early phase, the contribution of each pathway to the transport of radiocesium varied significantly with time. The radiocesium concentration in rainfall in the forest was high in the first months after the accident, but it became lower after the summer of 2011 [16–18]. On the other hand, the radiocesium concentration in litterfall and stem flow decreased gradually over a period of years, and their contribution increased after autumn 2011. However, it has become clear from observations that the contribution rate varies depending on the forest [17, 19].

The radiocesium concentration decreased with time due to the leaching effect, shedding of contaminated leaves and branches by litterfall, and development of new leaves and branches with low radiocesium concentration. Since the trend of decrease

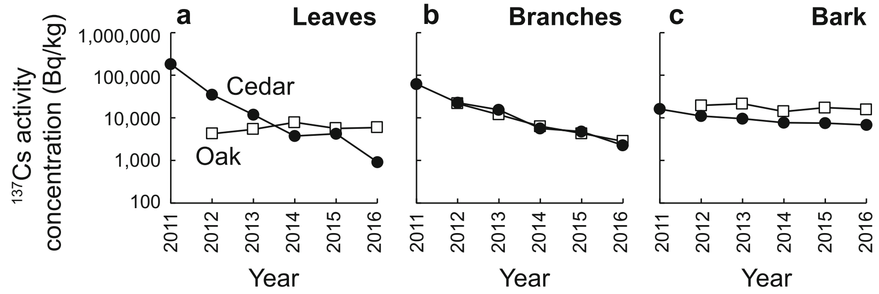


Fig. 3.3 Temporal changes in activity concentration of cesium-137 in (**a**) leaves, (**b**) branches, and (**c**) bark of Japanese cedar and konara oak (example from Kawauchi Village). Note that the vertical axis is the common logarithm. The cesium-137 concentrations in leaves and branches decreased exponentially, dropping to about one-hundredth in 5 years, while the cesium-137 concentrations in bark decreased only about one-third in Japanese cedar and hardly at all in konara oak (Source: Data from a survey by the Forestry Agency and the Forestry and Forest Products Research Institute, "Surveys on Radioactive Cesium Distribution in Forests" [21])

in concentration was generally exponential from the beginning to the transition phase, the concept of half-life (ecological half-life) can be applied (Fig. 3.3). The exponential change is expressed linearly when the vertical axis is logarithmic, as shown in Fig. 3.3. According to monitoring by the Forestry and Forest Products Research Institute, the radiocesium concentration in leaves and branches of cedar forests decreased in the 5 years up to 2015 with an ecological half-life as fast as 6 months to one and a half years [20]. The radiocesium concentration in bark decreased to less than half of its original concentration over the same period, but much more slowly than leaves and branches due to its longer lifespan and less radiocesium fall-off due to its shape and texture. As a result, immediately after the accident, the radiocesium concentration in the bark was lower than in the leaves and branches, but a few years later, the radiocesium concentration in the bark was higher than in the leaves and branches. In addition, the radiocesium concentration in the leaves of konara oak, which had not opened its leaves at the time of the accident, was lower than that of cedar and red pine in 2012, but there was no noticeable change in the concentration after that.

Some studies that have monitored the transfer of radiocesium from trees to soil at high frequency over time since the immediate aftermath of the accident suggest that migration may be better described by a superposition of two exponential functions (double exponential function) with a fast and a slow transfer component than by a single exponential function [16, 17]. This phenomenon is also observed in rivers and oceans, and is thought to be due to changes in the processes driving radiocesium transfer over time.

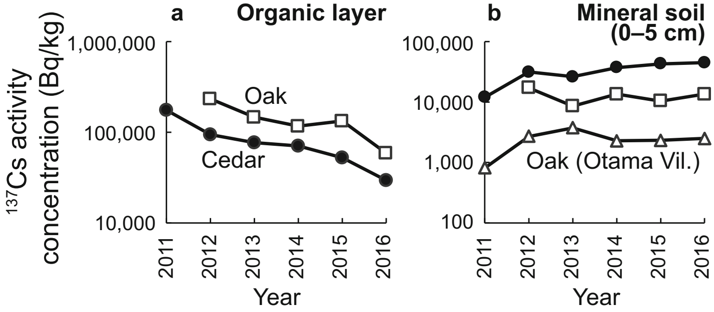


Fig. 3.4 Temporal changes in activity concentration of cesium-137 in (**a**) organic layer and (**b**) surface mineral soil (0–5 cm depth) (example from Kawauchi Village). Note that the range of the vertical axis is different in (**a**) and (**b**) to make temporal changes easier to understand. Data for konara oak in Otama Village is also included. (Source: Data from a survey by the Forestry Agency and the Forestry and Forest Products Research Institute, "Surveys on Radioactive Cesium Distribution in Forests" [21])

3.3.3 Not Remain Long in the Soil Surface Organic Layer

The radiocesium that transferred from trees to the ground surface during the initial period of rapid change did not remain in the organic layer (litter layer/O horizon) on the ground surface for long in many forests, but quickly transferred to the mineral soil underneath (Fig. 3.4a). The radiocesium concentration in the surface organic layer decreased despite the fact that radiocesium was supplied from trees by fallen leaves and rain. On the other hand, the radiocesium concentration in mineral soil showed an increasing trend after the accident (Fig. 3.4b).

One reason is that the organic layer of Japanese forests is thin, only a few centimeters thick. In European countries, such as Ukraine, Belarus and Fennoscandian countries, which were contaminated by the Chernobyl nuclear accident, the decomposition of organic matter is slower and the organic layer is thicker (e.g. more than 10 cm) due to cooler weather and less precipitation. As a result, radiocesium was retained in the thick organic layer in Europe. In general, in mineral soils, radiocesium is strongly adsorbed and fixed by clay minerals, making it difficult to move (see next section). However, in the organic layer, which does not contain clay minerals, radiocesium can move easily and be absorbed by plants. Future research will clarify how this difference in the retention of radiocesium in the organic layer affects the long-term movement of radiocesium in the forest.

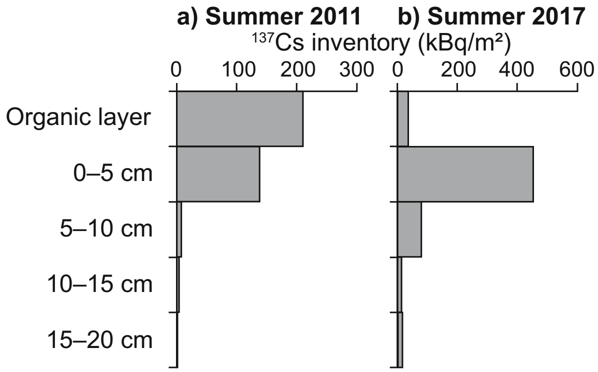


Fig. 3.5 Change in depth profile of cesium-137 in soil sampled in the summer of (**a**) 2011 and (**b**) 2017 (Japanese cedar forest, Kawauchi Village) (Source: Data from a survey by the Forestry Agency and the Forestry and Forest Products Research Institute, "Surveys on Radioactive Cesium Distribution in Forests" [21])

3.4 Radiocesium in Soil

Mineral soils have a mechanism to hold radiocesium in the surface layer.

3.4.1 Most of the Radiocesium Remains in the Surface Layer of Mineral Soil

Radiocesium transferred to mineral soil mainly stays in the shallow part of the soil. Figure 3.5 shows the results observed in 2011 and 2017 in the soil of a cedar forest in Kawauchi Village, Fukushima Prefecture. Some radiocesium had already reached a depth of 20 cm even in the summer of 2011. By 2017, the radiocesium in the organic layer had decreased significantly due to its transfer to the mineral soil, and most of it was distributed and remained at the shallowest depth of 0–5 cm.

3.4.2 Why Does Radiocesium Remain in the Surface Layer?

The retention of radiocesium in shallow layers of the mineral soil is due to the strong adsorption and fixation of cesium by clay minerals in the soil. There are several mechanisms for adsorption and fixation of cesium in the soil, and the ability to

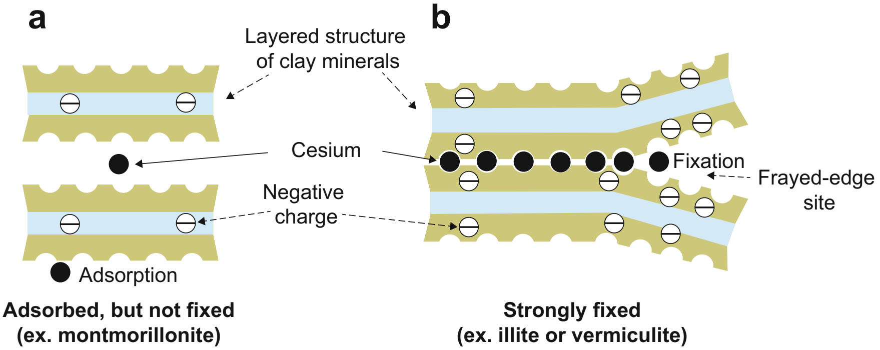


Fig. 3.6 Types of cesium (ionized) fixation by clay minerals. (**a**) Adsorbed, but not fixed (ex. montmorillonite), (**b**) strongly fixed (ex. illite or vermiculite) (Source: Adapted from Ministry of the Environment, BOOKLET to Provide Basic Information Regarding Health Effects of Radiation, "Chap. 4: Concept of Radiological Protection, 4.4 Long-term Effects, Behavior of Radioactive Cesium in the Environment: Adsorption and Fixation by Clay Minerals" [1])

adsorb/fix cesium varies depending on the type. The weakest immobilization occurs when cesium is adsorbed by the negative charge at the surface of soil organic matter and clay minerals. Since this negative charge has a high affinity for other cations, the adsorbed cations are easily exchanged and cesium is released [22, 23].

The ability of clay minerals to fix cesium differs depending on the type of mineral. Broadly speaking, there are two types of minerals: (1) those with high selectivity for cesium but reversible adsorption (both adsorbing and releasing cesium) (Fig. 3.6a), and (2) those with high selectivity for cesium and high fixation power (having frayed edge sites that are not easily releasable once adsorbed and fixed) (Fig. 3.6b). Some clay minerals, such as illite (a type of mica) and vermiculite (used as a soil conditioner), have a frayed edge site structure, and it is said that once ionic cesium enters the frayed edge site, it is difficult to be released again. An index called radiocesium interception potential[1] (RIP) is used to evaluate the immobilization capacity of radiocesium by frayed edge sites. There is also a study that shows that the absorption of radiocesium by plants (grasses) is suppressed in soils with high RIP [24]. This study also showed that the penetration of radiocesium into the soil depths was faster in soils with low RIP. It can be said that soil properties greatly affect the behavior of radiocesium in the forest.

There have been several studies in Fukushima on the fixation of radiocesium in the surface organic layer and mineral soil. In Fukushima, where not many years have passed since the accident, retention of radiocesium by organic matter is also important. In a study by Toriyama et al. [25] on the amount of radiocesium in the soil particles classified by the specific gravity, it was found that light particles, which are considered to be organic matter, have a radiocesium concentration that is about eight

---

[1] RIP: Refers to an index quantified by experiments of the ability of the frayed edge site origin to fix cesium in soil in preference to potassium.

times higher than that of heavier particles of mineral matter, and that organic matter particles retain 40% of the radiocesium contained in soil at a depth of 0–5 cm, despite the fact that they are only 10% by weight. In contrast to the previous results, which were mainly studied in agricultural lands with less organic matter than in forests, the study in forests with more organic matter suggests that the function of radiocesium fixation by organic matter as well as clay minerals cannot be ignored, at least in forest soils within a few years after the accident.

Some studies have examined the retention of radiocesium in the surface organic layer and mineral soil in detail. Manaka et al. [26] conducted extraction experiments from soil surface organic layer and mineral soil, and clarified the changes in the ratio of exchangeable radiocesium to the total amount of radiocesium in the organic layer and mineral soil for about 7 years after the accident. Their results showed that exchangeable radiocesium, which accounted for 10% and 6% of the total amount of radiocesium in the organic layer and mineral soil, respectively, in the first 5 months after the accident, decreased to about 2–4% after 2–4 years, and then remained stable and largely unchanged. This suggests that even after a sufficient amount of time has passed since the transfer of radiocesium into the soil, not all of the radiocesium adsorbed and fixed on organic matter and clay minerals will be strongly fixed, but some will be repeatedly adsorbed and released, and may exist in the soil in a form that is easily transferred and absorbed by plants. How fast the fixation of radiocesium proceeds in the soil and how easily it can move and reach an equilibrium state is an unresolved issue that needs to be watched very closely because it will affect the absorption by trees in the future.

Another important factor of the soil in the absorption of radiocesium by plants is potassium, one of the major essential elements for plants. Cesium and potassium are both alkali metal elements, and in the soil they are dissolved in water, ionized and exchanged, adsorbed by clay minerals and organic matter, and some of them are absorbed by plants as ions. Cesium is a larger element than potassium, but when ionized, its radius is close to that of potassium, and it behaves similarly in adsorption on clay minerals and absorption by plants. Potassium and cesium are absorbed into the plant through the roots via the same pathway, but the more potassium, an essential element, is present in the soil, the less cesium is absorbed by the plant. Using this property, potassium fertilization has become a condition for resuming farming in areas contaminated by radioactivity to reduce the absorption of radiocesium into crops. In forests as well, it was known that potassium in the soil was effective in reducing the absorption of radiocesium by trees, but there were not many research examples. After the Fukushima nuclear accident, the effect of potassium has been confirmed through potassium fertilization experiments in hinoki cypress forests [27] and tests using konara oak trees (*Quercus serrata*) in the laboratory [28]. In addition, although not through fertilization, studies on konara oak coppice forests (forests in which new branches have grown out from stumps to become mature trees again) have revealed that exchangeable potassium in forest soil strongly affects the absorption of radiocesium by trees (Sect. 6.5).

Cesium is one trace element not necessary for tree growth, but the stable isotope (non-radioactive) cesium-133 (^{133}Cs) is originally found in the earth's crust and soil in small amounts (a few μg in 1 g of soil [29]). Cesium is chemically similar to potassium, which is an essential element for plants, so it behaves similarly to potassium in soil and plant bodies, but not exactly the same. It should also be remembered that the radiocesium released from the accident fell on the forest in very small amounts, from 1/1000,000 to 1/1000 of the amount of the naturally occurring stable isotope cesium-133 (Chap. 4).

3.4.3 Migration of Radiocesium by Soil Animals and Fungi

As we have seen, radiocesium in the forest transfers from the aboveground to the ground surface by water movement (e.g. rainfall) and tree defoliation. Once it reaches the mineral soil, it moves very slowly within the soil layer, but over a long period of time, it gradually moves from top to bottom following water and gravity. On the other hand, the movement of radiocesium in the soil by soil animals and fungi cannot be ignored. For example, earthworms feed on the soil and excrete it as feces on the surface. Such disturbance by organisms is called bioturbation. It is not clear to what extent they contribute to the movement of radiocesium in the forest, as they have not been fully quantified in the Fukushima forests, but it is likely that some radiocesium is moved from top to bottom and vice versa by the activities of earthworms and other soil animals.

The function of fungi has also become clear. The high radiocesium concentration in mushrooms (the fruiting bodies of fungi) is widely known to be caused by the collection of radiocesium by mycelium. Many fungi have the ability to selectively absorb potassium. It is thought that cesium, which has chemically similar properties, is also absorbed along with potassium. Depending on the species, fungi that spread their mycelium widely in the organic layer and shallow part of the mineral soil are also considered to be involved in the transfer of radiocesium to some extent [30, 31]. Using this function, a method called “mycoextraction” has been devised in which wood chips are laid on top of contaminated soil to collect radiocesium from contaminated mineral soil using the power of natural fungi, and the wood chips are taken out of the forest ecosystem for disposal. The recovery rate is a few percent [30].

3.5 Transfer of Radiocesium into the Tree

Uptake into and movement within the tree vary depending on the species and environment.

Some of the radiocesium that fell directly onto the tree canopy or ground surface immediately after the accident, or that transferred from the tree canopy to the ground surface, is taken up by the tree. There are two pathways of uptake: radiocesium attached to the leaves and bark is directly absorbed into the tree, and radiocesium in the soil is absorbed through the roots. It has been reported that 25% of the total deposited amount of radiocesium was absorbed into the body of the tree from the surface of the tree other than the roots in an experiment in which radiocesium was sprayed directly onto saplings [32]. Imamura et al. showed that about half of the radiocesium in the tree could have been absorbed by the roots based on the data from the Fukushima study [33]. Immediately after the accident, radiocesium can be absorbed by both surface and root absorption pathways, but since most of the radiocesium will transfer to the soil within 2–3 years, absorption through roots is expected to account for most of the absorption thereafter.

The radiocesium that is taken into the tree moves through the tree with the flow of water and nutrients (translocation) [32, 34]. Trees, whether deciduous or evergreen, also shed their leaves. Before the leaves fall, some of the cesium is drawn back from the leaves into the tree just like any other elements, but the cesium contained in the fallen leaves transfers to the ground surface. Immediately after the accident, the distribution of radiocesium in the tree was uneven due to the multiple absorption pathways and the high concentration in the leaves and branches among the various parts of the tree, but the radiocesium concentration in each part of the tree changed over time due to the balance of absorption from the roots, nutrient and water transfer in the tree, and release by litterfall. And the transfer, absorption, and release between parts of the tree will then approach a balanced state during the transition phase.

3.5.1 Movement of Radiocesium in a Tree

The main part in a tree is the wood (xylem), which is used as lumber. The wood here refers to the trunk of the tree without the bark (Fig. 3.7). Since wood is used for various purposes such as construction, paper, mushroom cultivation (with bark), etc., special attention was paid to it after the accident and continuous monitoring was conducted. As a result, it was found that the trend of changes in the radiocesium concentration in wood varies greatly depending on the species. For example, the radiocesium concentration of Japanese cedar increased slightly or did not change much, while the concentration of konara oak increased significantly after the accident. In addition, when comparing the results of surveys conducted at several sites, there were large differences in the radiocesium concentration in wood of different sites, even for the same tree species. It has been reported that the potassium status in the soil affects the radiocesium concentration in trees (Sect. 6.5). In addition, studies conducted in Europe after the Chernobyl nuclear accident reported that the radiocesium concentration in trees growing in hydromorphic soil (soil that becomes reduced due to stagnation of water, such as in valley sides) and soil with thick deposits of humus tends to increase [35, 36]. Therefore, the differences in

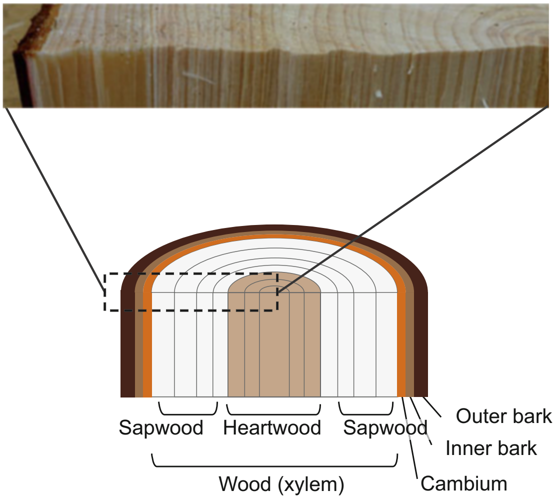


Fig. 3.7 The horizontal structure of wood (Photo: Courtesy of Shinta Ohashi, the Forestry and Forest Products Research Institute)

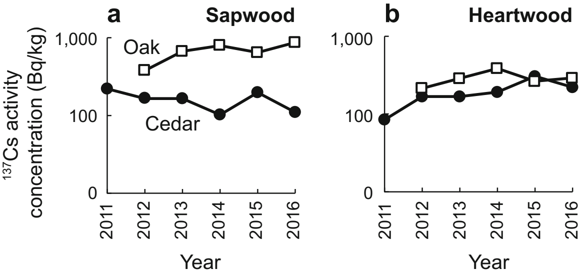


Fig. 3.8 Temporal changes in activity concentration of cesium-137 in the (**a**) sapwood and (**b**) heartwood of Japanese cedar and konara oak (example from Kawauchi Village) (Source: Data from a survey by the Forestry Agency and the Forestry and Forest Products Research Institute, "Surveys on Radioactive Cesium Distribution in Forests" [21])

radiocesium concentration among the same tree species in the studied forest can be considered to be greatly influenced by the nature of the growing soil, in addition to the differences in radiocesium deposition in the forests (detailed figures are given in the next section).

The wood is further divided into sapwood (outer part) and heartwood (inner part) (Fig. 3.7). Sapwood contains living cells that transport water and provide mechanical support for the entire tree. Heartwood, on the other hand, is made up of dead cells and has only a mechanical support function and is generally distinguishable from sapwood by its discoloration. The distribution of radiocesium in the sapwood and heartwood was also found to vary greatly depending on the species (Fig. 3.8). For 1–2 years after the accident, the radiocesium concentration in sapwood was higher than that in heartwood, regardless of the species. Thereafter, the radiocesium concentration in the heartwood of Japanese cedar gradually increased, and in one study site the radiocesium concentration in the heartwood was about twice as high as in the sapwood [37]. On the other hand, the concentration in heartwood remained low in konara oak. In cedar trees, potassium concentration in heartwood is known to be higher than in sapwood [38]. Similar to potassium, cedar trees seem to have a mechanism to move radiocesium to the inner part of the wood. The mechanisms and causes of this are currently being studied.

It is thought that the amount of radiocesium of each part of the tree will gradually become balanced between each part of the forest while cycling between trees and soils during the transition phase, approaching the steady phase where radiocesium concentrations appeared to be unchanged. According to the report of the International Atomic Energy Agency (IAEA, Sect. 5.3) after the Chernobyl nuclear accident, radiocesium in forests is considered to be in an early phase in which large changes in distribution occur for about 5 years after the accident, and after that it is considered to shift to a quasi-equilibrium state in which changes gradually become small [39, 40]. In Japan, 10 years have passed since the Fukushima nuclear accident, and the changes in the distribution in the forest have become smaller, so it can be said that we are approaching the equilibrium state after the early and transition phases.

3.5.2 Transfer Factor: Different Species Have Different Radiocesium Concentrations in Wood

The transfer factor (*TF*) is an indicator to estimate the degree of contamination of agricultural crops to protect people from internal exposure through food in areas contaminated by radioactivity. This is because the concentration of radioactive materials in contaminated crops varies depending on the type of crop and the type of soil in which it grows. In the case of crops, the *TF* is calculated as follows (Fig. 3.9a).

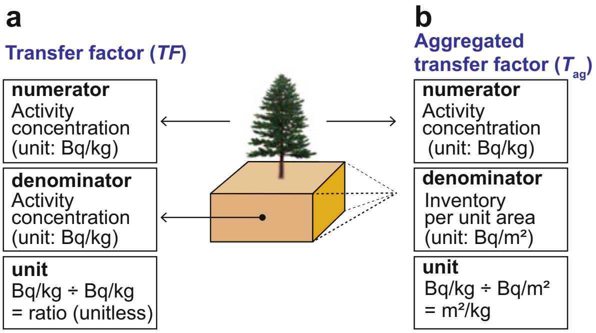


Fig. 3.9 Different definitions of (**a**) transfer factor (*TF*) and (**b**) aggregated transfer factor (T_{ag}). Both coefficients are ratios, but in the case of transfer factor, the units are canceled out because the units of the numerator and denominator are the same

$$TF = \frac{\text{the activity concentration of radionuclide in plants}}{\text{the activity concentration of radionuclide in soil}} \left(\frac{Bq/kg}{Bq/kg}\right)$$

The transfer factor concept has since been applied to the absorption and transfer of radioactive materials by various organisms in the environment. The aggregated transfer factor (T_{ag}), which is different from that for agricultural crops, is used to evaluate the degree of transfer for forest trees or other products, and is calculated as follows (Fig. 3.9b).

$$T_{\mathrm{ag}} = \frac{\text{activity concentration of radionuclides in tree compartments or forest products}}{\text{the total deposition to forest floor per unit area}} \left(\frac{Bq/kg}{Bq/m^2}\right)$$

While the radiocesium concentration in the soil is approximately uniform in the depth direction due to plowing and mixing in the agricultural land, the distribution of the radiocesium concentration in the soil differs greatly in the depth direction in forest soil, which is not plowed (Fig. 3.5). In addition, there is an organic layer on the forest surface. Therefore, if we collect soil samples in forests and calculate the transfer factor in the same way as for agricultural land, the factor varies greatly depending on the depth from which the soil is collected. Therefore, it is expressed as a T_{ag} with the integrated amount of radiocesium in soil per unit area (inventory) as the denominator and the radiocesium concentration in trees as the numerator. These TFs and T_{ag}s are not directly comparable because they have different definitions and units.

Another caveat is that the T_{ag} obtained in forests where the time since the accident has not been long enough, such as in the case of the Fukushima nuclear accident, do not necessarily reflect the absorption of radiocesium from the soil by trees. This is due not only to the absorption, but also to the large influence of radiocesium deposited directly on the tree surface. In the case of forest trees, T_{ag} can vary by a factor of 10 or more from the early to transition phase.

Observations in Europe affected by the Chernobyl nuclear accident are summarized in the International Atomic Energy Agency report [40] and in Calmon et al. [35]. According to this report, the T_{ag} for wood of coniferous trees is 1.5×10^{-3} m^2/kg (geometric mean, $n = 31$ surveys), for wood for deciduous trees 3.5×10^{-4} m^2/kg (geometric mean, $n = 12$ surveys), and the combined average is 1.0×10^{-3} m^2/kg (geometric mean). Although the number of studies is not necessarily large, it has been reported that the values differed by tree species and soil (e.g. very high in peat soils), and were higher in wet conditions.

There have been several reports after the Fukushima nuclear accident. Ohashi et al. compiled data from published papers and reports in a project of the International Atomic Energy Agency. The data for 2015, when multiple data were taken, showed an increase from about 10^{-4} to 10^{-3} m^2/kg for Japanese cedar and cypress, and from about 10^{-4} to 10^{-3} m^2/kg for konara oak (Fig. 3.10) [9]. When the T_{ag}s were compared for pine and oak trees with European studies after the Chernobyl nuclear accident, the values obtained from the Fukushima studies were lower for

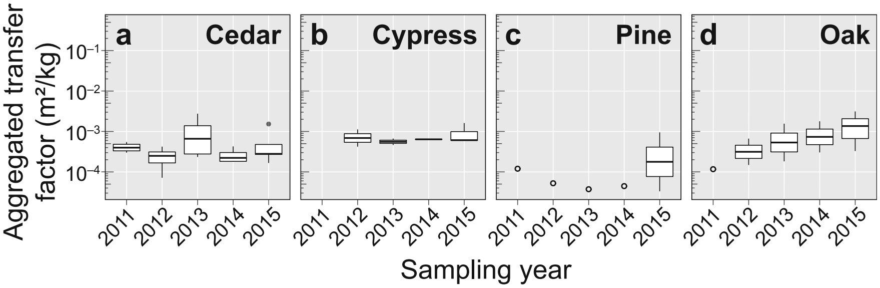


Fig. 3.10 Temporal changes in aggregated transfer factor (T_{ag}) of wood reported in Japan after the Fukushima nuclear accident. (**a**) Japanese cedar, (**b**) Japanese cypress, (**c**) Japanese red pine, (**d**) konara oak (Source: Adapted from IAEA, TECDOC-1927 [9])

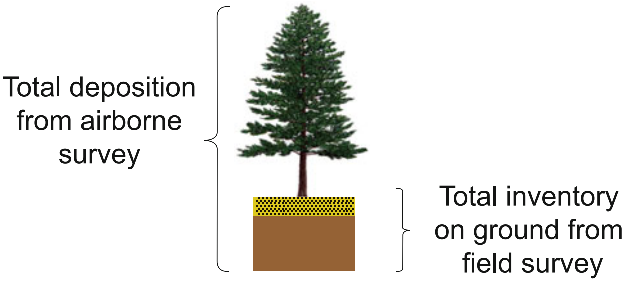


Fig. 3.11 Difference in denominators when determining the aggregated transfer factor and normalized concentration (Over time, most of the radiocesium in the forest ecosystem will transfer to the soil, then there will be little difference)

pine, but the number of data is not sufficient, so further verification is necessary. For conifers other than pine and oak, the values were similar [9].

In the study on the transfer of forest products from the Fukushima nuclear accident, a new index has been proposed to substitute for the T_{ag}. The T_{ag} takes the surface deposition as the denominator, whereas the denominator of the new index is the initial total deposition of the entire ecosystem (Fig. 3.11). The term "normalized concentration" is used in this document. After the accident at the Fukushima Daiichi Nuclear Power Plant, monitoring surveys of radiation dose and radioactivity levels from the sky using aircraft were quickly and repeatedly carried out. The observation results were published as maps and widely used by researchers. To calculate the T_{ag}, the accumulation of radiocesium in soil has to be measured. However, it is not easy to conduct ground surveys and collect soil samples in a wide area, especially in forested areas. Therefore, normalized concentration was devised as an index to evaluate the absorption characteristics of radiocesium by trees or forest products by using data from airborne monitoring and taking the initial total deposition of the entire forest as the denominator to eliminate the effects of different contamination levels between measurement points. The unit is the same as the T_{ag}.

After enough time has passed (e.g. after early phase) and most of the radiocesium in the forest ecosystem has transferred to the soil, the normalized concentration and the T_{ag} will become close to each other. Although there is a limitation that the resolution of the currently available airborne monitoring survey is quite large (250 m mesh), it is an effective method for utilizing and comparing radiocesium data in forest products in places where soil radioactivity is not known.

The T_{ag} makes it possible to compare and compile radiocesium concentration data of trees measured at various locations without the influence of the different contamination level of the location. In addition, it can also be used to calculate the approximate radiocesium concentration of trees at a location by multiplying the T_{ag} (e.g., 1×10^{-3} m^2/kg) by the accumulated amount at the location (e.g., 100 kBq/m^2).

3.6 Migration of Radiocesium out of the Forest

Forests have the ability to retain radiocesium.

3.6.1 Radiocesium Rarely Leaves the Forest

Stream water flowing through forests contains small amounts of fragmented fallen leaves and various substances dissolved in the water, which flow out of the forest system with the water, especially during large runoff events. According to research conducted after the Chernobyl nuclear accident, forests are said to retain radiocesium in the forest ecosystem and prevent it from flowing out of the system. However, since the topography of forests in Japan is much steeper than that of the areas surrounding Chernobyl, and since a large amount of rain often falls at once due to typhoons and storms, there was a concern that radiocesium could flow out of forests into rivers and farmland. Therefore, even after the Fukushima nuclear accident, a lot of monitoring has been conducted in mountain streams and downstream rivers. As a result, radiocesium was detected in streams and rivers, and the radiocesium concentrations were high immediately after the accident and decreased exponentially. It was also found that the rate of decrease was rapid in the early phase and slowed down after about a year had passed [41, 42]. The discharge characteristics of radiocesium are modeled by two exponential functions with different slopes.

Figure 3.12 shows the flow rate of stream water and the radiocesium concentration in the water observed in a stream in Koriyama City, Fukushima Prefecture, the year after the accident. On the second day of the observation, there was rainfall,

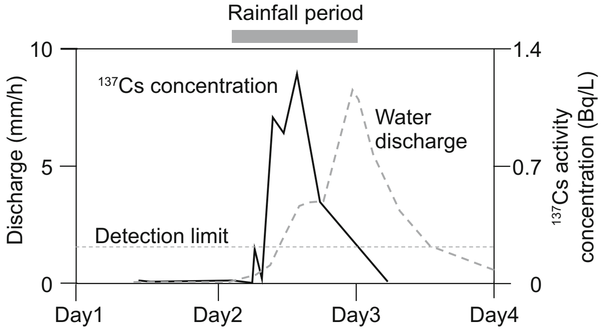


Fig. 3.12 Activity concentration of cesium-137 in stream water and water discharge observed in a stream in Fukushima Prefecture (Source: Adapted from Shinomiya et al. 2013 [45])

which increased the amount of water in the stream, and the amount of water decreased as the rainfall stopped. As the rainfall and stream water increased, the radiocesium concentration in the stream water increased. During normal times, before the increase in stream water, the radiocesium concentration in the stream water was below the detection limit, and after rainfall when the flow rate decreased, the concentration dropped below the detection limit again. This observation indicates that radiocesium is released from the stream when the stream water volume increases due to relatively heavy rainfall. This increase in the radiocesium concentration was not caused by radiocesium in the form of ions dissolved in the stream water, but by radiocesium attached to relatively large particles of soil and organic matter (suspended matter) in the turbid water. The fact that the peak in the radiocesium concentration appeared before the peak in the flow rate in this observation case can also be considered to be due to the fact that the particles with higher concentration flowed through first [43–46].

It is known that the discharge of radiocesium outside the forest system is also affected by forest disturbance. Nishikiori et al. conducted similar long-term observations and found that deforestation (clear-cutting) caused a slight increase in the discharge of radiocesium [46]. The discharge of radiocesium into stream water after major forest modification, such as deforestation or forest decontamination, can be considered to be affected by the distance between the stream and the forest area, as well as the point at which the water is collected.

When monitoring stream water in these contaminated areas, radiocesium is detected in the stream water when the water rises and causes turbidity, although the amount is much smaller than immediately after the accident. However, it is also important to look at runoff outside the forest as a percentage of the total forest accumulation. Comparing the amount of radiocesium discharged from the forest with the amount of radiocesium accumulated in the entire stream basin, it has been found that the annual discharge rate is less than 1% of the amount of radiocesium accumulated in the entire basin, even during the relatively early phases of the accident when radiocesium moves easily (e.g., Ministry of the Environment, BOOKLET to Provide Basic Information Regarding Health Effects of Radiation, "Chap. 4: Concept of Radiological Protection, 4.4 Long-term Effects, Behavior of Radioactive

Cesium in the Environment: Outflow from Forest Soil" [1]). It can be said that the amount of radiocesium flowing out of forests is very small compared to the total amount of radiocesium deposited in forests, even in Japan, where slopes are steep and rainfall is frequent and often intense. However, in recent years, large-scale floods caused by record-breaking torrential rains have been occurring frequently. It will be necessary to continue monitoring closely to see how much the runoff increases in such cases.

3.6.2 Little Radiocesium Re-Scattered by Forest Fires in Fukushima

As we have seen, forests have the property of retaining radiocesium while circulating a small part of it in the forest ecosystem. Forest fires have been attracting attention as a potential source of re-scattering (resuspension/redistribution) of radiocesium in the forest. When forest fires occur, soil surface organic layers and trees on the ground surface burn and generate airborne dust, and radiocesium, which has a low boiling point (671 °C), becomes a gas that can be released into the atmosphere and spread to other areas. In addition, burning of combustible materials in the forest will change the distribution of radioactive materials within the forest.

Studies conducted after the Chernobyl nuclear accident, both in artificially generated fire experiments and during actual forest fires, have confirmed the possibility that fires can re-scatter forest radiocesium into the air [47–50]. For example, two large fires in the Chernobyl exclusion zone in 2015 were estimated to have released 10.9 TBq of cesium-137 into the atmosphere [48]. In 2016, fires also broke out in the Red Forest, where the trees had died of high radiation during the 1986 accident [51].

In Fukushima after the accident, forest fires have occurred several times (Fig. 3.13). Kaneko et al. [52] investigated the burned areas of forest fires that occurred between April 29 and May 10, 2017 at Jumanyama mountain (in Namie and Futaba Towns and located approximately 10 km west of Fukushima Daiichi Nuclear Power Plant) in Fukushima Prefecture, and found that the radiocesium concentration (sum of cesium-134 and -137) in the organic layer on the ground surface was higher in the burned areas than in the unburned areas, although the number of surveyed points was limited. This can be considered to be due to the fact that the organic layer on the ground surface, which is made of dry organic matter, is easily burned, and the radiocesium concentration is higher due to the decrease in volume caused by combustion. In addition, there was concern that the loss of the organic layer, which has the function of preventing runoff and erosion of the surface soil, could result in the release of radioactive cesium from the forest. However, no significant movement or outflow of radiocesium within the forest has been observed [53]. It was also reported that no significant changes were observed in the air dose rate records at nearby monitoring posts [54].

Fig. 3.13 The site of a forest fire in Minamisoma City on April 3, 2016. Taken on April 11, 2016 (Courtesy of Shinji Kaneko, the Forestry and Forest Products Research Institute)

Forest fires can change the cycling, distribution, and fixation of radiocesium in forests, and increase the risk of re-scattering and redistribution, but the actual risk can be considered to vary depending on conditions such as the size (area) of the fire, fire intensity, distance from rivers, and distance from living areas. In addition, when forest fires occurred in Fukushima, some residents expressed concern about the spread of radiocesium. Therefore, it is important to steadily conduct monitoring at the sites of forest fires that have already occurred to clarify the actual situation and dispel the concerns of residents.

Globally, most forest fires are caused by natural causes, such as lightning strikes, mainly in arid regions, while forest fires in humid Japan are mostly caused by human activities. The risk of forest fires and their re-scatter may not be so high in the difficult-to-return areas in Fukushima because the general public is not allowed to enter these areas. On the other hand, if the amount of combustible materials such as fallen leaves and dead trees on the forest surface increases due to the loss of forest management, the risk of fire spread and intensity may increase. It has also been pointed out that climate change may cause the death of trees and inhibition of decomposition of organic matter on the ground surface, resulting in an increase in combustible materials on the ground surface [47]. It is important to prevent forest fires from occurring in the first place, but it is also essential to be prepared to extinguish fires in the early phases and prevent them from spreading if they do occur. In addition, in efforts to prevent the occurrence and spread of forest fires in contaminated areas, it is essential to carefully assess the risk of re-scattering in the event of a forest fire.

3.7 Predicting the Future Distribution of Radiocesium in Forests

Forecasting can be a powerful tool if used with an understanding of uncertainty.

3.7.1 Reproduction and Prediction by Computer Simulation

As we have seen, radiocesium is moving in the forest, and its distribution in the forest changes with time. Models are often used to capture the behavior of radiocesium in the forest. A model is a mathematical expression that describes and represents a natural phenomenon by dividing it into a number of elements and processes. Analysis using models is called modeling or simulation. After the Fukushima nuclear accident, research was also conducted to analyze and predict the contamination of forests through modeling [55−60]. Modeling of radiocesium in forests is a dynamic representation of the behavior of radiocesium in the forest by connecting the accumulated amount of radiocesium in each part of trees and soil with the amount of movement (flux) connecting these parts. For example, the radionuclide cycle model in forests (RIFE1 model) [57, 64], which was developed after the Chernobyl nuclear accident [61–63], was used in Fukushima studies. The model represents a forest by dividing it into leaves, branches, and bark that have undergone direct deposition, and wood that has not undergone direct deposition, the organic layer on the soil surface, and mineral soil, and the behavior of radiocesium in the forest is reproduced (Fig. 3.14).

What controls the behavior of a model is the structure of the model and the parameters that specify the amount of movement and accumulation. In general, a lot of observational data is used in building models to control the behavior of the model and to verify the model results. On the other hand, it is difficult to comprehensively study radiocesium in the forest through field observations but modeling can compensate for these difficulties and evaluate the movement of radiocesium, which allows us to understand the behavior of radiocesium in a more integrated way. Future predictions can also be made through simulations. Hashimoto et al. simulated the behavior of radiocesium in Japanese cedar and konara oak forests by adjusting

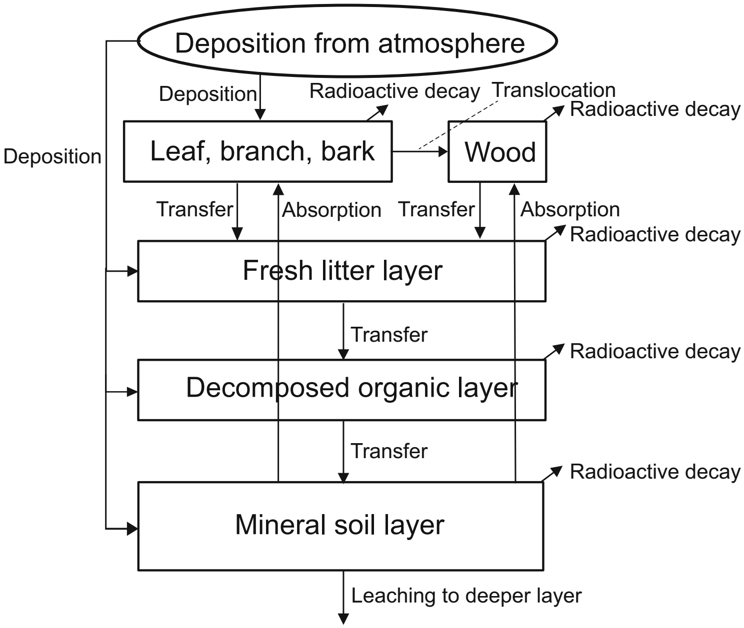


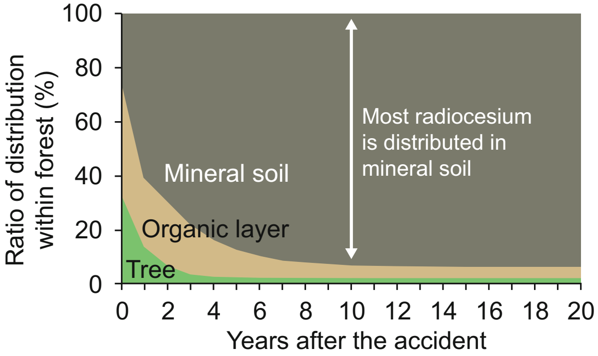
Fig. 3.14 Example of the structure of a radionuclide cycling model in forest (modified RIFE1 model) (Source: Adapted from Hashimoto, et al. [64])

the parameters of the RIFE1 model described above using data observed in Fukushima [57, 64]. As a result, it was predicted that most of the radiocesium in the forests would transfer to the soil after the second year after the accident, and that this state would continue in the future (Fig. 3.15). As a result of predicting the radiocesium concentration in the wood of Japanese cedar and konara oak for 20 years after the accident, it was predicted that there would be no change to a slight decrease in the radiocesium concentration in Japanese cedar, and that the increasing trend in the radiocesium concentration seen after the accident would cease in konara oak (Fig. 3.16).

To quantify the transfer of radiocesium in the forest, the amount of absorption by trees and transfer from trees to soil were analyzed from the output results of the model (Fig. 3.17). As a result, it was suggested that the transfer of radiocesium from trees to soil (emission) and the absorption of radiocesium from soil by trees would be balanced in 5–10 years after the accident, and that the cycling of radiocesium in the forest would move toward a steady state (equilibrium). On the other hand, it was also suggested that even after the steady state was reached, less than 1% of the total deposited amount of radiocesium in the forest immediately after the accident could continue to circulate in the forest.

In this way, modeling can clarify the important processes and the range of parameters involved in understanding the phenomena. By reflecting this information

Fig. 3.15 Predicted distribution of radiocesium in a Japanese cedar forest (Source: Adapted from Hashimoto et al. [64])



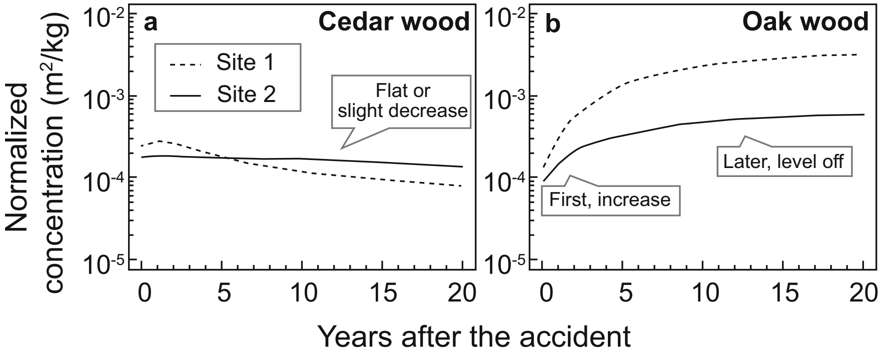


Fig. 3.16 Future prediction of cesium-137 concentration in wood of (**a**) Japanese cedar and (**b**) konara oak (Source: Adapted from Hashimoto et al. [64])

in monitoring, it will be possible to further enhance and develop observations. Several modeling studies have been conducted in the forests of Fukushima [55–59, 64]. It should be noted that there are differences in the prediction results depending on the structure of the model. Hashimoto et al. compared the prediction of radiocesium concentration in wood in Japanese cedar forests using the FoRothCs model developed by Nishina et al. [56, 58] with the RIFE1 model, and it was shown that the FoRothCs model resulted in a larger decrease than the RIFE1 model, although the two models were generally comparable. Such a comparison using multiple models was also made during the Chernobyl nuclear accident [65]. We also believe that it is important to constantly update future predictions by adding new data to verify that the predictions are correct. The close linkage between modeling and monitoring (observation data) is a useful way to deepen our understanding of the phenomena and improve the accuracy of future predictions.

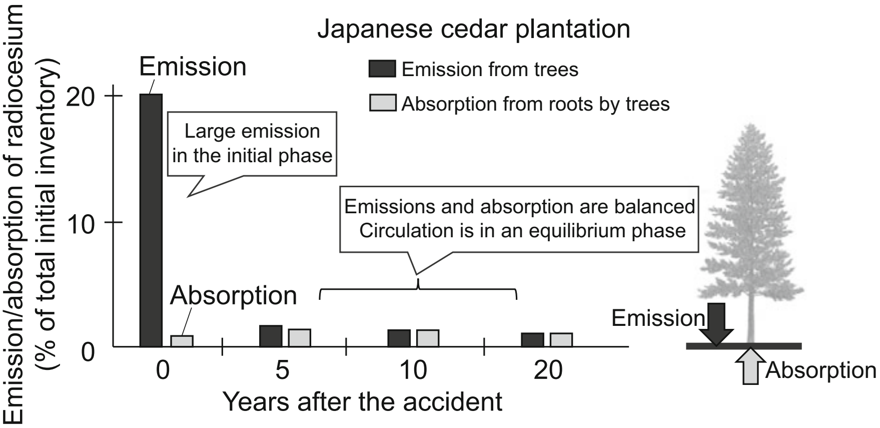
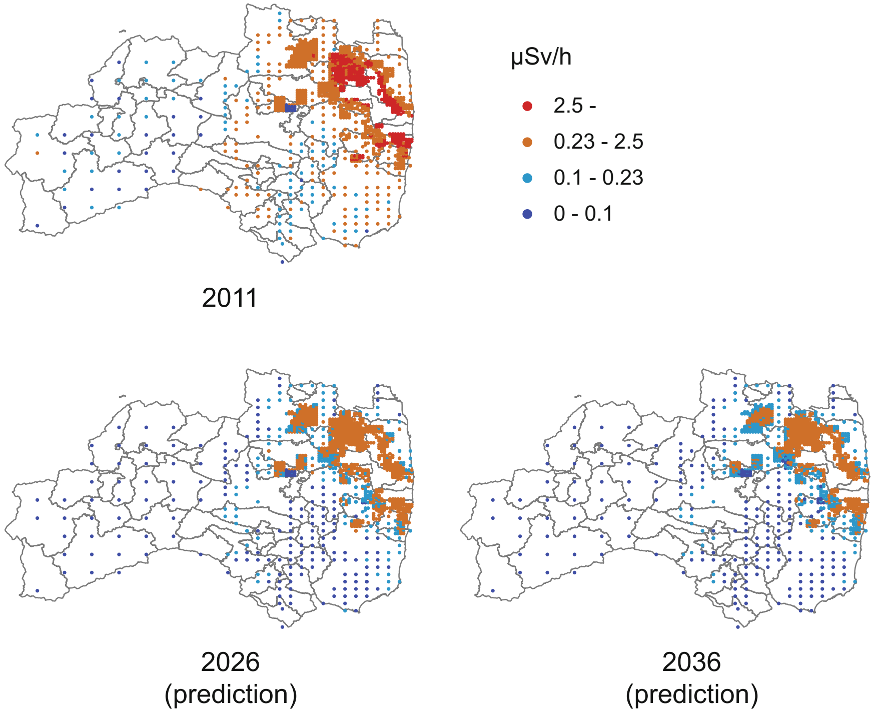


Fig. 3.17 Absorption and emission of radiocesium in the forest calculated by the model. Movement is shown as a percentage of the total amount in the forest immediately after the accident (Source: Adapted from the Forestry and Forest Products Research Institute, Collection of Research Results 2020 fiscal year, "Predicting the Movement of Radiocesium in Forests" [66])

3.7.2 Future Predictions of Air Dose Rates

As will be explained in detail in Chap. 6, air dose rates in forests are generally consistent with the predictions of decreases due to radioactive decay. Therefore, Fukushima Prefecture has been predicting how air dose rates in forests will change 15 and 25 years after the accident using data from multipoint surveys of air dose rates that have been conducted every year since the accident (Fig. 3.18) [67]. As a result, looking at the average air dose rate of 362 locations where surveys have been conducted continuously since 2011, the survey results for August 2011 show an average of 0.91 μSv/h, and those for March 2020 (9 years after the accident) show 0.20 μSv/h. Furthermore, the prediction based on the data for the first 9 years shows that the air dose rate will be 0.15 μSv/h in 2026 (15 years after the accident) and 0.12 μSv/h in 2036 (25 years after the accident). It should be noted that cesium-134 (half-life: 2 years), which was emitted along with cesium-137 during the accident, rapidly decays in the first few years after the accident, resulting in a significant decrease in air dose rates during that period, but after that the decrease will be slower due to the fact that only cesium-137 (half-life: 30 years) will remain (see Chap. 6). However, air dose rates have been steadily decreasing over time. Such a steady decrease in air dose rates can be seen in highly contaminated areas as well. Figure 3.19 shows the results of future predictions of air dose rates not only for forests but also for the region including the areas with high air dose rates extending northwest around the Fukushima Daiichi Nuclear Power Plant [68]. It can be seen that the contaminated areas are shrinking and the air dose rates are decreasing even in the areas with high air dose rates. On the other hand, it also shows that air dose rates



2011

2026 (prediction)

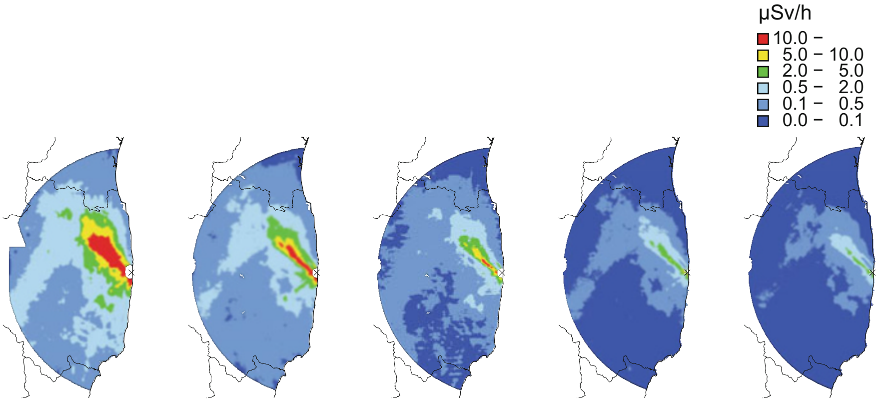
2036 (prediction)

Fig. 3.18 Future predictions of spatial distribution of air dose rate in the forest in Fukushima (Source: Data from Fukushima Prefecture's "Results of Radioactive Materials Surveys in Forests in 2019 fiscal year" [67], with a decrease due to radioactive decay applied based on the survey results for 2019 fiscal year)

in this northwestern extension of the region will still be high 30 years after the accident.

3.7.3 How Should We Deal with the Predictions?

Both the dynamics of radiocesium in forests and the prediction of air dose rates seen in this chapter are based on actual measurement data after the accident, and some kind of model is used to predict the future state. Such predictions are highly dependent on actual measurement data, and in the absence of sufficient measurement data, we may make predictions that deviate greatly from reality. Therefore, it is necessary to continue to conduct surveys at least over the next few decades to verify and monitor whether the predictions made by the models are correct, and to update the predictions as needed. There is also the problem that wide-area assessments do not sufficiently represent heterogeneity among locations, for example, they sometimes do not reflect minor differences in topography, forest types, and deposition.



2011 (observation) 2013 (observation) 2017 (observation) 2026 (prediction) 2041 (prediction)

Fig. 3.19 Future predictions of air dose rate distributions within 80 km of the Fukushima Daiichi Nuclear Power Plant (Source: Data from the observation of 1st, 7th 12th Airborne Monitoring Survey [3] and the prediction of Kinase, et al. [68]; Data of prediction: Courtesy of Sakae Kinase, Japan Atomic Energy Agency)

Furthermore, it is well known that the radiocesium concentration in various forest products varies widely even within the same study area. Nevertheless, understanding and predicting radiocesium concentrations and air dose rates over such a wide area is very important in terms of providing an overall picture and outlook of the problem of radioactive contamination over such a wide area as forests. The prospect of future contamination levels of the forest environment and forest products is of utmost concern to the residents of the affected areas and to those who are trying to restart and rebuild the forest industry. Information on the uncertainty of the forecast should be also provided, and it is important to take this into account when using the forecast information.

3.8 To Summarize the Behavior of Radiocesium in the Forest

In this chapter, we have looked at the distribution and transfer of radiocesium in the forest by part of the forest and by process. The overall picture can be summarized as follows.

As mentioned in the beginning of this chapter, in forests, the trees first trap radiocesium. Within a few months to a few years, the radiocesium transfers to the ground surface and then to the mineral soil. Depending on the forest, most of the radiocesium transfer to the soil and accumulate within a few years. A small

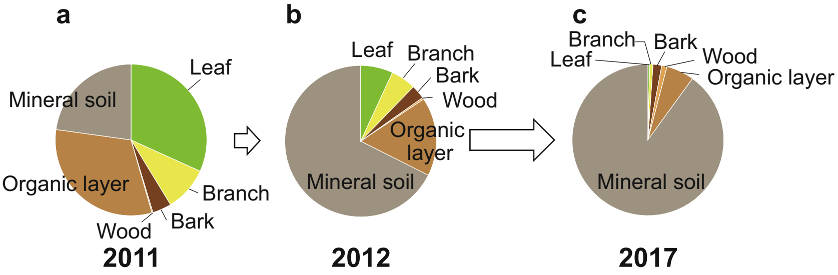


Fig. 3.20 Changes in radiocesium distribution in a cedar forest (example of a Japanese cedar forest). (**a**) 2011, (**b**) 2012, (**c**) 2017 (Source: Data from a survey by the Forestry Agency and the Forestry and Forest Products Research Institute, "Surveys on Radioactive Cesium Distribution in Forests" [21])

percentage of the total amount of radiocesium in the forest is absorbed by the trees, and eventually returns to the ground surface as litterfall. Most of the radiocesium remains in the surface layer of the soil. It is also clear that the amount of radiocesium leaving the forest through stream water is very limited compared to the total amount accumulated in the watershed. Figure 3.20 shows the distribution of radiocesium observed in a cedar forest in 2011, 2012, and 2017. It shows the distribution of radiocesium inventory per unit area in the forest, and shows that radiocesium, which was trapped in large amounts in leaves and branches in 2011, decreased significantly after 1 year, and by 2017 most of it had moved to mineral soil. The behavior of radiocesium in the forests of Fukushima is about to enter the phase of quasi-equilibrium and equilibrium from the early phase of contamination, when the radiocesium moved significantly within the forests.

Chapter 4
Forest Ecosystems and Radioactive Contamination

Abstract In this chapter, we will look at the impact of the Fukushima nuclear accident on forest ecosystems. Ecosystems can be viewed in two ways. One is to see it as a single system in which various substances and energy such as water, light, carbon, and nutrients circulate (material cycle), and the other is to see it as a coexistence of various animals and plants, including trees, soil, animals, and microorganisms, living together and interacting with the environment.

Surprisingly, radioactive contamination of forests, i.e. radiocesium entering the forest ecosystem, did not directly change the forest ecosystem in any significant way. In particular, the amount of radiocesium that entered the forest ecosystem was extremely small in relation to the amount of material (major elements) transferred in the material cycle of the ecosystem. However, from the perspective of plants and animals, there are many reports that organisms were affected in some way by radiation, albeit in a small way. Looking at it from a different perspective, changes in human activities in contaminated areas, especially in areas where human activities have suddenly ceased, such as the difficult-to-return areas, have created changes in the forest ecosystem in various ways. This is also an indirect impact on the ecosystem. From another perspective, radiocesium entering the forest can be used as a tracer to track the movement of materials in the forest. In this chapter, we will look at the impact and significance on the ecosystem.

Keywords Material cycle · Bioaccumulation · Food chain · Direct impact · Indirect impact · Wildlife · Abandonment · Radiation effects · Global fallout

4.1 Radiocesium and Material Cycles in Forests

The absolute amount of radiocesium is extremely small and does not affect the material cycle of the ecosystem.

S. Hashimoto et al., *Forest Radioecology in Fukushima*,
https://doi.org/10.1007/978-981-16-9404-2_4

In the forest ecosystem, various substances (carbon, nitrogen, water, nutrients, and various elements) are transferred/circulated through biological, chemical, and physical processes. For example, the so-called carbon cycle begins with the absorption of carbon dioxide from the atmosphere by trees. The trees use the carbon dioxide absorbed and the water and nutrients absorbed from their roots to carry out photosynthesis and grow. During the growth process, some parts of the trees die and fall to the ground. The organic matter is decomposed on the ground surface, and some of it is released as carbon dioxide into the atmosphere, while the rest stays there. In this cycle of carbon, nutrients also circulate. In addition to nitrogen, phosphorus, and other elements that are important for life support (essential elements), plants and animals also contain non-essential elements that circulate through the ecosystem in the same way as carbon. The movement of these substances is driven by the physiological functions of plants themselves, gravity, water movement, and the actions of organisms.

It can be said that radiocesium released into the atmosphere as a result of the Fukushima nuclear accident suddenly entered the forest (although some radiocesium was already there, as described in Sect. 4.4). Did the influx of this new anthropogenic element directly and significantly change the movement of materials in the forest? As it turns out, the amount of radiocesium itself is not enough to directly change the material cycle in the forest. Radiocesium is an alkaline element and behaves very similarly to potassium. Cesium-133, the stable isotope of cesium, is also found in nature, including forests. Cesium-133 has been circulating in the forest regardless of whether radiocesium enters or leaves the forest. Compared to cesium-133, the amount of radiocesium (cesium-134 and cesium-137) that entered the forest ecosystem as a result of the accident was very small, ranging from 1/1000 to 1/1,000,000 (Fig. 4.1). Therefore, the presence of newly entered radiocesium is not influential enough to change the movement of the elements in the first place.

On the other hand, the transfer of radiocesium newly introduced into the forest is driven by the movement of various materials in the forest, as mentioned earlier, and

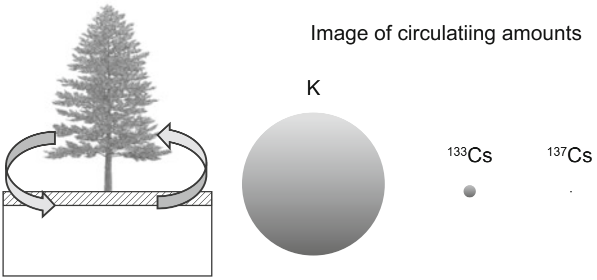


Fig. 4.1 A schematic image of circulating amounts of cesium-133 (^{133}Cs) and cesium-137 (^{137}Cs) in relation to the circulating amount of potassium (K). Cesium is an element that behaves in a similar way to potassium. The respective circulating amounts are shown instinctively in the form of circle sizes, but in reality the circulating amount of cesium-133 is about 1/100,000 of the amount of potassium, and that of cesium-137 is about one part in 10 billion of the circulating amount of potassium

is related to a very wide range of research fields such as forest hydrology, material cycle, plant nutrition, dendrology, and tree physiology. For example, radiocesium on leaves and branches transfers to the forest floor via rainfall (forest hydrology), and via litterfall (the fall of dead leaves and branches to the ground) (material cycle). In the soil, it also migrates from the soil surface to the deeper layers through water infiltration and decomposition of dead organic matter such as fallen leaves and branches (soil science and material cycle). In addition, the root system of trees absorbs radiocesium with nutrients that are mixed in the soil and it enters the tree (soil science, plant nutrition, tree physiology). The movement of radiocesium accompanying such dynamic material flows is a characteristic of forests, which are natural ecosystems with perennial and gigantic characteristics not seen in agricultural ecosystems.

The existence of a wide variety of organisms is also a characteristic of forest ecosystems. From small animals such as earthworms and insects to large wildlife, radiocesium is taken up by them. The uptake of radiocesium by organisms is influenced by their diet, living place, life cycle, etc. Disturbance of soil by earthworms and activities of large wildlife can be said to contribute to the migration of radiocesium to some extent.

The idea of using fungal uptake to recover radiocesium from the soil is another way of utilizing the ecological functions of forest ecosystems. Soil, leaf litter, and dead wood contain a wide variety of fungi in the form of mycelium, in addition to the occasional “mushrooms” (fruiting bodies) that are visible to the eye. The mycelium decomposes organic matter and takes in nutrients, or enters the roots of trees to live in symbiosis and exchange nutrients with each other. Radiocesium transfers along with this flow.

4.2 Radiocesium in the Food Chain

Bioaccumulation in the food web has not been confirmed, but high radiocesium concentrations have been detected in some organisms.

4.2.1 Radiocesium Concentration in Earthworms Is Lower than that in the Soil Surface Organic Layer

Earthworms, which are soil animals, play an important role in the material cycle of forest soil and the formation of soil structure by feeding on soil along with organic matter such as fallen leaves and excreting them as feces [69]. Since the Fukushima

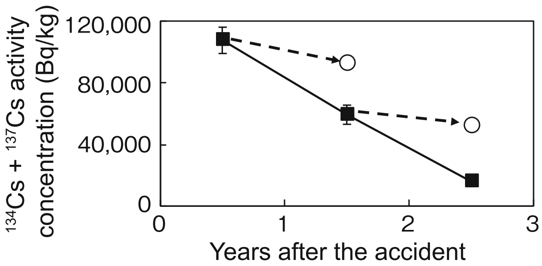


Fig. 4.2 Changes in radiocesium concentration (total of cesium-134 and -137) in earthworms collected from cedar forests in Kawauchi Village. Solid squares (■) indicate actual measured values, and open circles (○) indicate estimated values based on the assumption that the concentration was reduced from the actual measured values 1 year ago by radioactive decay alone. It can be seen that the radiocesium concentration in earthworms decreased faster than the decrease due to radioactive decay (Source: Redrawn from the Forestry and Forest Products Research Institute 2014 [72], the original paper is Hasegawa et al. [73])

nuclear accident, several studies have been conducted on the dynamics of radiocesium in earthworms. It has been found that most of the radiocesium deposited in forests stays in the shallow layers of mineral soil. Therefore, it was feared that earthworms, which feed directly on the soil, would concentrate the radiocesium. As a practical example, it is known that when eating fallen leaves containing toxic substances such as dioxin, the concentration of toxic substances in the earthworm's body increases more than the concentration in the fallen leaves [70, 71]. Furthermore, it was noticed that bioaccumulation of radiocesium may take place through the subsequent food chain in the forest. Therefore, Hasegawa et al. collected earthworms at fixed plots every year for 3 years from 2011 and examined the radiocesium concentration. As a result, the radiocesium concentration in earthworms showed a decreasing trend every year, which was faster than the decrease due to radioactive decay (Fig. 4.2).

In addition, when the radiocesium concentration in earthworms was compared with those in the soil surface organic layer and mineral soil layer in their habitats, it was found that the radiocesium concentration in earthworms was intermediate between that in the organic layer and mineral soil layer at all three survey sites (Fig. 4.3). Therefore, bioaccumulation of radiocesium by earthworms is not considered to have occurred.

To investigate why earthworms do not concentrate radiocesium, Fujiwara et al. studied the change in radiocesium concentration when earthworms were cultured in soil with a high radiocesium concentration and then transferred to soil with almost no radiocesium. As a result, the radiocesium concentration in the earthworms increased when they were cultured in soil with a high radiocesium concentration, but when they were transferred to soil containing no radiocesium, the radiocesium concentration in the worms decreased to an undetectable level in just 1 day [75]. Therefore, it was considered that the radiocesium in the soil eaten by the earthworms was immediately excreted as feces without being absorbed by the body. Later, when

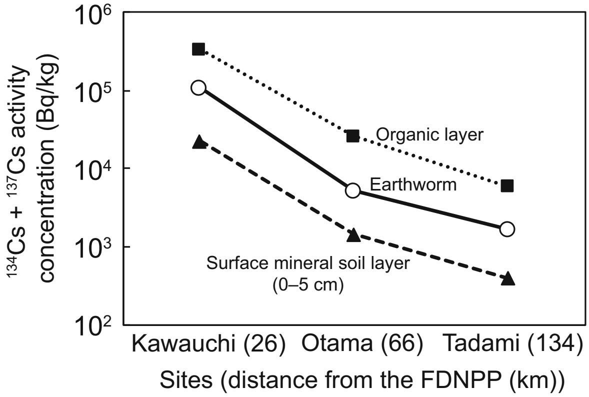


Fig. 4.3 Comparison of radiocesium concentrations (sum of cesium-134 and -137) in the organic layer, surface mineral soil layer (0–5 cm), and earthworms in cedar forests at three locations in Fukushima Prefecture collected 6 months after the Fukushima nuclear accident. The radiocesium concentration in earthworms varied depending on the contamination level of the study site, and was intermediate between the organic layer and the soil layer (0–5 cm) at all sites (Source: Data from the Forestry and Forest Products Research Institute 2014 [72]; the original paper is by Hasegawa, et al. [74])

the earthworms were dissected and examined, it became clear that most of the radiocesium in the earthworms was derived from their intestinal contents [76]. The radiocesium in soil is strongly adsorbed by clay minerals, and earthworms may not be able to absorb it.

4.2.2 Bioaccumulation Through the Food Chain Is Not Occurring

It was found that bioaccumulation of radiocesium does not occur in earthworms. However, biological communities in ecosystems have a series of predator-prey (eat and be eaten) relationships, creating a food chain. In addition, the actual predator-prey relationship is not linear, but rather a complex web of multiple organisms, which is why food chains are also called food webs. To verify the bioaccumulation of radiocesium through the food web of the ecosystem, it is necessary not only to examine radiocesium concentration in some organisms, but also to examine radiocesium concentration in several organisms located at the top and bottom of the food web. There was concern about contamination of small aquatic insects (lower in the food chain), large aquatic insects, and stream fish (higher in the food chain) in the stream. It is thought that radiocesium in river water does not dissolve in the water as ions (dissolved form[1]), but moves around in a suspended form attached to fine organic matter and soil particles. It has also been found that the radiocesium concentration in algae and fallen leaves collected in rivers is higher than that in sand on the river bottom [77]. Therefore, the radiocesium concentration was investigated for aquatic insects in the family Stenopsychidae that feed on algae and large aquatic insects that feed on smaller aquatic insects. As a result of this investigation was that the radiocesium concentration in aquatic insects was not higher than that in algae, and the possibility of radiocesium being concentrated in the food web higher up in the food chain of aquatic organisms was considered to be low. The results of no bioconcentration of radiocesium through the food chain have been reported for terrestrial insects as well as for aquatic insects [78].

In general, radiocesium taken into the body by animals through ingestion of food is excreted from the body in a period of several tens of days, which is much shorter than the physical half-life of radiocesium. Such a half-life that takes into account the elimination of radioactive materials by living organisms is called the biological half-life (Sect. 2.1). The reason for the short biological half-life of animals is that radiocesium does not have the property of binding to or being adsorbed by specific organs of animals. Therefore, broadly speaking, the radiocesium concentration in forest animals, insects, and other living creatures depends on the degree of contamination of the environment in which they get their food. Also, if the creatures can be moved to an uncontaminated environment, the contamination will decrease quickly.

4.2.3 Radiocesium Taken up by Large Wildlife

As we saw in Chap. 3, radiocesium is contained in forest plants and soil, and also in small animals such as soil animals and insects, as we saw in the previous section. As a result, radiocesium has also been detected in large animals at the top of the food chain. As we will see in detail in Chap. 6, different species have different levels and seasonality of radiocesium concentration in their muscles. These can be considered to be due to differences in the diet of different species (e.g., whether they sometimes eat surface soil with relatively high contamination concentration or not), their lifespan, and their ability to discharge radiocesium in the first place.

We consume the meat of wildlife, which raises the issue of regulation as food in addition to the perspective of cycling and diffusion of radiocesium in the ecosystem. The issue of radiocesium contamination of large wildlife and its regulation will be dealt with more in Sect. 6.3.

---

[1] In general, when an aqueous solution is passed through a filter with a certain fineness (e.g., pore size of 0.45 μm), the radiocesium that passes through is called the dissolved form, and the radiocesium that is trapped in the filter is called the suspended form.

4.2.4 *Fungi and Radiocesium*

Another factor that cannot be ignored when considering dynamics of radiocesium in forest ecosystems is fungi. As we saw in Chap. 3, the major movement of radiocesium, especially in the early phases after the accident, was driven in large part by rain and fallen leaves and branches, but once that movement slowed down, movement by other mechanisms also became noticeable. As we have seen in Sect. 3.4, the movement of radiocesium from the soil to the soil surface organic matter, for example, can also occur. The movement of radiocesium by mycelial functions is also expected to have some influence on the future behavior of radiocesium in the forest.

The most common form of fungi that we see is the fruiting body (mushrooms). Especially in mountain villages, there is a culture of collecting and eating wild mushrooms like in northern Europe and Eurasian region. For more details, please refer to Sect. 6.4, but the radiocesium concentration in mushrooms varies depending on the species, even if they were collected from the same place. Although it has been known for a long time that the ecology and function of mushrooms differ from one mushroom to another, the difference of radiocesium uptake among different mushroom species gives us another glimpse into the diversity of mushrooms [79].

4.3 Effects of the Fukushima Nuclear Accident on Forest Ecosystems

What direct and indirect effects did the radiation have on the creatures in the forest?

4.3.1 *Radiation Effects on Living Things*

To begin with, there are many naturally occurring radioactive materials on earth. Radiation also comes from space. Therefore, living things on earth are constantly exposed to natural radiation. However, regardless of its origin, it is known that exposure to high doses of radiation can damage cells beyond their natural repair function, resulting in a variety of effects, including morphological abnormalities and even death. The degree of sensitivity to radiation varies from organism to organism. The radiation effects on such organisms can be divided into acute exposure, where the organism is exposed to a relatively high level of radiation for a short time immediately after the accident, and chronic exposure, where the organism is exposed to a relatively low level of radiation for a long time afterwards [80]. In addition, radiation effects need to be considered at various scales: genes, cells, individuals, populations, and ecosystems.

Did the Fukushima nuclear accident in 2011 cause any changes in the plants and animals living in the forest as a result of the radiation? The papers reporting the effects range from insects and birds to mammals and trees [80, 81]. The studies have collected plants and animals in areas of Fukushima with various radiation doses and examined them. In the case of trees, there are reports that there was a correlation between the frequency of morphological abnormalities in fir and pine trees and the intensity of air dose rate [87, 88]. These morphological abnormalities of trees were also seen in the Chernobyl area. While there are many scientific papers showing that radiation had an effect in the contaminated areas, there are also those who say that some reported effect is not clear, and hence the debate is still going on [80, 82–85]. In fact, there is still continued debate on what the radiation effects were in the Chernobyl nuclear accident, which occurred in 1986, 25 years before the Fukushima nuclear accident [86]. Other factors (e.g., soil, topography, climate, genetic characteristics, etc.) also changed at the same time due to the different collection sites, making it difficult to determine whether the radiation dose actually affected the plants and animals. The effects of earthquakes, tsunamis, loss of human activity, and the lack of pre-accident data have also been pointed out as problems. One distinct effect on forest in the Chernobyl area is Red Forest. In the case of the Chernobyl nuclear accident, the reddish-brown, dead and dying vegetation, was caused by the exposure to very strong radiation (Fig. 4.4), but there was no such high radiation at Fukushima, and no forest die-off occurred. Although we need to continue monitoring, radiation levels will decrease over time, and it may be difficult to imagine any new major effects in the future [89].

4.3.2 Forest Ecosystems Without Human Activity

The forest ecosystem has been affected by the large decrease in human involvement in the forest, including in the difficult-to-return areas (areas where people have not lived for a long time, see Sect. 6.1). This is thought to be due to changes in vegetation caused by the lack of human intervention and also due to the absence of humans as a direct threat. Using satellite data, Ishihara et al. found that farmland had changed to grassland in the difficult-to-return areas [90]. With the disappearance of people from mountain villages, animals that used to live in forests began to appear in the villages that had become grassland and in forests near the villages (Fig. 4.5). It has also been observed that the decrease in human use of forests and the absence of humans has led to the flourishing of trees in cultivated areas and also to an increase in wildlife populations [91–93]. It has also been reported that the diversity of bird species was proportional to the radiation dose [94]. In particular, some species have been reported to increase the most in the difficult-to-return areas. These significant changes in the area can be attributed to indirect effects of radiation.

Fig. 4.4 View of Red Forest (whitish forest in lower right) and Chernobyl Reactor No. 4 (back of photo). In addition to dead trees, you can see the areas that were burned in a forest fire that occurred in 2016 (Source: Reprinted from Beresford et al. [86])

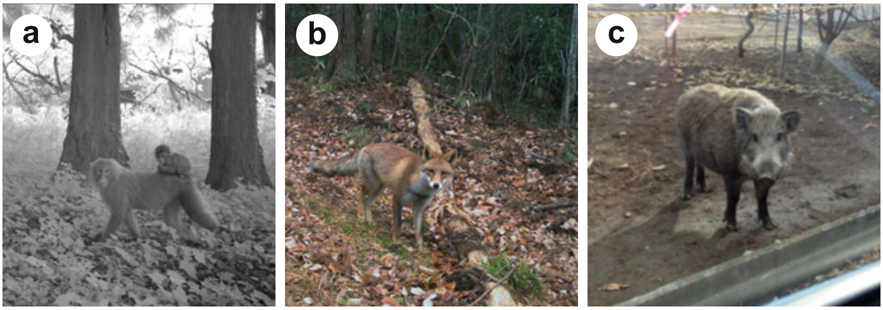


Fig. 4.5 Wildlife photographed in the evacuation zone. (**a**) Japanese macaque, (**b**) Japanese red fox, (**c**) wild boar (Courtesy of James C. Beasley, University of Georgia, using an automated camera (**a**, **b**), and Hirofumi Tsukada, Fukushima University (**c**))

The Chernobyl nuclear accident occurred in the spring of 1986, exactly 25 years before the Fukushima nuclear accident. Recent studies have confirmed that the area around Chernobyl is now home to a large amount of wildlife due to the designation as a protected area and the artificial introduction of several species [95].

In addition, many of the forests in Japan have been maintained by human intervention (forest management) in some way. Now that humans are no longer

Fig. 4.6 Broadleaf forest with mass dieback due to Japanese oak wilt (Courtesy of Shoichi Saito, Yamagata University)

taking care of the forests, maintaining forest health has become a problem. For example, forests that are poorly managed are more prone to disease and insect damage. Even if pests and diseases do occur, forests managed by humans can quickly eliminate the damaged trees and prevent further spread of the damage. In recent years, Japanese oak wilt caused by an insect called the oak ambrosia beetle (*Platypus quercivorus*) and its associated fungus (*Raffaelea quercivora*) has become widespread throughout Japan (Fig. 4.6). Japanese oak wilt is known to cause mass mortality of konara oak and mizunara oak (*Quercus mongolica* var. *crispula*) that have grown to large diameters without use [96]. If konara oak, which has been the major species for mushroom log forests, is left unattended due to being isolated because of radioactive contamination, there is a risk of serious damage from Japanese oak wilt. In addition, the pine wilt disease, which causes mass die-off of pine trees (pine dieback), is still causing damage in Japan. Since wilt trees become a new source of infection for both oak and pine wilt, it is necessary to manage dead trees to reduce the spread of damage (Fig. 4.7).

Fig. 4.7 Forest landscape affected by pine wilt disease and treatment work for dead pine trees. (**a**) Forests attacked by pine wilt disease, (**b**) fumigation of killed pine trees (Courtesy of Katsunori Nakamura, the Forestry and Forest Products Research Institute, taken outside Fukushima Prefecture)

4.4 Global Fallout: Cesium-137 Has Been in Forest Ecosystems for Half a Century

Radiocesium has been deposited in Japan since more than 50 years prior to the Fukushima nuclear accident due to atmospheric nuclear testing. The deposited radiocesium has also been used as a tool to investigate soil erosion.

4.4.1 What Is Global Fallout?

The accident at the Fukushima nuclear power plant released a large amount of radioactive materials into the atmosphere and contaminated the environment on a large scale, including forests. This led to an increased interest in the Chernobyl nuclear accident that occurred in 1986. Surprisingly, a large amount of anthropogenic cesium-137 was released into the environment 20–30 years earlier than the Chernobyl nuclear accident, in the late 1950s and early 1960s. By the 1980s, more than 500 atmospheric nuclear weapons testing had been conducted, and cesium-137, which reached the stratosphere in explosions, was spread by the jet stream and fell widely and thinly all over the world, mainly in the northern hemisphere [97]. The total amount of cesium-137 emitted from the Chernobyl nuclear accident was several times greater than that from the Fukushima nuclear power plant accident, and the

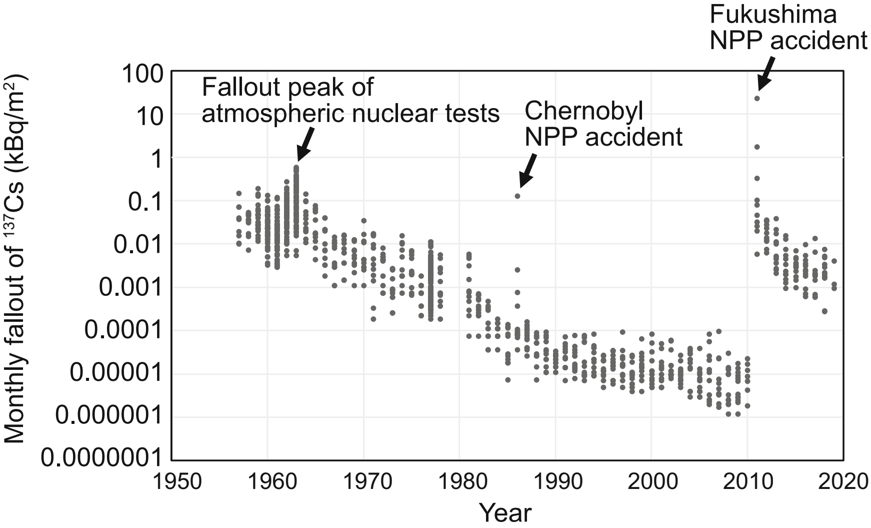


Fig. 4.8 Monthly fallout of cesium-137 observed in various locations of Japan, which was observed by the Japan Meteorological Agency, etc. (Source: Data from Nuclear Regulation Authority, "Environmental Radioactivity Database" [98])

total amount released from the atmospheric nuclear weapons testing was ten times greater than that released from the Chernobyl nuclear accident. The fallout to the earth's surface of radioactive materials such as cesium-137 from the atmospheric nuclear tests is called global fallout.

In Japan, the amount of cesium-137 fallout has been observed by the Japan Meteorological Agency and other organizations since the 1950s. Figure 4.8 shows the monthly fallout of cesium-137 from the 1950s to the present. The amount of fallout peaked in 1963 and rapidly decreased after the partial nuclear test ban treaty was signed in the same year; it was momentarily high after the Chernobyl nuclear accident in 1986, but returned to a low level in a few months because Japan was far away from Chernobyl. After that, the Fukushima nuclear accident in 2011 caused a sharp increase to levels much higher than the 1963 peak, and then a gradual decrease again.

Ito et al. analyzed cesium-137 in forest soil samples collected throughout Japan just prior to the occurrence of the Fukushima nuclear accident, and found that the average amount of cesium-137 accumulated up to a depth of 30 cm in the soil was 2.27 ± 1.73 kBq/m^2, with a higher amount accumulated on the Sea of Japan side from Hokuriku to Tohoku districts (northwestern coastal areas of the main island of Japan) (Fig. 4.9) [99]. As a result of analyzing whether the accumulated amount of cesium-137 based on the above soil analysis differs from those from the long-term monitoring of fallout by the Japan Meteorological Agency, no significant difference was observed between the two, and it became clear that it is highly likely that most of

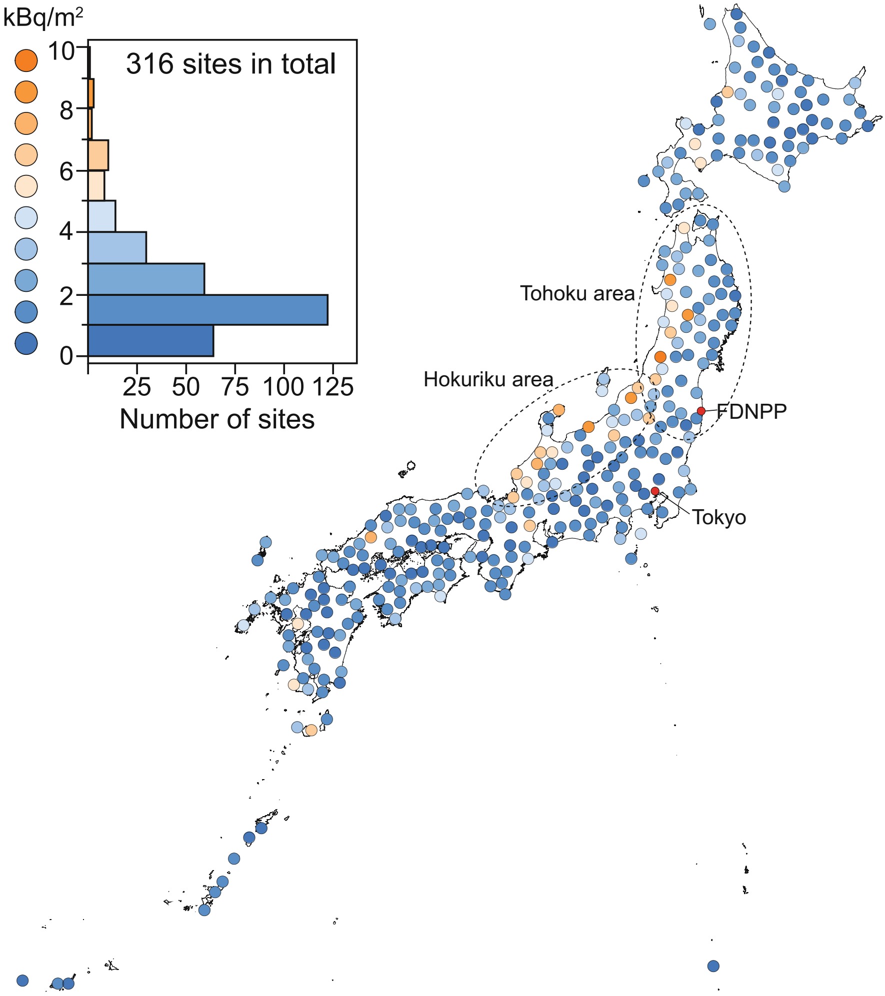


Fig. 4.9 Accumulation of cesium-137 in forest soil in Japan before the Fukushima nuclear accident. Decay corrected as of October 1, 2008. Frequency distribution of accumulation is shown in the upper left (Source: Data from Ito et al. [99]; Courtesy of Eriko Ito, the Forestry and Forest Products Research Institute)

the cesium-137 originating from atmospheric nuclear tests that fell half a century ago still remains in the forest area [99]. The result that cesium-137 remains in the forest even after several decades have actually passed since the fallout is also in line with the results of the study in Sect. 3.6, which showed that the runoff from the forest via stream water is small.

Among the areas contaminated by the Fukushima nuclear accident, in the relatively highly contaminated areas from the eastern to the central part of Fukushima

Prefecture, the amount of radiocesium originating from the Fukushima nuclear accident is several orders of magnitude higher than that from the global fallout, but in other areas with low contamination levels, the percentage of detected radiocesium originating from the global fallout is also higher, so care should be taken in interpreting the detected radiocesium. Cesium-134 is not included in the global fallout, since it is rarely produced in nuclear tests and has a short half-life of 2 years. On the other hand, since cesium-134 and cesium-137 were released at a ratio of approximately 1:1 in terms of radioactivity in the Fukushima nuclear accident, it was possible to estimate the ratio of radiocesium originating from the Fukushima nuclear accident by analyzing the ratio of cesium-134 and cesium-137 within a few years of the accident.

4.4.2 Using Radiocesium to Track the Movement of Materials in Forests

Cesium-137 is a radioactive element artificially created by nuclear power plants and nuclear testing, and is also added to forest ecosystems at certain times in the Earth's history, such as in global fallout, and remains in forests. In addition to being watched and monitored as contaminants for human radiation exposure protection, such radioactive materials have been used in research as tracers to track the movement of materials in forests. A tracer test is a research method used to add a certain amount of easily detectable substance to a system and observe the behavior of the substance within the system, or to investigate the movement of the substance throughout the system. In particular, cesium-137, which is adsorbed by soil and accumulates in the soil surface layer for a long time, has been frequently used as a tracer of soil erosion since the 1970s. Long-term monitoring of the increase or decrease of cesium-137 from its initial deposition provides information on the amount of erosion of soil on the surface and its outflow or storage in the slope [100]. The ratio of cesium-134 to cesium-137 can also be used to determine the depth from which trees and fungi have absorbed radiocesium from the soil surface organic layer and soil. As mentioned above, discriminating the amount of cesium-137 that was previously present in the forest ecosystem as global fallout and the amount of cesium-137 that was newly introduced due to the Fukushima nuclear accident by referring to the percentage of cesium-134 present is also a kind of tracer use. The applicability as a tracer can be enhanced by using multiple elements and isotopes. In this way, cesium-137 originating from the Fukushima nuclear accident also left clear traces in the forest ecosystem, and it can be used in future research as a tool to track the movement of materials in the forest [31, 101, 102].

4.5 Column: Looking Back on that Time (3)

Memoirs of the Fukushima Accident

George Shaw
Emeritus Professor, University of Nottingham

It is impossible to forget the Great East Japan Earthquake and the tsunami which followed. Sitting in our offices and homes in the UK, over 9000 km to the west, we witnessed the terrible sight of the tidal wave washing over Sendai and its surroundings almost in real time via the internet and news media. In the first hours of the disaster on 11th March 2011 we were unaware that, over the next few days, we would witness a succession of explosions at the Fukushima Daiichi nuclear power station, as a direct result of the tsunami. The first of these (reactor 1) occurred on Saturday 12th March and the second (reactor 3) on Monday 14th March. At that point, having watched the accident unfold over the weekend, I emailed some of my colleagues in Chiba and Rokkasho and I was relieved to receive replies that they were safe. News reports in the UK carried shocking movie images of the exploding reactors. I remember thinking clearly that this was very different from the Chernobyl accident because here were the explosions for everyone around the world to see, as they happened.

Back in 1986, the year of the Chernobyl accident, the world was politically and technologically different to what we knew in 2011. I was in the final year of my PhD studies in which I was using radioisotopes to measure metals and nutrients in plants and fungi under laboratory conditions. Everything changed on 28th April 1986 when the world was alerted to a possibly major nuclear accident somewhere in the Soviet Union. I use the words ‘possibly’ and ‘somewhere’ because nobody in the west knew for certain what had happened. The Chernobyl power station had actually exploded on 26th April 1986, 2 days before the alert was sounded in Sweden which received a cloud of radiocaesium fallout from northern Ukraine. This cloud would reach across the whole European continent over the following days, but we still had no details of the nature and extent of the accident which made emergency response very difficult at the time.

The causes of the Chernobyl and Fukushima accidents are hardly comparable. Both events were a consequence of human activities because nuclear reactors are designed and built by people. However, the Chernobyl accident was most definitely the result of human miscalculation whereas the tsunami which triggered the Fukushima accident can be seen almost as an ‘act of God’. The *consequences* of both accidents are partially comparable. Chernobyl released approximately 10 times more radioactivity than Fukushima, but the suite of radionuclides released and their impacts on the environment have been similar. However, because the Fukushima accident occurred in full visibility

(continued)

and because the Japanese authorities took immediate measures to shield the affected population, the health consequences of the Fukushima accident have been (and are likely to be) much less severe than those of Chernobyl. The environmental impacts of both accidents continue to make themselves known, primarily as a result of contamination of soils and sediments with caesium-137. This radionuclide has a radioactive half-life of 30 years. The soils contaminated by Chernobyl fallout in countries such as the UK currently contain slightly less than half the caesium-137 originally deposited 34 years ago in 1986. Time will eventually reduce this radioactive burden to almost nothing, but not until several decades have passed. During this time major ecosystems such as forests will continuously recycle the caesium, passing small but significant quantities on to other ‘downstream’ environmental systems including rivers, marshes, lakes and, eventually, the ocean. Remediation, or cleaning up, even small areas of contaminated forests is a huge task which may not be feasible, either due to financial cost or undesirable ecological side effects of actions such as removing forest floor litter or cutting down trees on a significant scale. Thus, it will probably be necessary to learn to live with the ongoing contamination, which means understanding which aspects of our interaction with forests are likely to lead to more or less exposure to radiation from caesium-137.

Since 2011 I have met and befriended numerous colleagues in Japan who were at a similar stage in their scientific lives at the time of the Fukushima accident that I was back in 1986. Their learning curve over the past 9 years has been very steep, as it was for me and many of my European colleagues in the 1980s and 1990s. Some of us with experience of the post-Chernobyl impacts on forest ecosystems in Europe and the former Soviet Union have tried to share our experiences with our Japanese friends. This has been a most gratifying process, especially as we have witnessed the diligent and expert way in which they have made thousands of measurements, amassing superb data sets which, because of earlier access to field sites the open and accountable way in which the science has been carried out, are of much better quality than we could achieve in the years after Chernobyl. They are now using these data to construct and refine computer models which will be of enormous help in managing the impacts of caesium-137 contamination of Japanese forests over the coming decades. I know from numerous conversations with my colleagues that they not only have an increasingly excellent scientific understanding of this problem, they also have a deep appreciation of the human cost of the Fukushima accident and that their work is ultimately intended to help alleviate this cost.

(continued)

Sampling in Kopachi pine forest, 3.5 km southeast of the Chernobyl nuclear power station. George Shaw is on the left. Taken in 2015 (Courtesy of George Shaw).

Chapter 5
Radiation Protection and Criteria

Abstract This chapter will explain the internationally agreed-upon concept of radiological protection and how Japan actually sets and operates criteria of radiation exposure dose and radioactivity concentrations based on this concept. In Chap. 3, we explained the dynamics of radiocesium that has fallen on the forest. As explained in Chap. 2, radiation emitted from radioactive materials is harmful, and it is important to protect people from exposure to it. Unlike air and water pollution which are often visually appealing for their adverse effects on health, radiation is invisible. This may give the impression that the health hazards of radiation are even more frightening. On the other hand, it is known that health hazards caused by radiation can be predicted to some extent by the amount of radiation received by the human body (exposure dose). In this regard, data from studies of the effects of the atomic bombs dropped on Hiroshima and Nagasaki are also treated as extremely valuable findings for assessing health hazards based on exposure dose. Since there is also radiation from natural radionuclides, radiation exposure cannot be completely avoided. The important thing is to live a balanced life with a certain amount of exposure taken into account. These basic ideas and methods of protection from radiation have been repeatedly discussed and proposed by an international academic organization.

Keywords Radiological protection · ICRP · IAEA · Countermeasure · Optimization · Reference level · Dose criteria

5.1 Internationally Agreed-upon Approach to Radiation Protection by the International Commission on Radiological Protection (ICRP)

The ICRP has put together a list of ideas for reasonably reducing exposure to radiation, depending on the situation.

S. Hashimoto et al., *Forest Radioecology in Fukushima*,
https://doi.org/10.1007/978-981-16-9404-2_5

The International Commission on Radiological Protection (ICRP) is a private, academic organization of experts from around the world who volunteer to formulate consensus on the basics of radiological protection and publish their recommendations in reports. Since 1928, the ICRP and its predecessors have been discussing the concept of preventing radiation hazards to human health and dose limits, and have repeatedly issued recommendations. The most recent recommendation on a system of radiological protection (ICRP Publication 103) [12] was issued in 2007, and ICRP Publications 109 [103] and 111 [104] were published in 2009 to advise on the application of Publication 103. However, these were all technical books for experts and were difficult for the general public to understand. Therefore, a commentary book on ICRP 111 was published in Japan in response to the radioactive contamination caused by the Fukushima nuclear accident [105]. In the following, we will mainly follow this understandable guide to explain the latest thinking on radiation protection.

The main points of the thinking behind ICRP 103 can be summarized in the following three principles.

- **The principle of justification:** Consider radiation exposure as a risk and allow activities only when the benefits of exposure outweigh the risks (disadvantages).
- **The principle of optimization of protection:** Making efforts to keep exposure reasonably low while maximizing the benefits to be gained from activities involving exposure, taking into account economic and social circumstances.
- **The principle of application of dose restrictions:** Stepwise reduction of exposure by setting dose targets (reference levels) according to the exposure situation from emergency to normal through recovery period.

This way of thinking is actually reflected in the measures taken by the government after the Fukushima nuclear accident. It is also useful for individuals to think about how to protect from and deal with radioactive contamination of forests by adopting the above three principles.

5.2 Approaches to Radiation Protection in Forests

It is important to consider forest contamination in a balanced manner.

What can be expected if the ICRP's concept is applied to forests where radioactive contamination has occurred? As described in Chap. 2, the main exposure routes for humans can be roughly divided into external exposure from radioactive materials in the environment such as soil and internal exposure from ingestion of radioactively contaminated food. Forests tend to have a higher air dose rate than residential areas because radiocesium stays there for a longer period of time (Sect. 6.1). In addition, wild mushrooms, wild plants, and other blessings obtained from forests tend to have higher radiocesium concentrations than crops grown in the agricultural fields (Sect. 6.4). Therefore, people living in mountain villages potentially could be exposed to higher levels of radiocesium when they stay in the forest for a long time or eat wild mushrooms than when they do not. Therefore, it is necessary to make reasonable efforts to reduce the additional exposure (optimization) so as not to exceed the criteria of annual doses (dose restrictions). To reduce external and internal exposure, it is possible to check the air dose rate in the forests one has been in and avoid staying in high radiation places for a long time, and to reduce the amount of radioactive materials in food through cooking (Sect. 6.4).

On the other hand, for people who have been using forests before the accident, the fact that the forests are unable to use as before may have a negative impact on them physically and mentally. It is necessary for each person to make a decision (justification) after considering the additional exposure from using the forests as a risk (cost) and weighing the benefits of using the forests on the other hand. The research on the actual situation of radioactive contamination of forests, that has been conducted since immediately after the Fukushima nuclear accident, will provide the objective evidence for promoting such optimization and justification measures.

It is not the purpose of this book to allow or recommend additional exposure for individuals. However, we feel that until now, domestic opinions after the Fukushima nuclear accident have emphasized the risks of radiation exposure. As the ICRP states, risks should be weighed against benefits, and we should act on the concept of radiological protection as our own.

5.3 Countermeasures in Contaminated Areas: The International Atomic Energy Agency's (IAEA) Approach

Each measure against radioactive contamination has its own advantages and disadvantages.

The International Atomic Energy Agency (IAEA) is an autonomous international organization within the United Nations system that aims to promote the peaceful use of nuclear energy and to prevent the military use of nuclear energy. In 2006, the 20th anniversary of the Chernobyl Nuclear Power Plant accident, the IAEA published a report on its experience with the environmental impact and remediation of the accident [39]. It also describes measures for forests. There are two main types of measures: one is a technology based countermeasure and the other is a management based countermeasure (Fig. 5.1). The former includes felling and removal of trees, removal of surface organic layer and mineral soil (decontamination), soil mixing, and

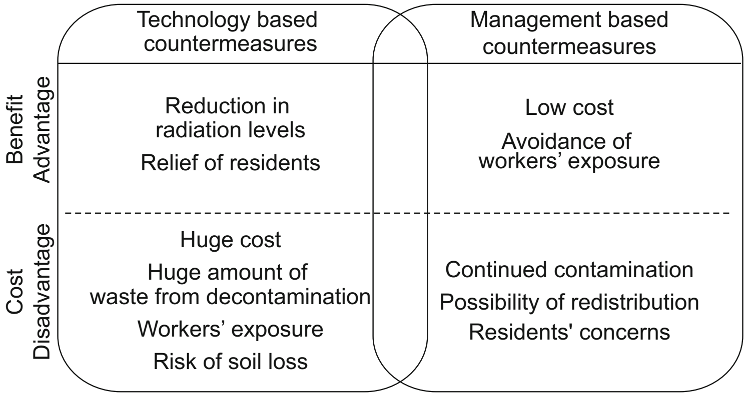


Fig. 5.1 Conceptual diagram of types of countermeasures and their benefit (advantage) and cost (disadvantage)

potassium fertilization. The latter includes access control (zoning) according to the degree of contamination and regulating the consumption of contaminated food. In practice, there are also intermediate measures that use both.

The two types of measures are known to have their own merits (advantages) and demerits (disadvantages). For example, soil removal, which is one of the measures to apply the technology, is effective to some extent in reducing radiation levels, but it is known to generate huge costs and huge amounts of waste, and it is not always clear how cost effective it is. There is also the issue of radiation exposure of the decontamination workers. The latter, on the other hand, has the advantage of being less costly, but requires a longer period of time than decontamination before the contamination drops to a certain level, since radioactive materials can only be reduced by radioactive decay. Whatever measures are applied, as recommended in the IAEA report, there is a limit to the number of measures that can be applied to forests, and it is important that the effectiveness, costs, and benefits are thoroughly examined before implementation [106]. In addition, communication and understanding with local residents are essential for implementation, and decisions cannot be made based on scientific rationality alone.

5.4 Concept of Setting Criteria in Japan

In Japan, various criteria have been set in consideration of the estimated annual exposure dose.

To control the exposure dose due to radioactive contamination, Japan adopted the ICRP approach and established criteria of annual exposure doses. The governmental regulations for exposure protection after the Fukushima nuclear accident are divided into two categories: limit values set by laws and regulations, and limit values provisionally set by notices issued by the departments in charge of the ministries and agencies. The former includes limits of annual exposure dose for the general public and workers involved in decontamination work, and the concentration of radiocesium in food, applied as "standard limits". In addition, for the use of forest products other than foodstuffs, the Forestry Agency of Japan has provided guidance to related industries in the form of notices using the term "index values" for radiocesium concentrations, which constitutes slightly more flexible but still substantial regulation as required by the Government of Japan. In this section, criterion/criteria (standard limits) is explained. The latter index values will be discussed in Sect. 6.2, which describes examples concerning the regulations for use of wood.

In the areas where radioactive contamination has occurred, the long-term goal is to keep individual exposure doses below 1 mSv per year, which is the reference level of exposure dose in normal times. However, it is not practical to set a uniformly strict criterion for all forms of exposure protection, since the situation varies depending on the degree of contamination, the relative importance of different sources of exposure and the time that has passed since the contamination occurred. Therefore, as mentioned earlier, the goal is to realize realistic and effective exposure protection by setting reference levels according to the contamination and social conditions and lowering the reference level in stages (optimization) [107]. The numerical value of 1 mSv is a target for effective implementation of radiation protection measures, and does not indicate that there is necessarily a health hazard if the exposure dose is higher than this value [108].

5.4.1 *Criteria of Air Dose Rates*

In environmental exposure protection, it is necessary to consider both external and internal exposures. As criteria for zoning and regulation of activities to reduce external exposure, air dose rates calculated by considering estimated annual exposure dose accompanying indoor and outdoor activities were used. In this section, we will discuss the criteria using air dose rates that are also related to activities in forests, including (1) the limit used to establish evacuation order zones (3.8 μSv/h, 20 mSv per year), (2) the target value for decontamination in the living area (0.23 μSv/h, 1 mSv per year), and (3) the limit of air dose rate which requires dose control in decontamination and other work (2.5 μSv/h, 5 mSv per year) (Fig. 5.2) [109].

1. **Limit used to establish the evacuation order zones (3.8 μSv/h, 20 mSv per year)**

In the immediate aftermath of the accident, emergency measures were necessary, and the ICRP set such a situation as an "emergency exposure situations" and set a

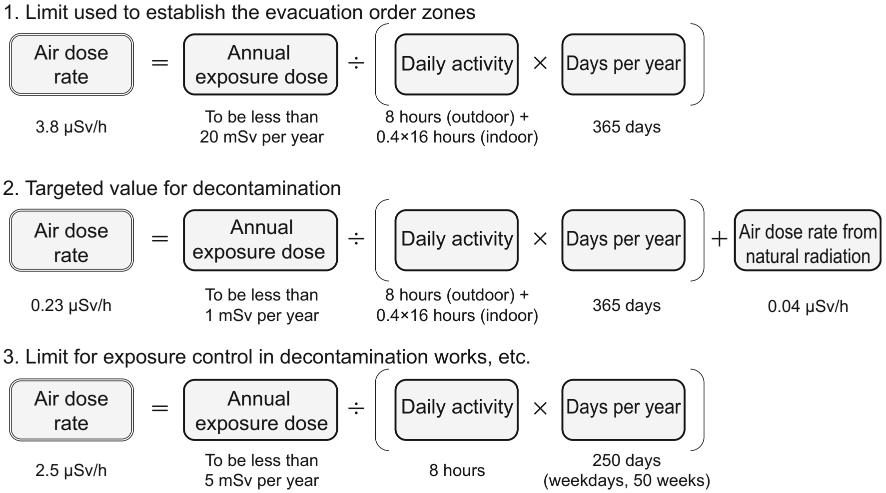


Fig. 5.2 Calculation formulas on which the three representative air dose rate criteria are based (Source: Adapted from the Forestry Agency, Considerations for Prevention of Radiation Hazards in Operations in Forests and Other Areas (Q&A), "Reference Air Dose Rates" [109])

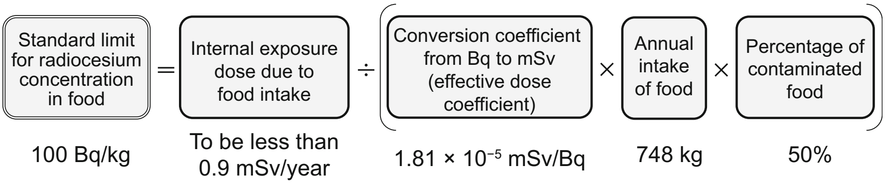
reference level of 20–100 mSv per year as a reasonable exposure dose to promote recovery from the emergency situation while avoiding excessive exposure. In Japan, 20 mSv per year, the lowest of the reference levels, was set as the limit for residence. The air dose rate at which the external exposure dose from daily life is 20 mSv or less per year is 3.8 μSv/h. This calculation assumes that people are outdoors for 8 h and indoors for the remaining 16 h of the day, and that the indoor air dose rate is 40% of that outdoors.

2. Target value for decontamination in the living area (0.23 μSv/h, 1 mSv per year)

Next, the ICRP sets a reference level of 1–20 mSv per year for the situation (existing exposure situations) where contamination exists but the goal is to further reduce the effects after the stage where emergency measures should be taken. Therefore, to achieve the long-term target of 1 mSv per year, a target value of 0.23 μSv/h was set as the air dose rate in the living area through decontamination. As is the case with the criterion for evacuation order zones, the air dose rate is 0.19 μSv/h based on the assumption that people will be outdoors for 8 h a day and indoors for 16 h a day. Furthermore, adding the air dose rate from natural radiation that existed before the accident (average of 0.04 μSv/h) yields 0.23 μSv/h.

3. Limit of air dose rate where individual dose control is required in decontamination and other operations (2.5 μSv/h, 5 mSv per year)

Exposure to radiation when performing work such as decontamination in contaminated areas is called occupational exposure and is distinguished from public



Conditions

1. From annual internal dose limit (1 mSv), 0.1 mSv is assumed to be from drinking water.
2. The radiocesium concentration below the internal dose limit differs depending on the age and sex. The standard limit is set at 100 Bq/kg, which is obtained from round down of the lowest value (120 Bq/kg for boys aged 13–18).
3. The effective dose coefficients take into account the effect of both ^{134}Cs and ^{137}Cs.
4. The annual intake of food is assumed to be 748 kg, half of which is domestic products.

Fig. 5.3 Formula for calculating the standard limit of radiocesium concentration in general food (Source: Adapted from Ministry of the Environment, BOOKLET to Provide Basic Information Regarding Health Effects of Radiation, "Chap. 8: Radioactive Materials in Food, 8.1 Approach for Calculation of Standard Limits (1/2)" [1])

exposure. While occupational exposure permits a higher exposure dose than public exposure, strict individual dose control is required according to a governmental regulation (Ionizing Radiation Ordinance for Decontamination)[1] [110]. The limit for the air dose rate to determine whether or not the work requires such dose control (work under a specific dose) is 2.5 μSv/h. This value is derived by dividing the annual exposure dose of 5 mSv by the work hours (40 h per week × 50 weeks). The limit of the regulation is also applied to forests, and is used as a guide for decontamination work in forests and normal forestry activities (Sect. 6.1).

5.4.2 *The Reason for the Criterion of 100 Bq/kg for Food*

As of April 1, 2012, the standard limit for general food has been set at 100 Bq/kg for the total of cesium-134 and cesium-137. The reason for this is that the annual internal exposure dose to humans from continuously eating food with a concentration of the standard limit under certain conditions was estimated to be 1 mSv (Fig. 5.3). Some assumptions are made in the calculation. The Codex Alimentarius (an international intergovernmental organization for the purpose of protecting the health of consumers and ensuring fair trade in food) and the EU have also set the criterion for food to keep internal exposure below 1 mSv per year. However, they set the criterion of

---

[1] The official name is translated as "Ordinance on Prevention of Ionizing Radiation Hazards at Works to Decontaminate Soil and Waste Contaminated by Radioactive Materials Resulting from the Great East Japan Earthquake and Related Works" (Ordinance of Ministry of Health, Labour and Welfare No. 152, enforced on January 1, 2012). https://www.japaneselawtranslation.go.jp/en/laws/view/2714.

radiocesium concentration in food at 1000 Bq/kg, which is higher than in Japan. This is due to different assumptions such as the ratio of foods containing radiocesium (50% in Japan, 10% in Codex and EU) [111].

Radioactivity inspection of food products was conducted based on the standard limit of radiocesium concentration. If the inspections show that the relevant food products widely exceed the standard limit within a municipality, shipping restrictions will be imposed. Wild mushrooms (mushrooms that occur naturally in the forests and fields) and wild plants (edible tree buds and shoots, bamboo shoots, and ferns, etc.), which are blessings of forests, have higher levels of radiocesium than other agricultural products, and shipping restrictions have been imposed over a wide area (Sect. 6.4).

5.4.3 8000 Bq/kg: Criterion for Waste

8000 Bq/kg is a standard limit for the safe disposal of waste. In the case of waste disposal, the amount of exposure was expected to vary depending on the type of waste and the work process. Therefore, the exposure doses from radiocesium in waste were estimated for residents living around the landfill site and for workers at the landfill site according to their work activities [112]. In the estimation of exposure doses for workers, it was assumed that half of the annual working hours were spent working with waste. As a result, it was calculated that the exposure dose from the landfill work of dewatered sludge, etc. was high, and it was confirmed that the concentration of waste should be kept below 8000 Bq/kg to keep the annual exposure dose from this work below 1 mSv. If the concentration is below 8000 Bq/kg, the waste can be disposed of in the same way as ordinary waste, but if it exceeds 8000 Bq/kg, the waste will be disposed of as designated waste under the management of the government.

In the case of forest contamination, the concentration in the bark of trees is high, and to ensure that the bark from the lumbering process does not exceed the standard limit for waste, areas in Fukushima Prefecture where wood can be used were set based on air dose rates. In addition, lower index values were set for firewood and charcoal because burning wood concentrates radiocesium in the combustion ash. These are discussed in Sect. 6.2.

Chapter 6
Impacts of Radioactive Contamination of Forest on Life

Abstract In this chapter, we will look at how radioactive contamination itself and regulations to prevent human exposure to radiation have affected the lives of the people living there and their social and economic activities. In forests, various regulations based on the criteria described in Chap. 5 have been established to reduce internal and external exposure. The impact of these regulations on access to forests, restrictions on the use of timber, wildlife, mushrooms and wild plants, and the effects of these restrictions will be explained, as well as the measures taken.

Keywords Air dose rate · Decontamination · Access control · Regulation · Wildlife · Forestry · Forest products · Wild mushroom · Wild plants · Mushroom cultivation · Communication

6.1 Effects of Increased Air Dose Rates

Air dose rates in forests behave differently from those in urban areas and agricultural lands.

Air dose rates are used as a criterion of external exposure due to activities such as living and working, and restrictions on entry and other uses are imposed based on the standard limits described in Chap. 5. In this section, the characteristics of air dose rates in forests will first be explained. This is followed by an explanation of restrictions on entry and activities set based on air dose rates, and finally, the effectiveness and limitations of forest decontamination, which is a measure to reduce air dose rates.

S. Hashimoto et al., *Forest Radioecology in Fukushima*,
https://doi.org/10.1007/978-981-16-9404-2_6

6.1.1 Characteristics of Air Dose Rates in Forests

First, let us look at the characteristics of air dose rates measured in forests, and how they differ from those in urban areas and flat open lands.

Air Dose Rates in a Forest Change Generally According to the Radioactive Decay of Radiocesium, But Changes in the Distribution of Radiocesium in the Forest also Have an Effect

When considering exposure due to activities in forests, external exposure due to radiation from radiocesium in the environment is the main exposure route. Therefore, it is important to know the distribution of air dose rates in the forest and their changes with time. In general, the air dose rate increases in proportion to the amount of radiocesium in the surrounding area and decreases with time due to radioactive decay of radiocesium. In the results of surveys conducted by Fukushima Prefecture since 2011 in fixed-point observations conducted at 362 forest locations, it has been observed that air dose rates decrease in accordance with radioactive decay of radiocesium (Fig. 6.1a). The same trend was also confirmed in a survey conducted by the Forestry Agency of Japan and the Forestry and Forest Products Research Institute (Fig. 6.1b).

However, Fig. 6.1b shows that the air dose rate at a height of 10 cm from the ground surface is higher than that at a height of 1 m, even at the same point. This can be attributed to the fact that a large amount of radiocesium accumulates in the soil in forests (Fig. 6.2). In addition, the values for 2012 and 2013 are slightly higher than the estimate based on the decay curve from 2011. This is probably considered to be due to the fact that in 2011, there was a relatively large amount of radiocesium attached to the tree canopies at a distance from the measurement height at 1 m above the ground, whereas in 2012 and 2013, radiocesium attached to trees had migrated to the ground.

Decrease in Air Dose Rate Due to Radioactive Decay (About Half in 3 Years)

Another thing that should be noted is the speed at which the air dose rate decreases. The amount of radiocesium decreases due to radioactive decay, but the air dose rate decreases at a faster rate than the amount of radiocesium. For example, if it is assumed that radiocesium falls on a certain place and does not move, and the air dose rate changes only due to radioactive decay, the amount of radiocesium (cesium-134 and cesium-137) will decrease to 65% of the initial amount in 3 years after the accident, while the air dose rate will be 52% (Fig. 6.3). This is because cesium-134 emits radiation approximately 2.7 times more intense than cesium-137 per decay. Of the radiocesium emitted in the ratio of 1:1 in the Fukushima nuclear accident,

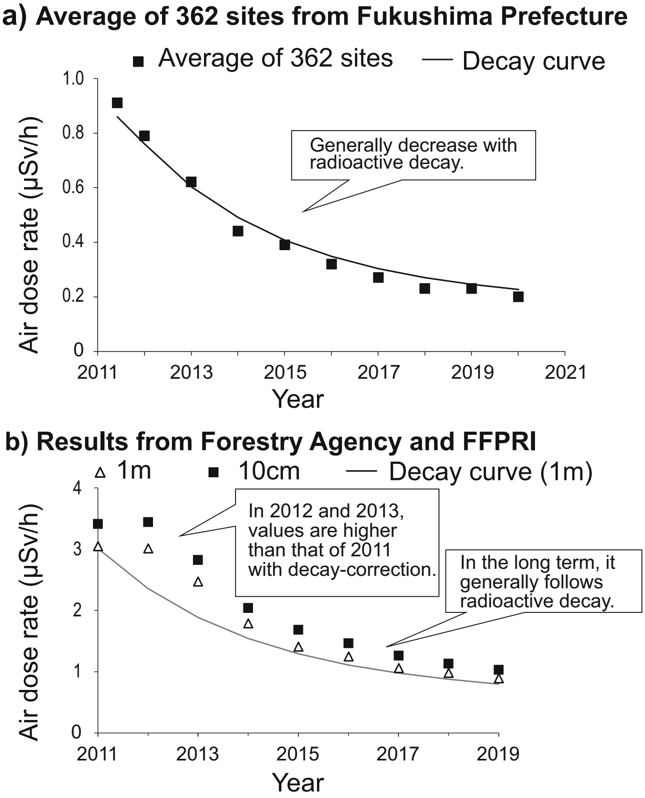


Fig. 6.1 Temporal changes in air dose rates in forests. The solid line in (**a**) is the change in air dose rates assumed to be caused by radioactive decay of cesium-134 and cesium-137 (decay curve). The solid line in (**b**) is also the estimate based on the decay curve from the measured values at a height of 1 m in 2011 (Source: (**a**) Data from Fukushima Prefecture, "Results of Radioactive Materials Survey in Forests in 2019 fiscal year" [67], (**b**) Data from a survey by the Forestry Agency and the Forestry and Forest Products Research Institute, "Results of Survey on Radioactive Cesium Distribution in Forests" [21])

cesium-134, which has a stronger impact on air dose rates, decreases faster, resulting in a faster decrease in air dose rates than the amount of radiocesium. This tendency to decrease air dose rates due to radioactive decay is a common phenomenon not only for forests but also for radiocesium in the environment. However, it is important information when considering external exposure to radiation from forests.

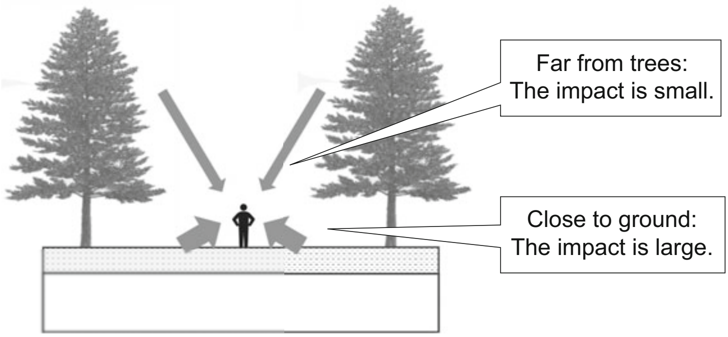


Fig. 6.2 Image of radiation in a forest (radiation from the ground surface is considered to have a stronger effect on air dose rates, which are often measured at a height of 1 m above ground level, than radiation from trees)

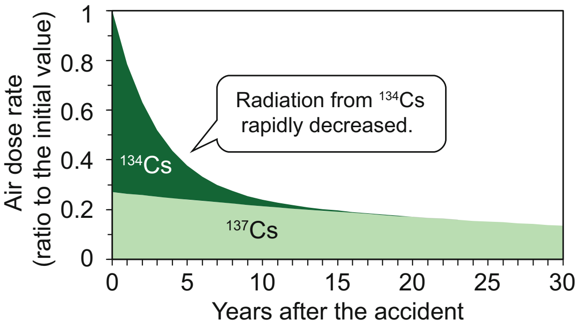


Fig. 6.3 Predicted decrease in air dose rates due to radioactive decay after the accident at the Fukushima Daiichi Nuclear Power Plant. Radioactivity ratios of cesium-134 and cesium-137 at the time of the accident are equal, and their contribution to the air dose rate is assumed to be 73% and 27%, respectively

Spatial Distribution of Air Dose Rates in Forests Is Uneven

The spatial distribution of radiocesium is non-uniform and varies with time, which in turn affects the air dose rate. For example, air dose rates may be higher at forest edges (forest ends bordering farmland and residential areas) or in areas where sediment tends to accumulate due to the movement of topsoil. In fact, forest edges are known to have higher air dose rates due to their location where airborne radiocesium is easily trapped. Figure 6.4 shows the results of a spatial survey in a forest conducted by the Forestry and Forest Products Research Institute, showing that air dose rates are distributed unevenly in a small forest [113].

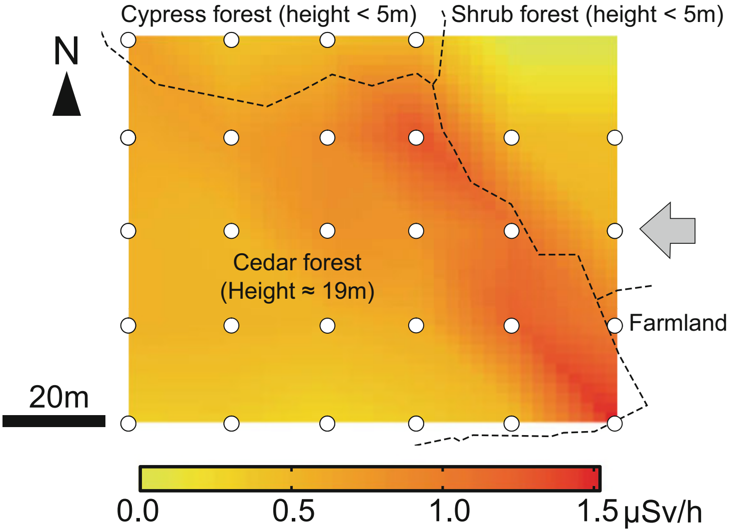


Fig. 6.4 Example of spatial survey results of air dose rates in a forest. Air dose rates at the forest edge were considered to have increased due to a plume containing radiocesium (arrow in the figure) hitting the forest from the east. White circles indicate measurement points (Source: Data from Imamura, et al. 2017 [113]; Data, courtesy of Naohiro Imamura, the Forestry and Forest Products Research Institute)

Air Dose Rates in Forests Are Higher than in Nearby Residential Areas

It is known that a very small percentage of the radiocesium that falls on forests flows out of them (Sect. 3.6). Also, most of the radiocesium in the soil stays in the surface layer. Since the distribution of radiocesium does not change and the amount of radiocesium flowing outside is small, the air dose rate in forests can be considered to generally decrease in accordance with radioactive decay of radiocesium over time. The air dose rates of forests with such characteristics were compared with those of other land uses (Fig. 6.5). Comparing the results of measurements on roads conducted by car-borne surveys and fixed-point measurements conducted on open flat land, it was found that the air dose rates in forests did not decrease easily over time [114]. This is due to the fact that air dose rates for land use other than forests are characterized by a faster decrease in air dose rates than the decrease due to radioactive decay of radiocesium. Because radiocesium tends to flow along roads, and even on flat land, radiocesium migrates in the direction of deeper soil and decontamination works reduce the amount of radiocesium.

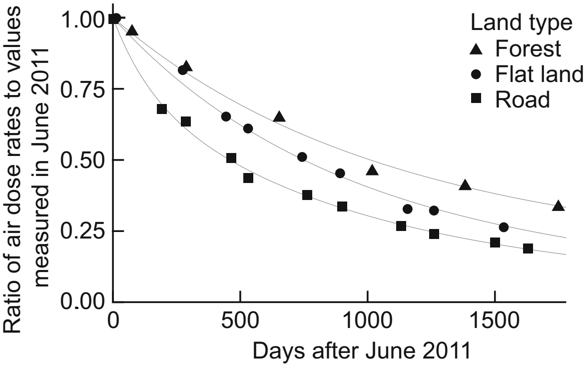


Fig. 6.5 Differences in the trend of decrease in air dose rates due to different land use. Values are expressed as a ratio of the value in June 2011. For forests, the values measured in August 2011 were corrected for decay in June of the same year and used as the reference values. Forests: 362 points in Fukushima Prefecture; Flat land: 6577 points of flat open land with little human disturbance within 80 km of the Fukushima Daiichi Nuclear Power Plant; Roads: based on car-borne surveys within 80 km of the Fukushima Daiichi Nuclear Power Plant. The trend of change in the average value for each land use category is approximated by a curve (Source: Same as Fig. 6.1a for forests, and data from Nuclear Regulation Authority of Japan "2015 fiscal year Report on the Results of the Project for Consolidating Distribution Data of Radioactive Substances Associated with the Accident at TEPCO's Fukushima Daiichi Nuclear Power Station" for flat lands and roads [115])

6.1.2 *Access Control Based on Air Dose Rates*

Designation of Areas Under Evacuation Orders and Their Changes

The designation of evacuation order zones based on air dose rates after the Fukushima nuclear accident had a strong impact on the lives and activities of residents. To protect residents from radiation exposure immediately after the accident, the area 20 km around the plant was first designated as an evacuation order zone (warning zone), and the area to the northwest, which was highly contaminated, was designated as a planned evacuation zone, where entry was restricted (prohibited) (Fig. 6.6). Subsequently, on April 1, 2012, the evacuation zones were reorganized into three areas with reference to the annual exposure dose of 20 mSv (3.8 μSv/h, Sect. 5.4) as recommended by the ICRP to facilitate the return of residents and the rehabilitation and reconstruction of the region. First, the areas where the annual dose is certain to fall below 20 mSv were designated as preparation areas for lifting the evacuation order, with the aim of lifting the evacuation order as soon as possible. The areas with annual exposure doses of over 20 mSv were designated as restricted residential areas, where people were prohibited from living (or staying), while decontamination and other restoration work was carried out to rebuild the infrastructure of daily life. Areas where the annual exposure dose exceeded 50 mSv and where the annual exposure dose was expected to exceed 20 mSv even after 5 years were designated as difficult-to-return areas where entry by the public was prohibited in

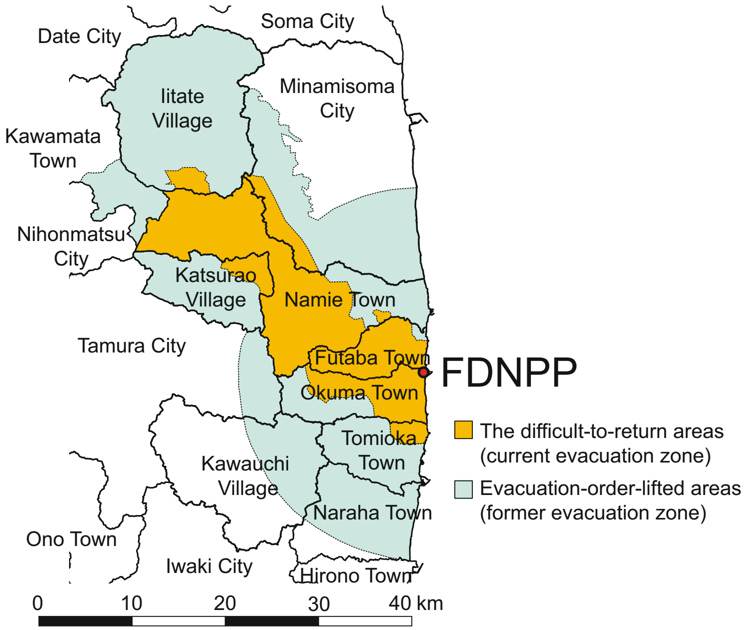


Fig. 6.6 Difficult-to-return areas and surrounding areas as of March 2020. Evacuation orders have been partly lifted in the area around the train stations in Futaba Town, Okuma Town and Tomioka Town (Source: Adapted from Ministry of Economy, Trade and Industry, Disaster Related Information, Information on Evacuation Orders to Date, "Conceptual Diagram of Evacuation Zone (as of March 10, 2020)" [117])

principle. Thereafter, as the air dose rate decreased due to decontamination and the radioactive decay, the evacuation order was lifted mainly in the preparation areas for lifting the evacuation orders and the restricted area, and the area of the evacuation order became smaller [116].

However, only some of the difficult-to-return areas with high radiation doses have been lifted, and as of March 2020, evacuation order zones have been established across seven municipalities. Forests in the difficult-to-return areas are inaccessible as well as residential areas. Although the government is promoting a plan for the further lifting of the evacuation order, according to the results of airborne monitoring, there are still places where the air dose rate exceeds 10 μSv/h. To meet the criteria for the lifting of the evacuation order, it is necessary to wait for a decrease in the radiation dose rate due to radioactive decay or to take measures such as decontamination to further decrease the radiation dose rate.

Table 6.1 Classification of work in contaminated forests

Description of work	Radiocesium concentration in soil[a]	Air dose rate	Classification
Producing tree seedling Planting Growing (limited to replanting) Building forest roads Disaster restoration	Exceeds 10,000 Bq/kg	Does not affect classification	Works for handling of designated contaminated soil and waste
	Not exceeding 10,000 Bq/kg	Exceeds 2.5 μSv/h	Works under a designated air dose rate
		Not exceeding 2.5 μSv/h	No obligation to take countermeasures[b]
Other	Does not affect classification	Exceeds 2.5 μSv/h	Works under a designated air dose rate
		Not exceeding 2.5 μSv/h	No obligation to take countermeasures[b]

Source: Data from the Forestry Agency, Considerations for Prevention of Radiation Hazards in Operations in Forests and Other Areas (Q&A), "Flow Chart for Working in Special Decontamination Areas, etc." [109]

[a] In the original flow chart referred, measurement of air dose rates precedes measurement of radiocesium concentration in soil, but in the actual classification, the results of radiocesium concentration in soil are referenced at the top instead of those of air dose rates, so the columns are rearranged for the convenience

[b] Although there is no obligation to take countermeasures, examples of voluntary efforts to further reduce exposure doses are given in the original chart

The Limit of Air Dose Rate for Forestry Activities is 2.5 μSv Per Hour or Less

Regulations are also in place for activities in the forest. Work in forests is also managed in accordance with the Ionizing Radiation Ordinance for Decontamination, as explained in Sect. 5.4 (See footnote in 5.4.1). In other words, when working in forests where the air dose rate exceeds 2.5 μSv/h, it is necessary to control exposure doses in compliance with the "Guidelines on Prevention of Radiation Hazards for Workers Engaged in Works under a Designated Dose Rate".[1] Furthermore, in the case of work involving soil, if the radiocesium concentration in the soil at the work site exceeds 10,000 Bq/kg, the work is classified as "Works for Handling Designated Contaminated Soil and Waste" and the "Guidelines on Prevention of Radiation Hazards for Workers Engaged in Decontamination Works" are applied. Soil handling work includes not only decontamination work but also tree planting and nursery (e.g. thinning) works (Table 6.1).

However, in practice, the principle is to reduce exposure doses as much as possible and have workers work under an air dose rate (2.5 μSv/h or less) that does not require dose control. Therefore, except for highly urgent work such as

---

[1] https://www.japaneselawtranslation.go.jp/notices/view/57.

restoration in areas affected by natural disaster such as earthquake, works in forests in areas where the air dose rate exceeds 2.5 μSv/h are refrained. In addition, forestry activities had not been allowed in the evacuation order zones due to the access control. As a result, as of August 2012, forestry activities were restricted in 13% of the forest area in Fukushima Prefecture (130,000 hectares) [118].

There Are No Restrictions on Temporary Entry into the Forest

On the other hand, there are no restrictions on entry into forests for recreational purposes, except for entry into evacuation order zones. This is related to the fact that the external exposure dose is calculated by multiplying the air dose rate by the time spent in the forest (Fig. 5.2). Because entry into forests for leisure is for a short time compared to work, and external exposure is considered to be small.

The Ministry of the Environment of Japan has estimated the external exposure dose in the case of leisure activities in Fukushima Prefecture (Ministry of the Environment, Environmental Remediation Website, "June 15, 2015, Committee on Environmental Remediation (15th Meeting) Document 4" [108]). The results of the calculations for each age and region show that the annual exposure dose will be limited to 0.06 mSv at most. Even when forests are used for recreation, the annual exposure dose is not expected to exceed 1 mSv, which is the upper target value of annual exposure dose for the public.

6.1.3 Forest Decontamination

Removing the Organic Layer Reduces the Air Dose Rate

In the farmland after the accident, a wide range of countermeasures against contamination has been taken, including removal of surface soil and inversion tillage (replacing topsoil with subsoil) to reduce radiocesium in the surface layer that is related to absorption by crops, and potassium fertilization to reduce the transfer of radiocesium to crops [119]. Agricultural land is generally flat and spread out over a wide area, which makes it possible to perform efficient work using agricultural machinery. On the other hand, in forests in Japan where the slopes are steeper and more undulating than in farmland, and trees and their roots are irregularly distributed, countermeasures are more limited. In forests with many technical limitations, the removal of the soil surface organic layer (so-called 'forest decontamination') became the main technical measure (Fig. 6.7).

Decontamination of forests is carried out by gathering and transporting contaminated organic layer out of the forests. As shown in Chap. 3, monitoring surveys conducted after the accident showed that much of the radiocesium in the forest transferred to the organic layer and surface mineral soil layer in the years following the accident. Therefore, the decontamination of forests involves the removal of the

Fig. 6.7 Forest decontamination (Source: Reprinted from The Forestry Agency, press release in December 27, 2011 [121]; Courtesy of Yoshio Tsuboyama, the Forestry and Forest Products Research Institute)

organic layer (fallen leaves and branches some of which are coarsely decomposed) of the forest. However, the forest decontamination did not cover the entire vast forest area, but was limited to the area within 20 m from the edge of the forest bordering residential areas, roads, and other living areas to reduce radiation exposure to the living environment (Ministry of the Environment, Environmental Remediation, "About Forest Decontamination, etc.") [120].

The Effective Range of Forest Decontamination is 20 m

This section describes a test in which the range of forest decontamination was determined to be 20 m [121]. The test was conducted in a coniferous forest and a broadleaf forest in Koriyama City, Fukushima in September 2011. A 20 m × 20 m test site was set up in the middle of a forest slope in each type of forest, and the changes in air dose rates were measured while gradually expanding the decontamination area from the center. Figure 6.8 shows the spatial distribution of the change ratio in air dose rates in the test site after decontamination of 12 m × 12 m and 20 m × 20 m. As the decontamination area was expanded, the area where air dose rates decreased also expanded. After the decontamination of 20 m × 20 m, air dose rates at the central point decreased to about 70% and 60% of those before decontamination in the coniferous and broadleaf forests, respectively. However, even when the decontamination area was extended from 12 m, the air dose rate in the central area did not decrease further. Thus, while forest decontamination is effective

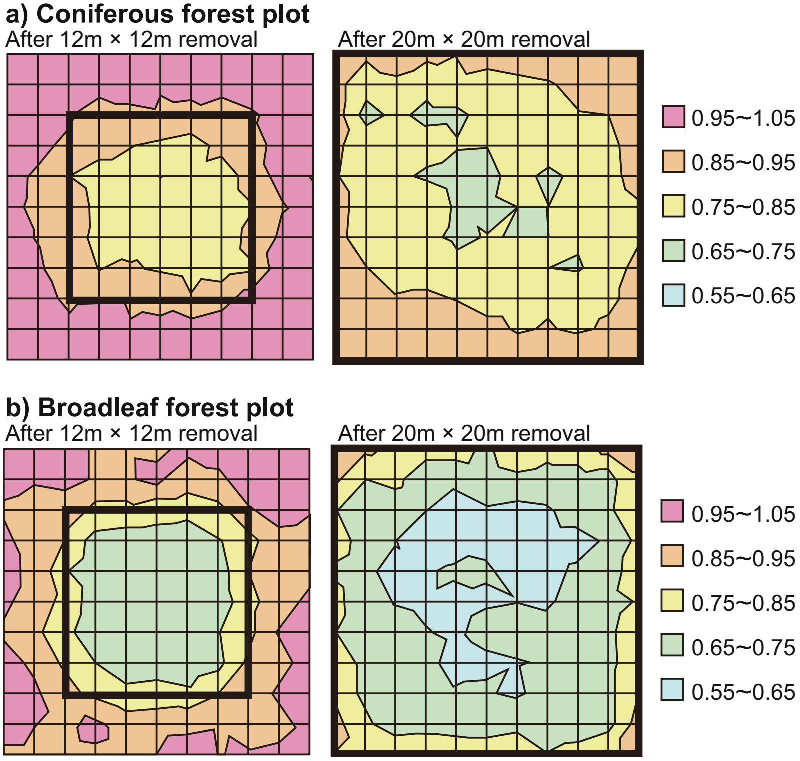


Fig. 6.8 Relationship between decontamination area (bold line) and changes in air dose rates. Distribution of the ratio in air dose rates measured at a height of 1 m before and after the removal of understory vegetation and organic layer. Grid spacing is 2 m (Source: Reprinted from the Forestry Agency, press release of December 27, 2011 [121]). (**a**) Coniferous forest plot. (**b**) Broadleaf forest plot

in lowering air dose rates, the effect reaches a ceiling as the decontamination area expands. In addition, since decontamination generates a large amount of waste, the decontamination area at a forest edge was set at 20 m to achieve a balance between effectiveness and cost.

After that, decontamination of forests was carried out in *satoyama* forests and other areas where people enter on a daily basis, and in some areas, a model project was carried out by the Ministries of the Government and Fukushima Prefecture to test surface decontamination (Satoyama Restoration Model Project) [122]. The target areas were the sites for bed-log cultivation of shiitake mushrooms, campsites, and walking trails. In the test sites that were flat and had no risk of soil runoff, scraping of the topsoil was also conducted, resulting in a reduction in air dose rates of up to 50% or more.

In addition to decontamination, tests have been conducted to reduce the air dose rate by spreading wood chips and to reduce the transfer of radiocesium from soil to trees by applying potassium fertilizer. In addition, to utilize the high cesium-absorbing capacity of fungi for decontamination, tests have been conducted to absorb radiocesium by mycelium infected in the laid chips [30]. However, this has only been done on a trial basis and not on a large scale.

As described above, removal of the organic layer has been an effective method for reducing air dose rates in forests. However, caution must be exercised when decontamination should be conducted. As described in Chap. 3, a large amount of radiocesium, which was contained in the organic layer immediately after the accident, has shifted to the surface layer of mineral soil over time. Since the purpose of decontamination is to remove as much radiocesium as possible, it will only be possible to do so effectively for a few years up to 10 years after the accident.

Does Cutting Down Forest Trees Reduce Air Dose Rates?

It was explained that the removal of the organic layer is effective in reducing the air dose rate in forests. Subsequently, changes in air dose rates in the forest were also investigated by combining forest management practices such as clear-cutting (cutting all trees) and thinning (partial cutting), in addition to removal of the organic layer. As a result, although air dose rates decreased in the thinned area, they also decreased in the control area without thinning, and the effect of thinning on air dose rates was not clear (Fig. 6.9). In the case where litter removal was combined with thinning or clear-cutting, there was no significant difference from the values in the test area where only litter removal was conducted. The fact that the effect of the

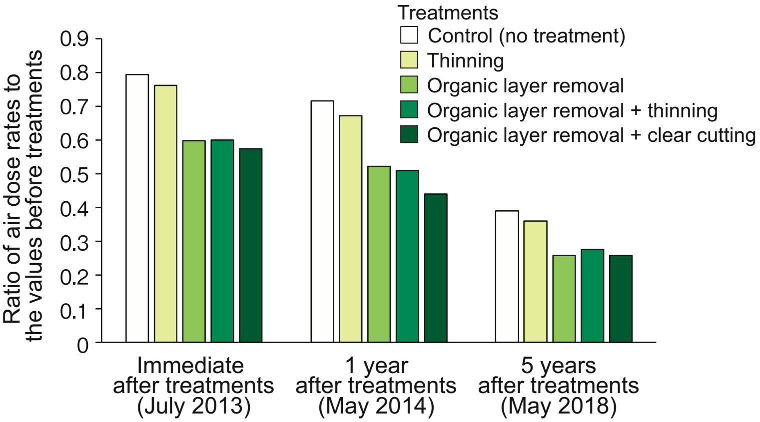


Fig. 6.9 Effect of combining forest operations and removal of organic layer (litter layer) on air dose rates in forests. Expressed as a ratio to the air dose rate before treatments (November 2012) (Source: Data from the report from the Forestry Agency, "2019 fiscal year Results of the Validation and Development Project for Countermeasures against Radioactive Substances in Forests" [123])

treatment was not clearly observed can be considered to be due to the fact that most of the radiocesium had already migrated to the ground surface in the winter of 2012. On the other hand, the effect of litter removal was found to be long-lasting.

Is It Realistic to Decontaminate All Forests?

Decontamination was carried out in residential areas and farmland, prioritizing areas where people spend a lot of time as living areas. Forest decontamination was carried out within a 20-meter width area adjacent to the living area from the forest edge, but the purpose was only to reduce the air dose rate in the living area. Now that most of the plans for decontamination of residential areas and farmland have been completed, forests might be candidates for new decontamination. However, it is not realistic to decontaminate all the forests. The area of forests is huge and the topography is complex, so much of the work needs to be done by human power. Decontamination also generates a huge amount of waste, which results in huge costs for storage. Yasutaka et al. [124] estimated the cost of decontamination in Fukushima Prefecture, including the storage of the decontaminated soil. As a result, the cost of decontaminating 20 m from the forest edge was estimated to be 23–46 billion US dollars, while the cost of decontaminating the entire forest would be over 145 billion US dollars. In addition, as a result of estimating the impact of decontamination on the external exposure of residents, it was calculated that even if the decontamination area was expanded to include all forests, the effect on reducing external exposure would be very small. As well as the enormous costs involved, from the standpoint of cost-effectiveness in that the return from effort is not deemed rewarding, it is considered difficult to actively implement forest decontamination. Furthermore, decontamination of the entire forest is not feasible due to the increased risk of topsoil runoff caused by the loss of understory vegetation and soil surface organic layer and the additional exposure of workers due to the required extensive decontamination. We believe that decontamination undertaken to date has given a certain sense of security to local residents. However, it is also important to explain the limitations of the effect of decontamination on a huge area for reducing radiation exposure to residents (Fig. 5.1).

The concept of forest decontamination is also discussed in Chap. 7.

6.2 Wood-Related Regulations and Their Impact

The index values of regulations differ among wood products depending on the type and use.

In wood-related regulations, the term “index value” is used in this book to distinguish the regulations for wood products from those based on the criteria described in Chap. 5. The index values are recommended by a notice from the department in charge of the Forestry Agency and are not regulated by law unlike the criteria (“standard limit”) for food, which means there is slightly more flexible, but still substantial regulation by the Government of Japan. The “provisional permissible values” set by the Ministry of Agriculture, Forestry and Fisheries is also the same type of regulations which provides a notice from the department in charge of the ministry. See also Sect. 5.4 for “standard limit”, which is a similar term.

6.2.1 Regulations Related to Wood

External Exposure from Living in Wooden Houses Is Negligible

Wood from trees can be used for a variety of purposes. The first use that comes to mind would be for housing. Since external exposure is determined by multiplying the air dose rate by the time spent on that spot, the effects of wood building materials used in living spaces have attracted attention. However, no index values have been set for the wood building materials from the time of the accident to the present. This is because even if the radiocesium concentration in the wood materials is high, the amount is much smaller than that of soil in the surrounding area, and the effect of the wood building materials on air dose rates is small. When living in a house made of wood obtained from where access is currently permitted, the annual exposure dose from wood has been estimated as 0.04 mSv at most [125] (Fig. 6.10, the Forestry Agency, “Approximate Calculation of Exposure in an Occupied Room Surrounded

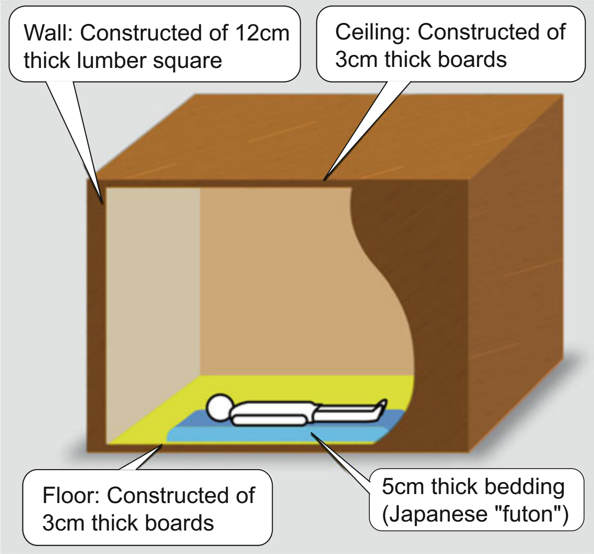


Fig. 6.10 A room used to estimate exposure dose from wood building materials (Source: Reprinted from the Forestry Agency, “The Current State of Radioactive Substances in Forests and Regeneration of Forests and Forestry 2018 Edition” [126])

by Timber, IAEA-TECDOC-1376”). In addition to these results, the Fukushima Prefectural Timber Cooperative Associations has voluntarily conducted surface dosimetry of wood (inspection of radiation levels detected on the surface of wood). In 2018, the maximum value was reported to be 44 cpm (equivalent to 0.001 μSv/h in terms of air dose rate) [126].

Disposal of High Concentrations of Bark Is a Problem

Although there was no problem in using lumber from the affected areas as building materials, the disposal of the bark generated during the lumbering process became a problem. Before the accident, the bark was generally used as compost or bedding material for livestock. However, the radiocesium concentration on the bark is higher than that of the wood because it was directly contaminated with radiocesium during fallout (Fig. 3.3 and Fig. 3.8). Depending on the conditions, there was a possibility of exceeding the criterion (8000 Bq/kg, Sect. 5.4) that must be properly disposed of as designated waste. Therefore, based on the relationship between the concentration of bark and the air dose rate, Fukushima Prefecture set 0.5 μSv/h as the index for forests that can be logged without inspections. Then, for logs felled from forests with air dose rates exceeding 0.5 μSv/h, the inspection of the radiocesium concentration of bark was required [127]. As of November 2014, 90% of the privately owned forests in the Fukushima Prefecture were below the index value of 0.5 μSv/h and could be logged without inspections [128].

Criteria (Index Values) for Firewood, Chips, and Charcoal

On the other hand, various regulations have been established for the use of trees for purposes other than building materials (Table 6.2). In the case of logs used for mushroom cultivation (bed-logs), to ensure that mushrooms do not exceed the standard limit for food of 100 Bq/kg, index values of 50 Bq/kg and 200 Bq/kg have been set for bed-logs and sawdust medium (a mixture of wood sawdust and nutrients such as rice bran), respectively [129] (to be explained in detail in Sect. 6.5). In the case of firewood, charcoal, pellets, and other combustion materials, the index values were set as ash generated after combustion not to exceed 8000 Bq/kg, which can be disposed of as general waste. When comparing firewood and charcoal, the index values are 40 Bq/kg and 280 Bq/kg, respectively, with firewood having a stricter limit. This is because the change in weight of firewood is greater when it is burned (more radiocesium is concentrated per weight). The Ministry of the Environment of Japan has estimated that the exposure dose from the use of firewood is low. According to the calculations, the annual exposure doses for children using wood stoves and baths boiled with firewood with combustion ashes of 8000 Bq/kg were 5.8 μSv and 5.0 μSv, respectively [130]. With regard to fertilizers and livestock bedding containing bark compost made by fermenting tree bark, an index value (a provisional permissible value) of 400 Bq/kg has been set as a criterion

Table 6.2 Current index values for mushroom logs, firewood, charcoal, pellets, etc.

Applicable items	Current index value (Bq/kg)	Publication
Logs for shiitake cultivation	50	March 2012
Sawdust medium for mushroom cultivation	200	March 2012
Firewood (for cooking)	40	November 2011
Charcoal (for cooking) (for soil conditioner, 400 Bq/kg)	280	November 2011
Wood pellets (white pellets, whole-tree pellets) (for bark pellets, 300 Bq/kg)	40	November 2012
Bark compost and livestock bedding	400	August 2011

Source: Data from the Forestry Agency, “The Current Status of Radioactive Substances in Forests and Regeneration of Forests and Forestry 2018 Edition” [126]; The Forestry Agency, “Establishment of Index Values for Mushroom Logs and Cultivars, and Firewood and Charcoal for Cooking and Heating. In: Sectoral Information” [129]; Ministry of Agriculture, Forestry and Fisheries, “Provisional Permissible Values for Fertilizers, Soil Conditioning Materials, Culture Soil and Feed Containing Radiocesium” [131]

that will not exceed 100 Bq/kg, which is within the range of variation of past radiocesium concentrations in farmland soil, even after 40 years of continuous application [131]. Although there is no index value for wood chips, business or public entities that handle chips as fuel often set the acceptance criterion at 40 Bq/kg in accordance with the index for firewood. On the other hand, in the case of chips used for paper manufacturing, many companies set the index value at 400 Bq/kg, the same as for compost and bedding. In this way, the index values for the use of wood and its by-products are based on the respective exposure dose estimates, and different values are set depending on the subject. If the regulations for use are adhered to, it will be possible to reduce the additional exposure of users.

6.2.2 The Impact on Forestry from Statistics

In this way, as a countermeasure to the radioactive contamination of the forests caused by the Fukushima nuclear accident, access to the forests and the use of timber were restricted. Let’s take a look at the impact that the forestry has suffered as a result through statistics. When looking at the impact of the accident on the industry, it is necessary not only to look at the changes before and after the accident, but also to compare them with changes in the rest of the country, and to examine whether the changes are a common phenomenon across the country or a unique phenomenon that occurred in the prefectures affected by the disaster (or for other reasons). The following is a list of changes that were observed before and after the accident.

First of all, looking at material production of logs (harvest volume of logs), the supply of domestic timber had originally been on a downward trend as foreign imports had been increased, but the national average bottomed out in 2002 and has

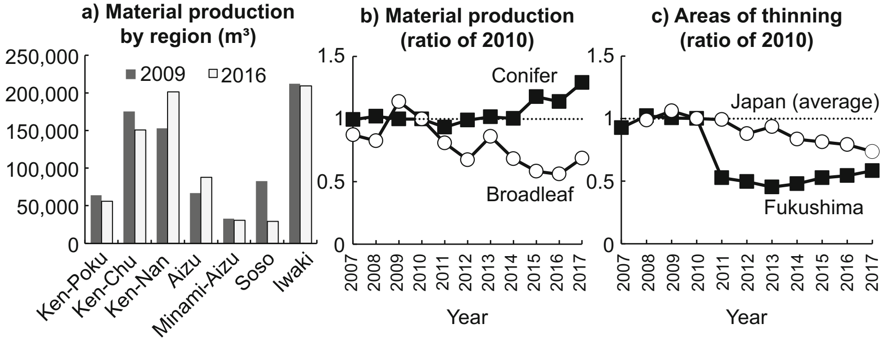


Fig. 6.11 Impacts on production of logs (harvest volume of logs) and the area of thinning in Fukushima Prefecture. (**a**): Comparison of production of logs by region in Fukushima Prefecture between 2009 and 2016. Ken-Poku, Ken-Chu, and Ken-Nan are the north-central, central, and south-central areas of Fukushima Prefecture, respectively. Aizu and Minami-Aizu are the north-west and south-west areas, respectively. Soso is a coastal area around the Fukushima Daiichi Nuclear Power Plant. Iwaki is a south coastal area in Fukushima. (**b**): Change in material production in Fukushima Prefecture compared to 2010 for coniferous and broadleaf trees. (**c**): Changes in the area of thinning for the whole country and Fukushima Prefecture compared to 2010 (Source: Data from Agriculture, Forestry and Fisheries Department, Fukushima Prefecture, “Fukushima Prefecture Forest and Forestry Statistics FY2018” [7]; The Forestry Agency, Forest and Forestry Statistics Handbook 2019, “Actual Thinning and Utilization of Thinned Wood” [132])

been on an upward trend even after the accident. On the other hand, production of logs in Fukushima Prefecture declined after the accident and has been recovering, but the recovery has been slow, and the ratio of 2015 to 2010 is 104%, lower than the national average (117%) and results of neighboring prefectures (114–121%) [118]. Looking at the demand and production of logs in the prefecture by region in Fukushima Prefecture, a significant change was observed. Both supply and demand declined significantly in the Soso region (a coastal area consisting of 12 cities and towns located around the Fukushima Daiichi Nuclear Power Plant, including Soma City and Futaba Town), while demand increased in central region extending from north to south and Iwaki (south coastal) region, and supply increased in Ken-Nan (southern-central) and Aizu (north-west) region (Fig. 6.11a). As a result, demand exceeded supply in the prefecture as a whole [118]. The Soso region includes many municipalities that have been designated as difficult-to-return areas, such as Futaba Town and Okuma Town, where the Fukushima Daiichi Nuclear Power Plant is located. It is expected that the industries in these areas will be depressed in a wide range from before the accident. It is thought that the restriction due to the high air dose rates have reduced forestry activities, leading to a decline in the production of logs.

In addition, hardwood (broadleaf) production declined while softwood (conifer) production increased in Fukushima Prefecture, and the balance of supply between hardwood and softwood has changed significantly (Fig. 6.11b). The decline in hardwood can be attributed to lower production of fuel chips and logs for mushroom cultivation. The radiocesium contamination of hardwood for bed-log cultivation is a major problem not only in Fukushima Prefecture but also in neighboring prefectures. The details will be described in Sect. 6.5.

Looking at the area of forest maintenance in Fukushima Prefecture, it has been reduced by half compared to the area before the accident [125] (Fig. 6.11c). The purpose of forest maintenance is to bring out the various functions of forests through activities such as planting, clearing, thinning, and maintenance of forest roads. In the short term, it is difficult to see the effects of stagnation in forest maintenance, but in the long term, there is concern that forest functions will be degraded, resulting in a decline in the quality of wood and carbon sequestration capacity, as well as an increase in the risk of disasters during heavy rainfall (e.g. landslides), and other effects on the multiple functions of forests.

6.2.3 Utilization of Contaminated Forests

Some experimental ideas have been tested on how to resume the use of forests that had stopped due to high levels of radiocesium. However, except for the common method of treating combustible waste, which is to burn it, reduce its volume, and store it in a storage facility, there is no practical method that has been implemented on a large scale at this point.

Volume Reduction of Contaminated Wastes

The highly concentrated radioactive byproducts (unused parts) of logging in contaminated areas and the organic matter yield from forest decontamination have turned into waste. The waste shall be transported and stored to a storage facility, which is costly, so the volume needs to be reduced for efficiency. In forests, the use of wood crushers to reduce the volume of waste was considered. The volume reduction rate using wood crushers has been reported to be 45–63%. To further reduce the volume of combustible wastes including fallen leaves and branches from decontamination, a temporary incineration facility was built in Fukushima Prefecture. Tests with the high-temperature incineration facility showed that the volume reduction rate was very high (96–99%) and that the transfer of radiocesium to the exhaust air was very low (up to 0.3 Bq/m^3, test in Okuma Town) [133]. However, since radiocesium concentrates in combustion ash at high concentrations (up to two million Bq/kg in Okuma Town), special attention is required for subsequent management.

Conversion to Energy Use and to Other Uses

Instead of using wood from contaminated areas for construction or for mushroom cultivation, it can be used as biofuel (e.g. pellets) for biomass power generation. The index value for fuel wood and pellets is set at 40 Bq/kg, which is stricter than 50 Bq/kg for mushroom logs (Table 6.2). However, the radiocesium concentration in tree trunks is highest in the bark (Sect. 3.3), and if the bark is removed to make chips, the radiocesium concentration in the chips can be lowered, so there are cases where materials that cannot be used as logs can be used as chips. However, it is necessary to take measures to ensure that the combustion ash does not exceed the criterion of 8000 Bq/kg for designated waste, and to be careful about the release of radiocesium into the environment during combustion, since cesium has the property of vaporizing at high temperatures. On the other hand, volume reduction while utilizing energy from bark and wood containing radiocesium can be considered as an option by using biomass power generation facilities on the premise that the combustion ash will become designated waste. However, as mentioned in the section on volume reduction, it is necessary to take appropriate measures for exhausting radiocesium, and to fully explain to local residents and obtain their understanding when implementing such measures.

For other uses, Otsuka et al. [134] developed a technology for methane fermentation of woody biomass, which had been technically difficult. It was found that methane gas does not contain radiocesium and most of it remains in the fermentation residue. Since this technology has two advantages: energy production from wood and volume reduction of contaminated biomass, it is expected to be utilized in contaminated areas (Fig. 6.12).

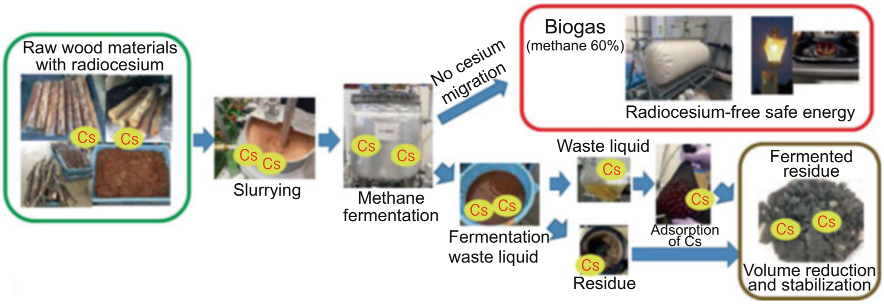


Fig. 6.12 Technology to produce radiocesium-free biogas from trees containing radiocesium (Source: Reprinted from Otsuka et al. 2018 [134], courtesy of Yuichiro Otsuka, the Forestry and Forest Products Research Institute)

6.3 Radioactive Contamination of Wildlife

Radiocesium levels in large wildlife are high in a wide area, complicating the problem of recent population growth.

Large wildlife such as wild boar, bear, and deer are deeply involved in the lives of people in mountain villages (Fig. 6.13). They are harmful animals that appear in the living area and cause damage to fields and residents. On the other hand, such wild animals and birds are hunted as game animals and their meat is consumed as "gibier (game meat)". The radiocesium concentration in the muscles of large wildlife

Fig. 6.13 A wild boar (upper left), an Asian black bear (upper right), and a sika deer (bottom) taken by camera traps (Courtesy of Hayato Iijima, the Forestry and Forest Products Research Institute)

Table 6.3 Prefectures where restrictions on shipping of meat from wild animals have been imposed (as of November 16, 2020)

Species	Number of prefectures	Prefectures
Wild boar (*Sus scrofa*)	6	Fukushima[a], Miyagi, Ibaraki[b], Tochigi[b], Gunma, Chiba[b]
Asian black bear (*Ursus thibetanus*)	6	Fukushima, Iwate, Miyagi, Yamagata[b], Gunma, Niigata[b]
Sika deer (*Cervus nippon*)	5	Iwate[b], Miyagi[b], Tochigi, Gunma, Nagano[b]
Japanese hare (*Lepus brachyurus*)	1	Fukushima
Spot-billed duck (*Anas zonorhyncha*)	1	Fukushima
Green pheasant (*Phasianus versicolor*)	1	Fukushima
Copper pheasant (*Syrmaticus soemmerringii*)	2	Fukushima, Iwate

Depending on the species and prefecture, the restriction is not imposed to the entire prefecture

Source: Data from Ministry of Health, Labour and Welfare, Restriction of Distribution and/or Consumption of Contaminated Food, “Shipment Restrictions on Foods Based on the Act on Special Measures Concerning Nuclear Emergency Preparedness: As of November 16, 2020” [135]

[a] Consumption of wild boar in Fukushima Prefecture is restricted in 20 municipalities, where self consumption is also prohibited

[b] Excluding meat of which quality (concentration) is controlled in accordance with the policies of shipping of the prefecture

has been high since the accident. Based on the results of inspections, restrictions on shipping and intake have been imposed in a wide area. In 2020, a total of 10 prefectures have set restrictions on shipping of the three large wildlife species mentioned above. In addition, 20 municipalities in Fukushima Prefecture have imposed intake restrictions of wild boars (Table 6.3). However, some prefectures and municipalities have taken measures to “partially lift” the restrictions, allowing shipments after establishing safety confirmation schemes such as testing all animals slaughtered (all wild meat taken in the region is inspected before shipping).

6.3.1 Large Wildlife Populations Are Increasing Across the Country

These shipping restrictions have brought new problems in wildlife management. The distribution of large mammals such as wild boar and deer in Japan has been declining since the Edo period (1603–1868) due to habitat changes caused by hunting and land development [136]. However, since the latter half of the twentieth century, the distribution range of large wildlife has expanded rapidly and their populations

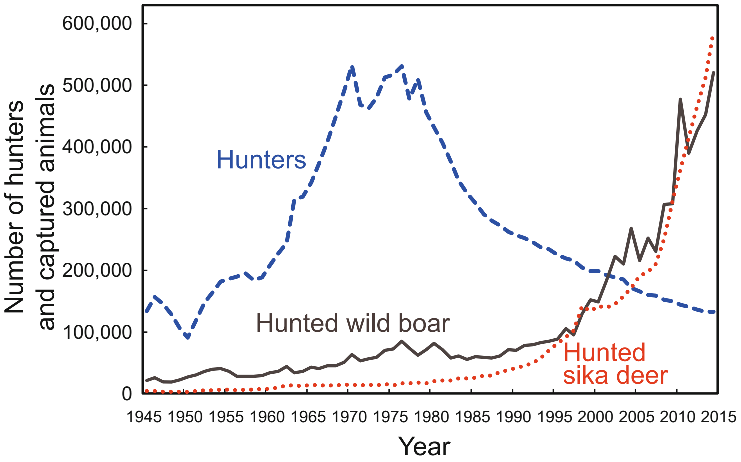


Fig. 6.14 Trends in the number of registered hunters and the number of wild boars and deer hunted nationwide. The number of hunted animals has increased since 2000, because the Japanese government has strengthened measures to control the wildlife population (Source: Data from Ministry of the Environment, "Statistics on Birds and Animals" [139])

have increased (Fig. 6.14). The increase in the population is thought to be influenced by various factors such as conservation policies of the wildlife, the extinction of wolves as predators, the decrease in the number of hunters due to aging, the increase in abandoned land due to the depopulation of mountain villages, and warmer winters due to global warming [137]. In particular, in the Abukuma Highlands (between Hamadori and Nakadori) near the Fukushima nuclear power plant, there are no deer and the distribution of bears is limited, but wild boars have established themselves over a wide area, and crop damage has become a problem. In eastern Japan, the Fukushima nuclear accident led to a decline in willingness to hunt contaminated wildlife and a decrease in the population leading to an increase in abandoned land, resulting in a marked increase in the number of wildlife [138]. In a questionnaire survey of hunters, the number of people who stopped hunting is significantly higher in Hamadori and Nakadori (Eastern coastal and central areas of Fukushima Prefecture, respectively) than in other areas, indicating that radioactive contamination has a strong effect on the lowering of the motivation of hunters [140].

6.3.2 Trend of Radiocesium Concentration

The trend of the radiocesium concentration in wildlife since the accident is important to know for assessing the human internal exposure due to ingestion and to consider the future prospects of shipment restrictions. Therefore, the radiocesium concentration in the muscles of hunted wildlife is continuously being monitored through

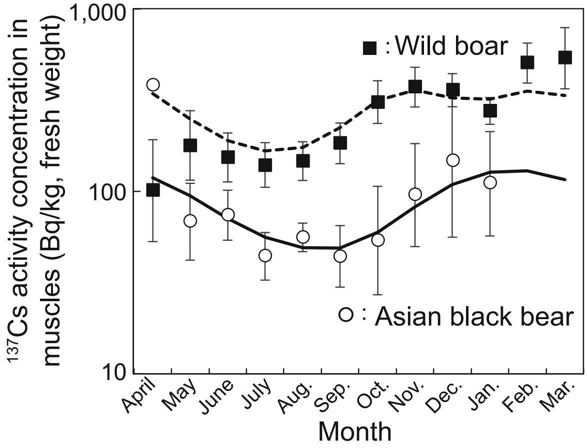


Fig. 6.15 Seasonal changes in activity concentration of cesium-137 (per fresh weight) in muscles of wild boars (■) and black bears (○) hunted in Fukushima Prefecture. Values are shown in logarithmic graphs. The concentration differs tenfold for each tick, and the lines indicate the trend of seasonal changes estimated by the model. (Source: Adapted from Nemoto, et al. 2018 [142])

hunting and capturing for inspections. Wild animals are sampled in different locations at different times of the year, and the higher the amount of radiocesium in their habitat, the higher the radiocesium concentration in the muscle. Therefore, instead of simply comparing the radiocesium concentration in muscles, it is effective to compare the radiocesium concentration with the aggregated transfer factor (unit: m^2/kg) (Fig. 3.9), which is calculated by dividing the radiocesium concentration by the amount of radiocesium accumulated in the soil at the capture point (amount of radiocesium per unit area, unit: Bq/m^2). As a result of the comparison, it was shown that the radiocesium concentration in wild boars and black bears in Fukushima Prefecture tended to decrease with the passage of years [141]. On the other hand, clear temporal trend in radiocesium concentration in Japanese deer has not been observed in the data up to 2015.

Seasonal variation of radiocesium concentrations in wildlife has also been studied. In Europe, after the Chernobyl nuclear accident, there have been many publications on seasonal variations in the radiocesium concentration in wildlife. A study of wild boars and black bears in Fukushima Prefecture also revealed seasonal variations in the radiocesium concentration in muscle meat. As shown in Fig. 6.15, the radiocesium concentration in both wild boars and black bears was lower in spring and summer, and higher in autumn and winter [142]. According to European studies, the radiocesium concentration in wild boars is revealed to be higher in summer and lower in winter, and it is said that the fact that they eat a lot of high-concentration mushrooms called “deer truffles” (*Elaphomyces granulatus*) in summer has an effect on the seasonal increase in concentration [143]. On the other hand, Japanese wild boars are believed to be omnivores, and there are no reports of them foraging for mushrooms. In addition, wild boars feed mainly on plant underground stems during the winter [144], and it is thought that they take in high concentrations of surface soil with them, but the detailed mechanism is not clear.

6.3.3 Countermeasures: Testing All Animals Slaughtered and Population Control

The increase in the population of wildlife caused by the complex factors as mentioned above has been accelerated by radioactive contamination in eastern Japan. Now the complexity of wildlife issues becomes very difficult to take countermeasures. To reduce wildlife damage to crops and forests, we must not only control the population by hunting, but also develop different measures according to the degree of contamination in the area, as the number of hunters is decreasing.

After the Fukushima nuclear accident, restrictions on the shipping meat of wildlife have been extensively imposed in a wide area of eastern Japan, Fukushima and surrounding prefectures (Table 6.3). However, the level of contamination decreases as the distance from the nuclear power plant increases. Furthermore, depending on the species, it is expected that the radiocesium concentration will decrease over time, and the percentage of wild meat with radiocesium concentration lower than the standard limit for food will increase. Therefore, in areas where meat of wildlife were originally used for food, there was a movement to ensure safety by conducting inspections of all slaughtered individuals and preventing the shipping of meat that exceeded the standard limit. In fact, wild boar meat processing facilities in Nakagawa Town, Tochigi Prefecture, and Ishioka City, Ibaraki Prefecture, have adopted a system to test the radiocesium concentration in specific parts (e.g. thigh meat) of all slaughtered animals and ship wild boar meat only if it is below the standard limit [145].

On the other hand, in areas where forests are highly contaminated and the consumption of wildlife is restricted, the meats of most large wildlife may exceed the standard limit of 100 Bq/kg, making it difficult to use them for food. Therefore, to control damage by wildlife, it is necessary to manage the population through active extermination with the premise of disposal. For example, in Fukushima Prefecture, a management plan has been implemented to adjust the wild boar population from an estimated 49,000 in 2014 to 5200, taking into account the balance between maintaining the population and reducing agricultural damage caused by the wildlife [138]. If active disposal is to be undertaken, the method of disposal also needs to be considered. At present, in many cases, the bodies are buried where they were captured, and some are disposed of in existing incinerators. Therefore, the burden on hunters and local residents should be considered. Under these circumstances, there is a movement to develop special incinerators or biological treatment facilities using microorganisms with the help of subsidies [146].

6.4 Radiocesium Contamination of Wild Mushrooms and Wild Plants

The impact on leisure activities in the forest was probably greater than the impact on the forestry.

6.4.1 *The Value of the Forests' Bounty to Local Communities*

One of the blessings of the forest is edible wild mushrooms. Most of the mushrooms that we see in grocery stores are grown on medium in factories or cultivated in villages using logs cut from the forests (these are called cultivated mushrooms and will be discussed in Sect. 6.5). Wild mushrooms differ from such artificially cultivated mushrooms in that they are found growing wild in the forest. In Japan, there is a culture of collecting and eating a variety of wild mushrooms. One of the most common mushroom species in Japan is matsutake (*Tricholoma matsutake*), which cannot be cultivated artificially. Wild mushrooms have a different flavor from factory-grown mushrooms, and the fun of searching for mushrooms in forests has led to widespread mushroom hunting in the mountainous areas.

Another great blessing of the forest is edible wild plants, which are called "Sansai" in Japanese. It is difficult to clearly define what wild plants are and how they differ from vegetables. The Japan Special Forest Products Promotion Association [147] defines wild plants as edible plants that grow naturally in the forests and fields of Japan and have been eaten for a long time. In general, the vegetables differ from wild plants in that they have been bred for cultivation over a long period of time. However, in recent years, some of the wild plants, such as water dropwort (*Oenanthe javanica*), Japanese honeywort (*Cryptotaenia canadensis* subsp. *japonica*), Japanese butterbur (*Petasites japonicus*), Japanese spikenard (*Aralia cordata*), and taranome (*Aralia elata*), have been developed for forcing cultivation. Although the boundary between wild plants and cultivated vegetables is not clear, most wild plants are not suitable for mass production. In addition, Saito [148, 149] mention that the characteristics of wild plants are that different species and parts are used (or recognized) in each region, that many of them have a unique taste and bitterness, that they require a lot of work to be eaten, such as removing harshness, and that many of them have few calories and are not used for "subsistence".

Wild mushrooms and wild plants with these characteristics are treated as valuable foodstuffs that enrich the lives of mountain village communities (Fig. 6.16). Not only are they used as seasonal ingredients, but they are also processed as preserved foods and used as offerings for special occasions (called "hare" in Japanese) such as Bon Festival (a Japanese Buddhist custom in August) and New Year's Day.

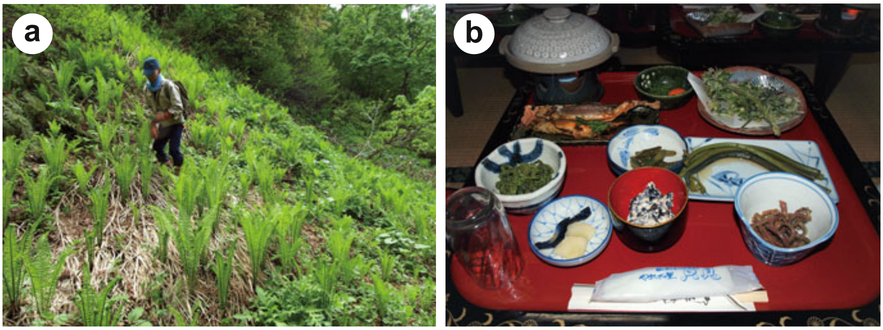


Fig. 6.16 Collecting wild plants (Ostrich ferns, *Matteuccia struthiopteris*) (**a**) and cuisine using wild plants (**b**) (Courtesy of Toshiya Matsuura, the Forestry and Forest Products Research Institute)

Mushrooms and wild plants also serve as a communication tool for the community. Collecting wild mushrooms and plants is also a popular leisure activity for local residents. It is difficult to evaluate the economic value of the collected wild mushrooms and wild plants since they are usually consumed at home. However, Matsuura et al. [150] estimated the economic value of wild mushrooms and plants collected annually in a town of Fukushima Prefecture before the accident to be in the tens of millions of yen (hundreds of thousands of US dollars). It has been shown that the activity of collecting these wild forest foods is more frequent in an area with more days of snowfall [151]. Therefore, wild mushrooms and wild plants have been familiar in the deep snow areas of Fukushima Prefecture. The radioactive contamination of forests caused by the Fukushima nuclear accident may reduce people's motivation to collect them regardless of whether the bounty of the forest is restricted or not and consequently degrade the vitality of the inhabitants in the mountainous areas.

6.4.2 *Radioactive Contamination of Wild Mushrooms*

Since the Fukushima nuclear accident, wild mushrooms and wild plants have been subject to shipping restrictions in a wide area. For example, looking at the test results for agricultural products, most of the foods that exceed the standard limit of 100 Bq/kg are wild plants in spring and wild mushrooms in autumn (92% of foods exceeded, data since 2014) (Fig. 6.17). The reason for the high radiocesium concentration in wild mushrooms and plants can be attributed to the fact that radiocesium accumulate in the forest due to the low flowing rate of radiocesium flowing out of the forest ecosystem and the lack of decontamination of the forest, and the fact that wild mushrooms and plants are high in minerals and have the ability to absorb radiocesium efficiently. The circulated quantity of wild food obtained from forests

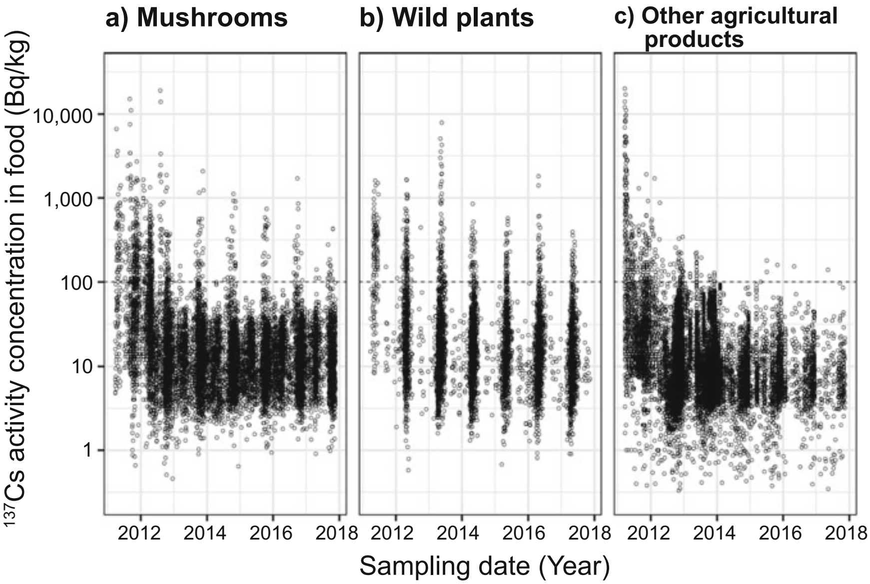


Fig. 6.17 Results of cesium-137 activity concentrations in agricultural products obtained from food monitoring conducted by local municipalities and compiled by the Ministry of Health, Labour and Welfare. The results are separately plotted for (**a**) mushrooms, (**b**) wild plant, and (**c**) other agricultural products. In 2011, when the accident occurred, food exceeding the standard limit of 100 Bq/kg were observed regardless of the type, but, after that, many cases of wild mushrooms and wild plants exceeding the standard limit in spring and autumn were reported (Source: Data from Ministry of Health, Labour and Welfare, Information on the Great East Japan Earthquake, "Levels of Radioactive Materials in Foods Tested in Respective Prefectures" [152])

is much smaller than that of cultivated food, so the economic impact of shipping restrictions is considered to be relatively small. However, the role played by the blessings of the forest in mountain villages is not small. Clarifying the levels of radiocesium in wild mushrooms and wild plants is important for people to live in the areas affected by the accident.

Species-Independent Batch Restrictions of Shipping

As a result of inspection after the Fukushima nuclear accident, wild mushrooms were found to often exceed the standard limit in a wide area of the eastern Japan, and as of November 2020, 117 municipalities in 11 prefectures have imposed shipping restrictions (including 15 municipalities in 3 prefectures where restrictions were lifted for some species) (Fig. 6.18). It is also said that there are 4000–5000 species of wild mushrooms, and hence it is difficult to identify the species and the concentration characteristics of each species, unlike other agricultural crops. Therefore,

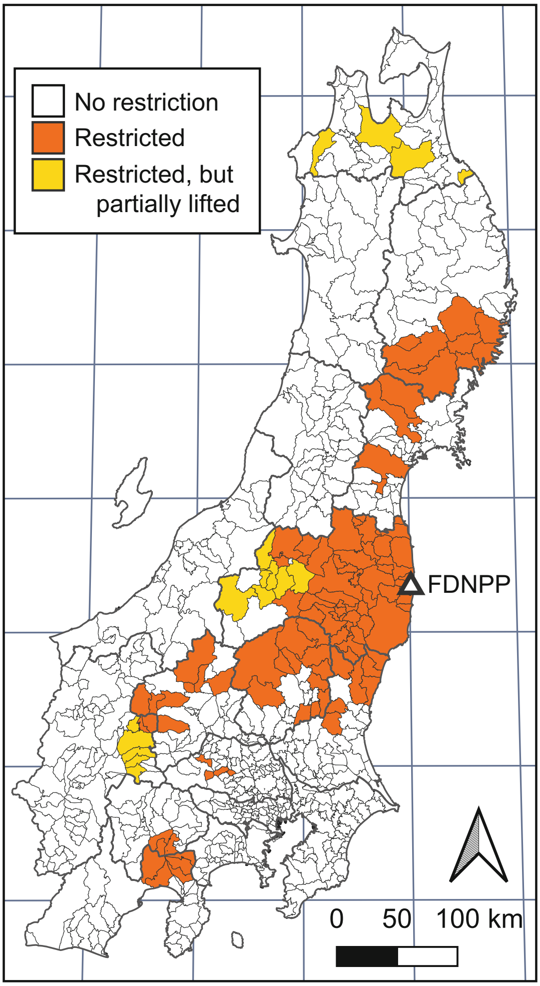


Fig. 6.18 Distribution of wild mushroom shipping restrictions, as of November 16, 2020 (Source: Data from the Forestry Agency, "Status of Shipment Restrictions on Mushrooms and Wild Plants" [153])

shipping restrictions are implemented for all wild mushroom species in a lump, not for individual species.

Analysis of Wild Mushrooms Using the Results of Food Monitoring

As a result of compiling research on wild mushrooms conducted mainly in Europe after the Chernobyl nuclear accident, it was found that the trends of radiocesium concentration differed by species and genus. If the characteristics of radiocesium concentration in wild mushrooms in Japan can be classified according to species, it will be helpful in reviewing shipping restrictions and helping local people make decisions of collecting wild mushrooms. However, it is not easy to continuously

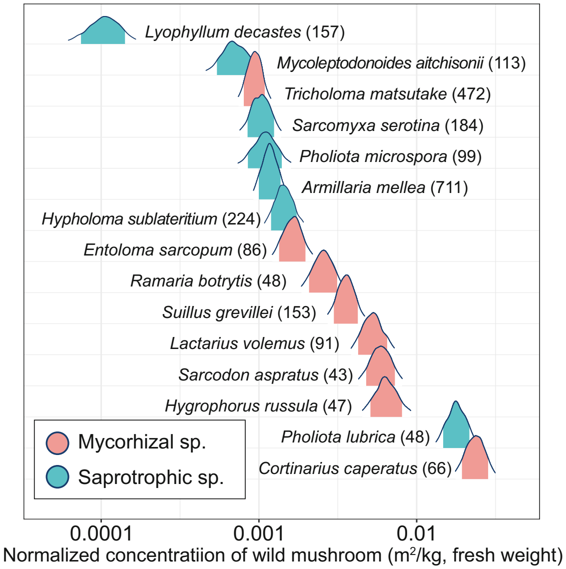


Fig. 6.19 Normalized concentration of radiocesium in wild mushrooms with more than 40 samples collected. Results are shown as probability distributions, where a higher mountain position indicates a higher probability prediction. Numbers in parentheses indicate the number of samples (Source: Data from Komatsu et al. [154])

sample specific species, because the amount, timing, and location of their occurrence are not stable from year to year. In addition, to study the trend of radiocesium in wild mushrooms in Japan as a whole, it is necessary to collect data from multiple locations, which limits the ability of researchers to conduct surveys alone.

Therefore, Komatsu et al. [154] focused on the data of radiation monitoring of foods by the government. The Ministry of Health, Labour and Welfare (MHLW) of Japan compiles and posts the results on its website [152]. From the data reported from August 2011 to November 2017, measurement data of 3189 edible wild mushroom specimens of 107 species were obtained from 246 municipalities. In addition, the radiocesium concentration of mushrooms is considered to be affected by the contamination level at the point of occurrence. Therefore, Komatsu et al. analyzed the total amount (including both in soils and in plants) of radiocesium deposition per unit area (Bq/m^2) by airborne monitoring as an indicator of the contamination level, and the concentration characteristics of each species and region were analyzed.

Komatsu et al.'s analysis assumes that the radiocesium concentration varies depending on the species, municipality, and date of collection. Furthermore, there are variations (errors) in concentration that cannot be explained by these conditions. The concentration characteristics of each species were expressed in terms of a numerical value called "normalized concentration". The results are summarized in Fig. 6.19. In this figure, two types of fungi are shown: mycorrhizal fungi, which live in symbiosis with trees, and saprotrophic fungi, which obtain nutrients by decomposing dead wood and leaves.

The Radiocesium Concentration in Wild Mushrooms Varies Greatly Among Species

Comparing the concentration characteristics, there was a general trend for mycorrhizal fungi to have higher radiocesium concentrations than saprotrophic fungi, but this varied greatly depending on the species. Some saprotrophic fungi such as a scalycap mushroom (*Pholiota lubrica*) also had higher concentrations. In fact, the scalycap mushroom is a species of which radiocesium concentrations exceeded the standard limit in areas even far from the Fukushima Daiichi Nuclear Power Plant such as Nagano Prefecture (250 km from the power plant). It is thought that the physiological and ecological characteristics of mushroom species would decide the radiocesium concentration, but the mechanism is not clear at this stage.

Results indicating that the radiocesium concentrations in wild mushrooms would be different according to species, are helpful in considering the framework of shipping restrictions of wild mushroom, which are currently implemented in a species-independent manner. However, some caution should be exercised in interpreting the results. There are three points to be aware of: (1) there are still large uncertainties (variations) in the prediction of radiocesium concentration in wild mushrooms, (2) the trend of annual changes is not fully understood, and (3) there are also variations in the radiocesium concentration in mushrooms collected in the same municipality. It is necessary to conduct more detailed surveys in the future to clarify the effects of species and regions on radiocesium concentration and its temporal trends.

6.4.3 Radioactive Contamination of Wild Plants

Differences in Restricted Areas of Shipping by Species and Growing Conditions

Table 6.4 shows the number of municipalities with shipping restrictions for each type of wild plants (as of November 16, 2020). Although wild plants used to be obtained from natural conditions such as forests and fields, in recent years some species have been cultivated. Therefore, the shipping restrictions of wild plants are differently imposed according to their growth conditions as well as species. In other words, it would be imposed only for naturally grown products or for both natural and cultivated products. The number of restricted municipalities that do not distinguish between natural and cultivated products indicates the spread of restrictions on shipping of cultivated products, while the sum number of municipalities ("Sum" columns in Table 6.4) indicates the spread of restrictions on naturally grown products. For Japanese spikenard (*Aralia cordata*), taranome (*Aralia elata*), Japanese butterbur (*Petasites japonicus)*, etc., which are being promoted for cultivation (forcing cultivation), there are almost no shipping restrictions when their growth conditions are not distinguished. On the other hand, shipping restrictions are more

Table 6.4 Number of municipalities implementing shipping restrictions for each species of wild plants

Species	Naturally grown products	All products without distinction between naturally grown or cultivated	Sum
Japanese spikenard (*Aralia cordata*)	6	0	6
Uwabamisou (*Elatostema umbellatum*)	2	0	2
Ostrich fern (*Matteuccia struthiopteris)*	4	15	19
Koshiabura (*Eleutherococcus sciadophylloides*)	43	70	113
Japanese pepper (*Zanthoxylum piperitum*)	4	0	4
Asian royal fern (*Osmunda japonica*)	9	13	22
Bamboo shoots (*Phyllostachys heterocycla, P. bambusoides, P. nigra* var. *henonis*)	–	33	33
Taranome (*Aralia elata*)	44	0	44
Japanese butterbur (leaf stalk, *Petasites japonicus*)	3	1	4
Japanese butterbur (scape, *Petasites japonicus*)	11	0	11
Western bracken fern (*Pteridium aquilinum*)	17	6	23
Wild mushrooms (for reference)	117		
Shiitake mushrooms with bed-log cultivation (for reference)	93[*1]	17[*2]	

[*1] Outside cultivation (56 of them, partially lifted)

[*2] Indoor cultivation (16 of them, partially lifted)

Source: Data from Ministry of Health, Labour and Welfare, Restriction of Distribution and/or Consumption of Contaminated Food, “Shipment Restrictions on Foods Based on the Act on Special Measures Concerning Nuclear Emergency Preparedness: As of November 16, 2020” [135]

frequently imposed on naturally grown products, indicating that the wild plants growing in the natural conditions are likely to have higher concentration than the cultivated products. Also, the number of municipalities with shipping restrictions varies greatly by species. When results for naturally grown products are included, the shipping of koshiabura (*Eleutherococcus sciadophylloides*) has been most extensively restricted (113 municipalities in total), about the same as for wild mushrooms (117 municipalities).

The number of municipalities with shipping restrictions is 44 on wild taranome, second only to koshiabura. Bamboo shoots were originally introduced from China and are not strictly considered as naturally grown wild plants, but are widely restricted in shipping.

Why Is the Concentration in Koshiabura so High?

Wild plants are eaten in various parts, such as leaves, shoots, roots, etc., and surveys have revealed that the radiocesium concentration in wild plants varies depending on not only the species, but also the part of the plant even within the same species [155]. Among wild plants, it has been found that the radiocesium concentration is high in koshiabura and yamadori-zenmai (*Osmundastrum cinnamomeum* var. *fokeiense*), and low in katakuri (*Erythronium japonicum*) and Japanese red elder (*Sambucus racemosa* subsp. *sieboldiana*), while taranome, royal fern (*Osmunda japonica*), and ostrich fern (*Matteuccia struthiopteris*) are in the middle. These results also correspond to the high/low number of municipalities that have implemented shipping restrictions for each species (Table 6.4).

Among the wild plants, the concentration of koshiabra is noticeably high. It is a tall tree of the Araliaceae family with five leaves spreading out like a palm from a single bud. The young shoots just about to open like those of the taranome are plucked, and it is commonly eaten as a tempura or boiled dish. A study of the relationship between radiocesium concentrations in the leaves, soil, and organic layer of koshiabra, showed that radiocesium concentrations in the leaves of koshiabra are more strongly correlated with radiocesium concentrations in the organic layer than in the soil [156]. It may be that koshiabura is capable of efficiently absorbing radiocesium from the organic layer and the surface layer of mineral soil, where radiocesium concentration is high. The role of microorganisms living symbiotically in the roots of koshiabra has also been investigated as a reason for the high radiocesium concentration [157]. Measurements of samples collected in 2017 also indicate that radiocesium concentrations in koshiabura leaves may increase further [156]. There is a concern that the radiocesium concentration in koshiabra may increase and exceed the criterion even in areas with low radiocesium deposition, and caution should be exercised.

6.4.4 Impact on Leisure Activities of Local Inhabitants

We explained that forests are not only a place for timber production, but also provide forest blessings such as wild mushrooms and wild plants. In addition, forests are also used for other activities such as fishing in mountain streams and mountain climbing. In this way, the forest has been used as a place for various leisure activities (recreation) by local people. However, comparing the data obtained from surveys and the number of users before and after the Fukushima nuclear accident, it became clear that recreational activities using natural reserves such as forests were definitely affected by the accident. For example, a survey revealed that the number of people participating in nature-based recreational activities (number of tourist arrivals) and the number of mountain climbers in Fukushima Prefecture dropped significantly in 2011, the year of the accident, and have not returned to normal since 2012 until at

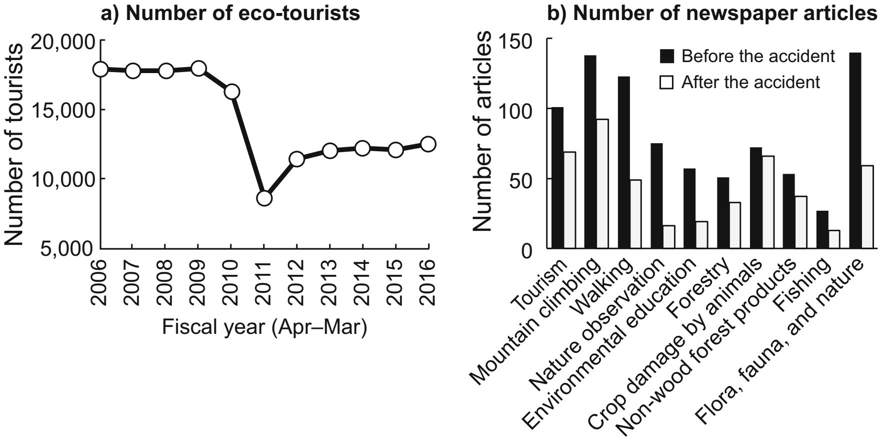
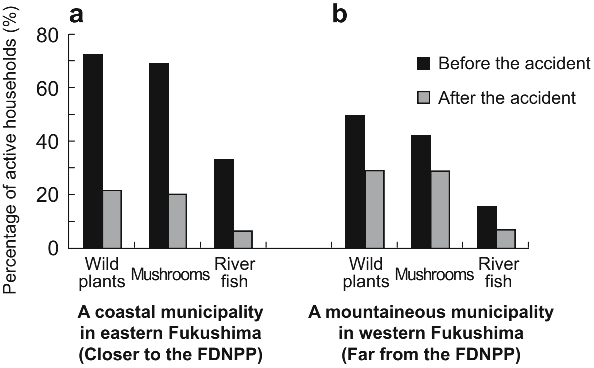


Fig. 6.20 Impacts on outdoor recreational activities. (**a**) Number of tourist arrivals for nature experience-type activities in Fukushima Prefecture, (**b**) comparison of the number of newspaper articles in Fukushima Prefecture for 3 years before and after the accident (Source: Adapted from Shigematsu et al. [158], courtesy of Yuki Shigematsu, Nagasaki University)

least 2016 (Fig. 6.20a). In the case of mountain climbers in particular, the decline was stronger in the Abukuma Highlands (between Hamadori and Nakadori), which is closer to the nuclear power plant and has a higher level of contamination than the Ou mountain range (between Nakadori and Aizu). The number of urban tourist arrivals also showed a similar downward trend, indicating that the Fukushima nuclear accident has affected various recreational activities, both nature-based and non-nature-based. Furthermore, a survey of the number of newspaper articles in Fukushima Prefecture shows that the number of articles related to outdoor activities such as nature and forests, including mountain climbing, forestry, and environmental education, has decreased since the accident (Fig. 6.20b). On the other hand, there was no change in the number of articles on crop damage caused by wildlife, suggesting that the trend of the damage by wildlife has not changed due to the accident.

The accumulation of radiocesium in wild plants, mushrooms, and mountain stream fish was confirmed in a wide area due to radioactive contamination of forests, and the motivation to collect these items in mountain village areas was greatly reduced. Figure 6.21 shows the changes in the percentage of households that collect wild plants and mushrooms, and go mountain stream fishing surveyed by a questionnaire of all households in two municipalities in Fukushima Prefecture in 2015; Hamadori, near the nuclear power plant, and Minami-Aizu, far from the nuclear power plant [159]. As can be seen here, these recreational activities were enjoyed by many people in the forest areas before the accident, but after the accident, there was a large decline especially in Hamadori, which is close to the nuclear power plant, and also even in Minami-Aizu, which is far from the nuclear power plant. This result

Fig. 6.21 Impact on leisure activities in forests in mountain villages before and after the nuclear accident. Interviews with residents in municipalities in Fukushima Prefecture; (**a**) A coastal municipality in eastern Fukushima (close to the FDNPP) and (**b**) a mountainous municipality in western Fukushima (far from the FDNPP) (Source: Adapted from Matsuura 2021 [159])



clearly shows that the people in the mountain (forest) areas of Fukushima have moved away from leisure activities in the forest. In addition to the aging of the population, which is common in mountain villages, the delay of return of residents to the areas around the Fukushima Daiichi Nuclear Power plant is also thought to affect the decline in outdoor leisure activities.

6.4.5 Reduction of Radiocesium Concentration in Wild Plants by Cooking

There are many ways to prepare different kinds of wild plants. For example, taranome and butterbur scapes are cooked as tempura (Japanese deep-fried dish), and a harshness of wild ferns such as royal ferns and bracken ferns is removed using baking soda. Also, since the harvesting period of wild plants is limited, drying and salting methods have been developed for long-term preservation. Therefore, Kiyono et al. [160] compared the effect of removing radiocesium from different cooking methods by the ratio of the amount of radiocesium contained in the wild plants before and after cooking (food processing residual coefficient). As a result, it was found that the amount of radiocesium in wild plants decreased compared to that before processing by the following treatments: soaking in hot water, boiling in salted water, removing the scum, and pickling in salted water (Table 6.5). In particular, the reduction in the amount of radiocesium was significant for royal ferns that had been treated with a combination of removing scum by baking soda and drying which is used for long-term preservation, and for wild plants that had been salted and removed after several months. On the other hand, the concentration per weight of tempura was apparently smaller due to the increased weight by tempura batter coating, but the residual rate of radiocesium was almost the same as before processing.

Table 6.5 Residual ratio of radiocesium in wild plants by species and cooking method

Cooking method	Wild plants	Residual ratio of radiocesium after processing (unitless)
Soaking in hot water	Japanese knotweed (*Fallopia japonica*)	0.08 ± 0.04
	Scape of Japanese butterbur (*Petasites japonicus*)	0.99 ± 0.09
	Momijigasa (*Parasenecio delphiniifolius)*	0.41 ± 0.14
Boiling with salt	Japanese spikenard (*Aralia cordata*)	0.56 ± 0.18
	Taranome (*Aralia elata*)	0.85 ± 0.22
	Koshiabura (*Eleutherococcus sciadophylloides*)	0.65 ± 0.004
	Western bracken fern (*Pteridium aquilinum*)	0.089
Removing scum with baking soda	Asian royal fern (*Osmunda japonica*)	0.32 ± 0.04
	Asian royal fern (dry)	0.009 ± 0.012
	Western bracken fern	0.017 ± 0.012
Salt pickling and removal	Asian royal fern Koshiabura	0.016 ± 0.015 0.041 ± 0.012
	Aleutian ragwort (*Senecio cannabifolius*)	0.24 ± 0.15
	Scape of Japanese butterbur	1.12 ± 0.19
Tempura	Taranome	0.83 ± 0.19
	Koshiabura	1.11 ± 0.02

Source: Data from Kiyono et al. [160]

Among the salted treatments, it was found that although the residual rate decreased in the case of Aleutian ragwort (*Senecio cannabifolius*, “Hangonso” in Japanese), the reduction effect was smaller than that of other wild plants. The same treatment may have different effects on different wild plants. In addition, Nabeshi et al. [161] reported that the reduction effect of baking soda was greater than that of flour or salt, even though they were used in the same process of removing scum. Even in areas with relatively high levels of radioactive contamination, it is possible to avoid ingesting radiocesium by understanding the differences in the concentration of different wild plants and devising cooking methods to increase the reduction effect.

6.5 Cultivated Mushroom

Radioactive contamination has halted the bed-log cultivation using local trees.

6.5.1 *Mushroom Cultivation Is an Important Industry Within Forestry in Japan*

Forest products produced from forests, excluding timber (lumber), are collectively called non-wood forest products. In addition to food products such as mushrooms, nuts, and wild plants, non-wood forest products include medicinal plants, materials for crafts such as lacquer, woody products for craft such as bamboo and paulownia wood, and fuel materials such as firewood and charcoal. In Japan, the non-wood forest products account for more than half (57%, 2.5 billion US dollars) of the total forestry production (4.4 billion US dollars, 2017), and cultivated mushrooms account for 80% of the output of non-wood forest products (2.1 billion US dollars) [162]. There are two methods of mushroom cultivation: bed-log cultivation (Figs. 6.22a and 6.23), in which spawns (the mycelium that grows into mushrooms, or in the case of logs, wooden plug spawns) are driven into logs cut from the forest, and sawdust medium cultivation (Fig. 6.22b), in which spawns are grown in an artificial medium made of sawdust mixed with rice bran and other nutrients. In Japan, bed-log cultivation of shiitake mushrooms (*Lentinula edodes*) spread in the

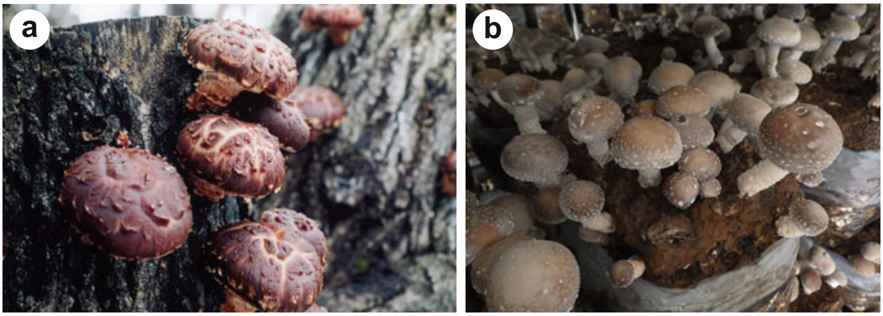


Fig. 6.22 Photographs of shiitake mushrooms grown by (**a**) bed-log cultivations and (**b**) sawdust medium cultivations (Source: Reprinted from IAEA, TECDOC-1927 [9], courtesy of Munehiko Iwaya, Japan Special Forest Products Promotion Association (**a**), and Hiromi Mukai, the Forestry and Forest Products Research Institute (**b**))

Fig. 6.23 Inoculation of shiitake mushroom to log woods. Workers drill holes in the logs with a drill at regular intervals to inject the plug spawns. The spots on the logs in the foreground are holes that have already been inoculated (Courtesy of Yoichi Ishikawa, Tochigi Forestry Center)

1930s. After that, the method of sawdust medium cultivation of various mushroom species developed in the 1980s and was replaced as the main mushroom cultivation method as companies have set up production systems in factories. Currently, bed-log cultivation is mostly for shiitake, and 76% of bed-log production for shiitake is dried shiitake (production on a fresh weight basis). While total mushroom production in Japan has remained flat over the years, the share of bed-log cultivation in production and the number of farmers have been on a downward trend, indicating a consolidation of mushroom production operations while effecting the elimination of small-scale mushroom farmers (Fig. 6.24). Given the heavy labor involved in bed-log cultivation, such as cutting and periodically rearranging the logs, the decline in the number of farmers can be attributed to the aging of farmers who are leaving the industry, as well as to the growing preference among consumers for mushrooms other than shiitake. Under such circumstances, the radioactive contamination caused by the Fukushima Nuclear Power Plant accident has had a significant impact on the cultivation of shiitake.

6.5.2 Contamination of Bed-Logs and Shiitake Mushrooms

After the accident, it was confirmed that fallen radiocesium had directly adhered to shiitake mushrooms cultivated outdoors, or that radiocesium adhered to incubated bed-logs transferred to shiitake mushrooms. As a result, the production and shipment

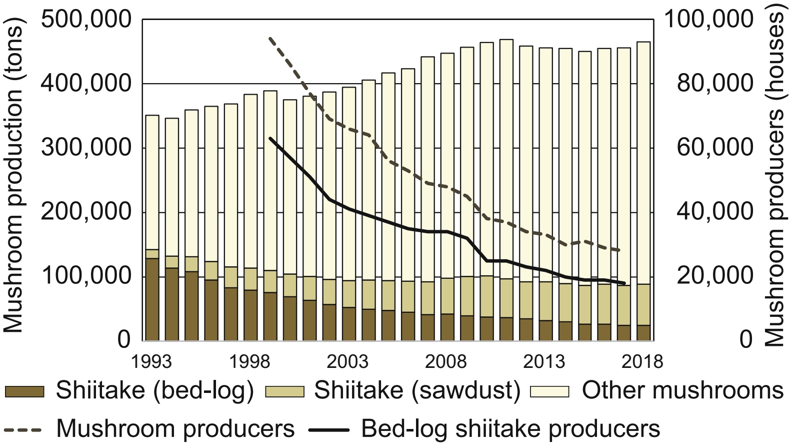
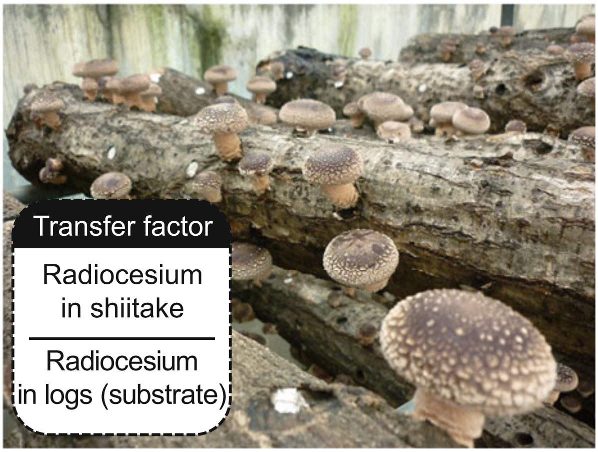


Fig. 6.24 Domestic production of mushrooms (left axis) and number of mushroom producers (right axis) (Source: Data from the Forestry Agency, Annual Report on Forest and Forestry in Japan, 2018 fiscal year, Part 1, Chap. 3, Section 2 "Trends of Special Forest Products (1) Trends of Mushrooms" [162])

Fig. 6.25 Conceptual diagram of the transfer coefficient (to determine the rate of transfer of radiocesium from bed-logs to shiitake mushrooms, the radiocesium concentration for each was measured and the concentration ratio was determined. As with the transfer coefficients for crops (see Fig. 3.9)



of shiitake mushrooms was restricted in a wide area. Using the transfer coefficient (Fig. 6.25), which is the ratio of the radiocesium concentration in the bed-logs and shiitake mushrooms, we can set the upper limit of radiocesium concentration in the logs that can be used without exceeding the standard limit for mushrooms by backward calculation. Therefore, a survey on the transfer coefficient was conducted in 2011 after the accident. The study showed that although it varied according to logs the maximum transfer coefficient was about 2 [163] (Fig. 6.26). Since the standard

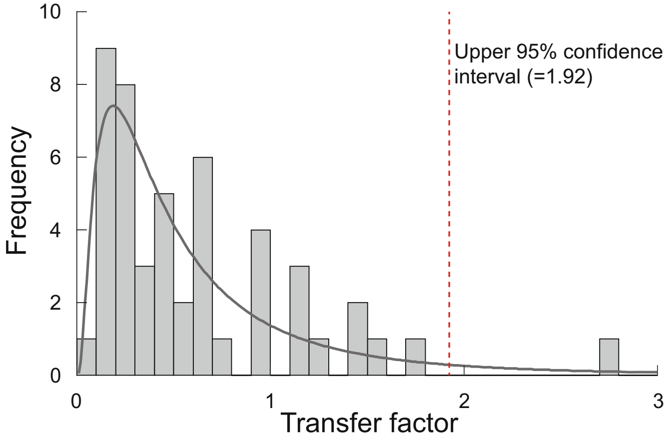


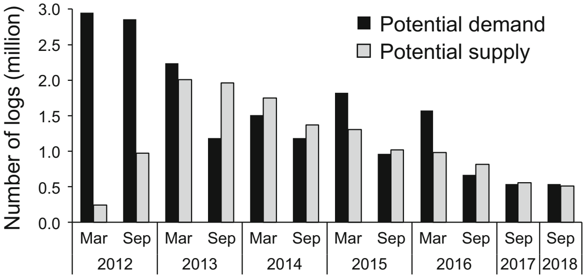
Fig. 6.26 The transfer factor for shiitake mushrooms from bed-logs. Transfer factor was measured from the radiocesium concentration in 48 sets of logs and shiitake mushrooms. The length of the vertical bar indicates the frequency at intervals of 0.1. The curve is a mathematical expression (lognormal distribution) of the frequency distribution. The upper 95% value of the distribution curve was 1.92 (dotted line), and the upper limit of the transfer coefficient was set to 2 from the safety point of view (Source: Adapted from the Forestry and Forest Products Research Institute, “Project Report on Measures for Stable Supply of Safe Mushroom Logs in 2011 fiscal year” [163])

limit for food is 100 Bq/kg (fresh weight), 50 Bq/kg was set as the index value for logs.

6.5.3 Radioactive Contamination of Deciduous Broadleaf Trees for Bed-Log Cultivation and Its Impact on Industry

A survey on radiocesium contamination was conducted in broadleaf forests used for mushroom logs, and it was found that mushroom log forests with wood exceeding the index value of 50 Bq/kg were spread over a wide area in eastern Japan, including Fukushima Prefecture. Fukushima Prefecture used to produce a large amount of mushroom logs and supply them to other prefectures before the accident. But after the accident, the supply was completely stopped due to the contamination. In Eastern Japan, the supply of shiitake mushroom logs could not keep up with the demand, resulting in a mismatch between supply and demand (Fig. 6.27). To solve the mismatch, the Forestry Agency worked to find new sources of supply, for example by distributing flyers [164]. In recent years, the mismatch has been resolved in terms of volume. However, the mismatch between supply and demand by tree species remains, with mushroom producers requesting konara oak (*Quercus serrata*) and the supply of logs mainly consisting of sawtooth oak (*Quercus acutissima*).

Fig. 6.27 Supply and demand for shiitake mushroom logs (Source: Data from the Forestry Agency, 2018 fiscal year Forestry White Paper "Chap. 6, Section 2: Recovery from Nuclear Disaster (2) Management and Supply of Mushroom Logs, etc." [162])



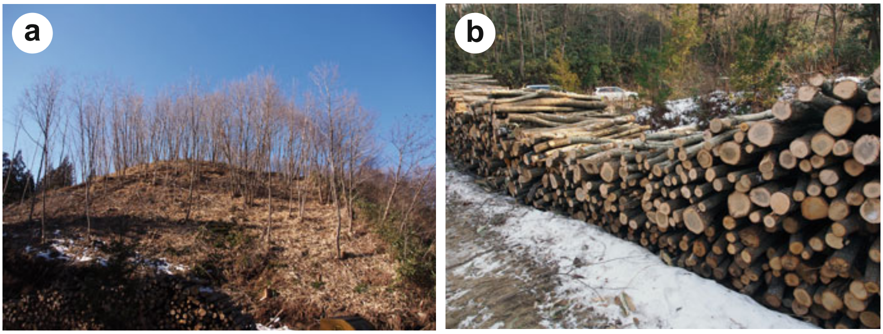


Fig. 6.28 Logged konara oak forest after the accident (Miyakoji-machi, Tamura City, Fukushima Prefecture). (**a**) Logged forest, some trees are left not to be cut down (called retention harvesting). (**b**) Logs that had been cut down, originally intended to be used for mushroom cultivation, but after the accident, they were all shipped as chips (Photos taken by the author in January 2014)

As mentioned above, the Abukuma region, which is located in the eastern part of Fukushima Prefecture and was heavily contaminated by the Fukushima nuclear accident, was a major producer of mushroom logs (Fig. 6.28).

To grow deciduous broadleaf trees such as konara oak and sawtooth oak for shiitake mushroom logs, the trees used to be cut down about every 20 years, allowing coppice shoots coming out of the stumps to grow large enough. However, due to the accident, the deciduous broadleaf trees used as logs were directly contaminated and the radiocesium concentration was detected to be more than 10 times higher than the index value, so the log production was completely stopped in an extensive area of eastern Japan.

Next, let's take a look at changes in shiitake production. Shiitake mushroom production has been flat nationwide over the years, and prices have temporarily increased (Fig. 6.29). On the other hand, shiitake cultivation in Fukushima Prefecture has been greatly affected by the accident. The production of shiitake mushrooms in both cultivation methods of bed-log and sawdust has decreased significantly since

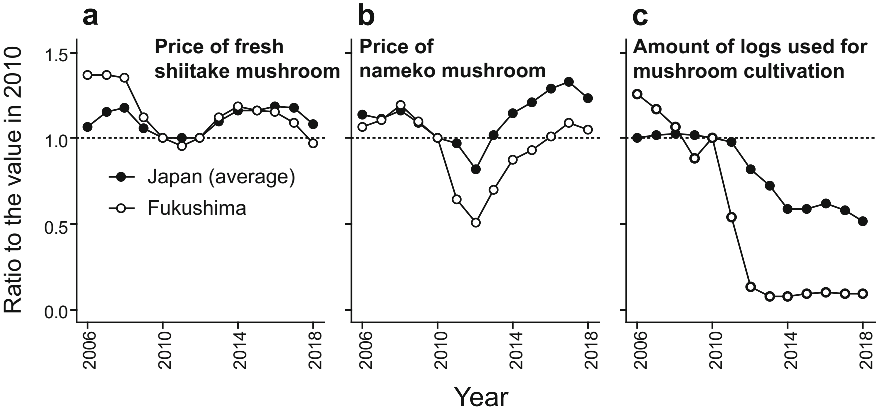


Fig. 6.29 Comparison of the price of (**a**) fresh shiitake mushrooms, (**b**) nameko (*Pholiota microspora*) mushrooms, and (**c**) the amount of shiitake logs grown in Fukushima Prefecture and throughout Japan before and after the accident (Source: Data from Tokyo Metropolitan Central Wholesale Market, "Market Statistics (Monthly and Annual Reports)" [165]; Ministry of Agriculture, Forestry and Fisheries, "Statistical Survey on Production of Non-wood Forest Products" [166]; Fukushima Prefecture, Agriculture, Forestry and Fisheries Department, "Fukushima Prefecture Forest and Forestry Statistics FY2018" [7])

the accident. In 2012, it was about one third of the pre-accident level. The shiitake production by sawdust medium cultivation has turned to recovery, and the amount of production in 2018 was to 92% of the 2010 level. But the amount of production in bed-log cultivation has not recovered and remains $<$10% of the 2010 level. The price of dried and fresh shiitake has dropped to 64% and 86% of the national average, respectively.

6.5.4 *Transfer Mechanism of Radiocesium to Shiitake Mushroom*

Transfer of Radiocesium from Bed-logs to Shiitake

Since the radiocesium concentration varies in different parts of the tree, it is important to know from which part of the log the shiitake absorbs radiocesium. Iwasawa [167] measured the radiocesium concentrations in each part of bed-logs separately and compared them with the concentration of emerging shiitake mushrooms (Fig. 6.30). The results showed that the radiocesium concentration in shiitake mushrooms was more highly correlated with the concentrations in the inner bark, sapwood, and heartwood of the logs (upper panels of the figure) than with those in the whole log or the outer bark (lower panels of the figure), of which the surface was

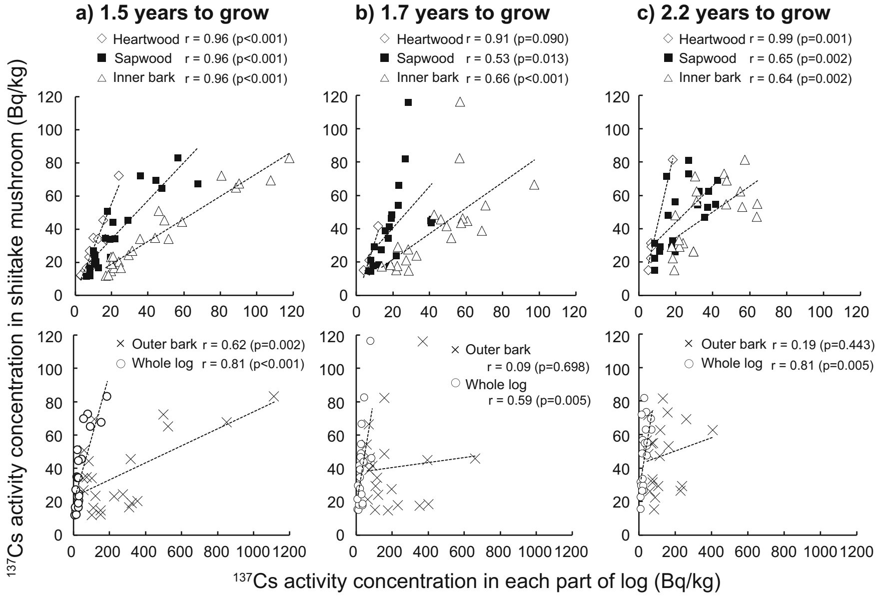


Fig. 6.30 Relationship between cesium-137 activity concentrations in various parts of shiitake mushroom and bed-logs. (**a**) 1.5 year to grow, (**b**) 1.7 year to grow, (**c**) 2.2 year to grow (Source: Adapted from Iwasawa 2017 [167], courtesy of Masami Iwasawa, Chiba Prefectural Agriculture and Forestry Research Center)

directly contaminated. In addition, when the surface of bed-logs was washed, the radiocesium concentration in the whole logs decreased because the radiocesium attached to the bark surface fell off. However, the radiocesium concentration in the shiitake mushroom did not change regardless of washing treatment [168]. Therefore, it can be assumed that the shiitake mushroom absorbs radiocesium from the inside of logs (wood in Fig. 3.7) rather than from the outer part. The radiocesium concentration in various parts of trees, such as konara oak, changes over time (Fig. 3.8, Fig. 3.10). Therefore, the transfer factor calculated from the radiocesium concentration in the whole log may also change over time and should be monitored carefully.

Even if the radiocesium concentration is high, the bed-logs can be used if the transfer of radiocesium to the shiitake is controlled. Therefore, several attempts have been made to control the transfer. One of them is a test using a substance called Prussian blue ($Fe_4[Fe(CN)_6]_3$) to inhibit the absorption of radiocesium. Prussian blue is a substance that binds strongly to radiocesium and is used as an antidote to promote the removal of radiocesium from the body after an accidental ingestion. It was found that shiitake mushrooms produced from bed-logs infiltrated with Prussian blue had less than half the radiocesium concentration compared to shiitake mushrooms from untreated logs [169]. However, Prussian blue is a cyanide compound that may adhere to shiitake during emergence, making it difficult to apply to food products. Other methods were also proposed, such as mixing plug spawns with zeolite that would reduce the transfer of radiocesium, and spraying wet blasting (a mixture of water and abrasives) on the bed-logs to remove radiocesium [170, 171]. None of these methods have been put to practical use, but they have been shown to be effective in reducing the radiocesium concentration in shiitake mushrooms.

Additional Contamination from the Growing Environment

There are two ways of bed-log cultivation: outdoor cultivation, in which the inoculated bed-logs are placed and incubated in an outdoor environment such as a forest, and house cultivation, in which the bed-logs are placed in a building such as a greenhouse. There have been cases where the radiocesium concentrations in logs and shiitake mushrooms cultivated outdoors have increased. It is believed that additional contamination from the environment may occur in outdoor cultivation. Therefore, tests were conducted to counteract the additional contamination. Since radiocesium is circulating in the forest, various pathways are expected to cause additional contamination in the outdoor condition. One pathway is to transfer from the ground. In the case of nameko (*Pholiota microspora*) mushroom cultivation using logs, it has been reported that the radiocesium concentration in the emerging nameko mushroom was reduced when the surface soil in the forest was removed [172]. These results indicate that radiocesium distributed in the soil transfers to mushrooms for some reason. In addition, in forests, radiocesium is contained in the rainfall that passes through the forest canopy (throughfall) (Sect. 3.3), and hence the transfer of radiocesium from the canopy to mushrooms in outdoor cultivation should also be monitored.

At present, the pathways and mechanisms of additional contamination are not fully understood, and countermeasures have not yet been established. The effects of additional contamination may differ depending on the region and conditions. Compared to the tests conducted in the first 2–3 years after the accident (early phase, Fig. 3.2), the tests conducted 4–5 years after the accident (transition phase) report that additional contamination of shiitake mushrooms from the environment has been reduced. In any case, the resumption of outdoor cultivation of shiitake mushrooms in contaminated forests should be done cautiously, using a variety of recommended measures while verifying their effectiveness.

6.5.5 *Countermeasures Against Contamination of Cultivated Mushrooms*

Guidelines

The mechanism of radiocesium transfer to shiitake is not fully understood. However, it is known that we can produce less contaminated mushrooms when we use logs with radiocesium concentrations below the index value, and the cultivation is carried out under the conditions avoiding additional contamination as with cultivating indoor and managing thoroughly. Therefore, the Forestry Agency is promoting the matching of the supply of uncontaminated (free or less radiocesium) logs and thorough management for producing less contaminated shiitake mushrooms based on the guidelines [173]. The restricted area for shipping is gradually decreasing as the guidelines are being followed and the restrictions are being lifted on a per-farm basis.

On the other hand, mushroom farmers are required to adopt different cultivation methods than before, such as using logs from different areas and cultivating indoor conditions. In addition, purchasing logs from outside the prefecture incurs costs. The local farmers used to establish an efficient system of bed-log cultivation using local deciduous broadleaf trees from their own forests, but the radioactive contamination has made it impossible to continue the system. Therefore, it is necessary to consider ways to gradually return to the original way. The radiocesium concentration in deciduous broadleaf trees varies depending on the environment even within the same area, and it is thought that there are logs that can be used even within the contaminated area. Therefore, an attempt is being made to find usable logs by a non-destructive inspection machine for logs (Fig. 6.31).

Contamination of Deciduous Broadleaf Trees and Countermeasures

Factors that determine the variation of radiocesium concentration within trees have been vigorously researched for konara oak trees, which have high commercial value, and research results have been reported suggesting the influence of exchangeable potassium in the forest soil as well as agricultural land. A survey of 40 areas of broadleaf forests for logs production in Tamura City, Fukushima Prefecture, revealed a strong negative correlation between the radiocesium concentration in the current year's branches of konara oak and exchangeable potassium in the soil surface (0–5 cm depth) layer (Fig. 6.32). In this study, the radiocesium concentration in the current year's branches differed up to 100 times or more among the study sites which received the similar amount of radiocesium deposition. Of course, the degree of contamination of the soil itself is important, but if the soil has a high concentration of exchangeable potassium, the radiocesium concentration in konara oak will be low, and it may be possible to use it as logs for shiitake cultivation. Research has also been conducted to actively suppress radiocesium absorption by potassium fertilization. For example, Kobayashi et al. [28] showed from experiments with konara oak seedlings that cesium absorption by konara oak was determined by absorption competition based on the ion ratio of potassium and cesium in the culture medium. It is also expected that potassium fertilization will make logs available even when soil radiocesium concentration is high.

Fig. 6.31 A non-destructive inspection machine for logs (Courtesy of Yoshinori Imai, Tochigi Forestry Center)

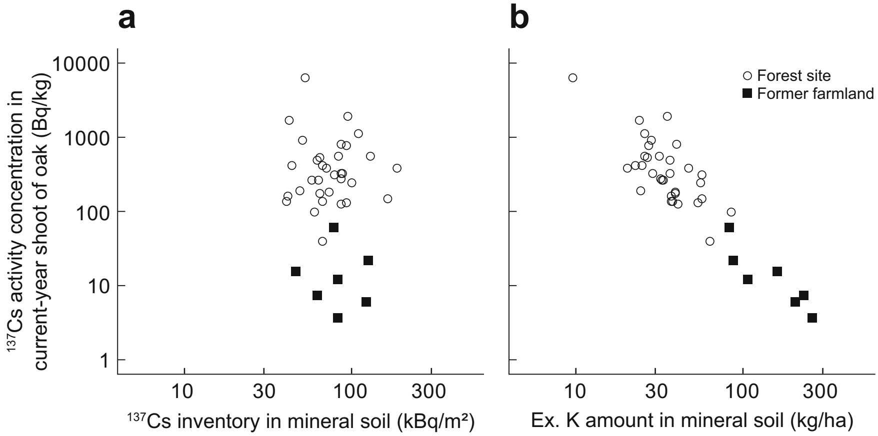


Fig. 6.32 Relationship between cesium-137 activity concentration in current year branches and (**a**) cesium-137 inventory in mineral soil and (**b**) exchangeable potassium amount in soil. Samples were taken in Miyakoji-machi, Tamura City, Fukushima Prefecture (Source: Redrawn from the Forestry and Forest Products Research Institute, "Resumption and Restoration of Use of Shiitake Mushroom Log Forests in Radioactively Contaminated Areas" [175], with some results published in Kanasashi et al. [174])

6.6 Providing Information to Residents

A variety of methods were used to communicate the vast and complex information to the residents.

As we have seen, the dynamics of radiocesium in forests and changes in air dose rates have been clarified through surveys conducted by researchers and the government during the past 10 years. To rebuild the lives and industries in the affected areas, it is important not only to clarify the actual situation of contamination, but also to provide the obtained information to the local residents in a prompt, accurate, and easy-to-understand manner. To this end, the Forestry Agency, the Ministry of the Environment, Fukushima Prefecture, and other government agencies, national research institutes, and universities took the initiative in providing residents with a variety of information. Various methods were used, including symposiums (Fig. 6.33), dialogue meetings (Fig. 6.34), creation of pamphlets (Fig. 6.35), and construction of websites (Fig. 6.36). Recently, there have been symposiums with a popular YouTuber as a guest. In particular, in symposiums and dialogue meetings, in addition to the presentation of the latest research results by researchers and administrators, questions from the public were answered and direct communication took place.

The Forestry Agency of Japan has also taken the lead in producing a comprehensive pamphlet on radioactive contamination of forests. The pamphlet explains the situation of the forests in Fukushima as well as information on countermeasures and future plans, and is updated every year with new results. In addition, the ministries and agencies have been releasing data sets of information on radiocesium in crops and forest products reported by municipalities. These data sets have been used by researchers as well as providing information to residents. These websites and pamphlets can be viewed and downloaded from the links at the end of the book. Compared to the Chernobyl nuclear accident that occurred in the Soviet Union more than 30 years ago, the Fukushima nuclear accident has provided information with a high degree of transparency and speed, and in a variety of ways. It is important that we continue our efforts to return the research results to society.

Fig. 6.33 Symposium scene of "Considering Countermeasures against Radioactive Contamination of Forests Based on Research in Chernobyl and Fukushima", June 5, 2018, The University of Tokyo (Courtesy of Shinta Ohashi, the Forestry and Forest Products Research Institute)

Fig. 6.34 Scene of a dialogue meeting with residents. Left: after the lecture, one of the residents asked about air dose rates. Right: roundtable discussion on future wood utilization held at a forest cooperative in Fukushima Prefecture, July 2017 (Courtesy of Shinji Kaneko, the Forestry and Forest Products Research Institute (left), and taken by the author (right))

Fig. 6.35 Example of a pamphlet created by the Forestry Agency of Japan to raise awareness and communication. (**a**) Japanese version and (**b**) English version (Source: The Forestry Agency, “The Current State of Radioactive Substances in Forests and the Regeneration of Forests and Forestry, 2018 edition” [126])

▸ 本文へ | ▸ 各種窓口案内 | ▸ サイトマップ
日本語 | English | Français | 한국어 | 中文

環境省
Ministry of the Environment

住民の皆さまへ 安心できる毎日を。
除染情報サイト

検索 文字サイズの変更 小 中 大

Environmental Remediation (English site) 新着一覧 除染情報サイト サイトマップ お問い合わせ

トップページ | 除染についての基礎情報 | 政策資料・ガイドライン | お役立ちリンク集
特定復興再生拠点 | 除去土壌等の管理 | 除染の状況 | 除染アーカイブサイト

トップページ > 除染についての基礎情報 > 環境省の取組 > 森林の除染等について

環境省の取組
- 除染の加速化・円滑化のための施策
- 森林の除染等について
- 除染のフォローアップについて
- フォローアップ除染の考え方
- 環境回復検討会
- 除去土壌の処分に関する検討チーム会合

森林の除染等について

森林の除染等の取組
生活環境の安全・安心の確保に向けた取組
住居周辺の里山の再生に向けた取組

森林の放射性物質に関する知見
1. 森林における放射性物質の分布等 2. 森林からの放射性物質の飛散
3. 森林からの放射性物質の流出
①森林から林縁部への流出 ②流域から河川等への流出
③間伐等による流出抑制効果
4. 空間線量率低減に効果的な除染範囲
5. 森林に立ち入る際の被ばく線量（レクリエーション活動）

福島の森林・林業の再生に向けた総合的な取組
I. 森林・林業の再生に向けた取組 II. 調査研究等の将来に向けた取組の実施
III. 情報発信とコミュニケーション 里山再生モデル事業 イメージ

▸ Link to main body | ▸ Sitemap
日本語 | English | Français | 한국어 | 中文

Ministry of the Environment
Government of Japan

Environmental Remediation

Search Font size S M L

▸ From Webmaster ▸ Links ▸ News & Topics ▸ 除染情報サイト（日本語サイト）

HOME | Decontamination | Interim Storage Facility | Movie & Publication | Policy & Document

Publication Manga "Nasubi no Gimon (Nasubi asks Questions)" Food Edition

Updated Information

2020.8.21 NEW
"Off-site Environmental Remediation in Affected Areas in Japan" is updated.

Fig. 6.36 Example of a website created by the Ministry of the Environment of Japan for awareness raising and communication. Above: in Japanese. Below: in English (Source: Ministry of the Environment, Environmental Remediation Website, "About Forest Decontamination, etc." [108])

6.7 Column: Looking Back on that Time (4)

Memoirs of the Fukushima Accident

Yves Thiry
Project Manager, French Radioactive Waste Management Agency

I learned the possible occurrence of mass releases of radioactivity to the atmosphere following the earthquake and tsunami of March 11, 2011 in Japan by radio. We were on March 16, 2011 on the road with a colleague of EDF R&D and two other collaborators from Sweden to visit a field trial in the East of France. At that period, we were working on chlorine biogeochemistry in the forest. The surprise was high. In absence of more detailed information, I was worried about possible consequences for Japanese populations and the environment.

In the following weeks and months, the media reported more on the gravity of the situation and the different measures rapidly taken by the national government, the local government and the operator and then those that followed in an evolutionary manner given the situational awareness. The number and rigorousness of countermeasures to minimize the consequences of radiological exposures, notably the large-scale start-up of decontamination of homes and land, impressed me.

In the end of 2011, the Institute for Radiological Protection and Nuclear Safety (IRSN) in France contacted me to join a vast consortium in charge of a new national research project for several years funded by the French National Research Agency (ANR). The general aim of the AMORAD project (https://www.irsn.fr/en/research/research-organisation/research-programmes/amorad/Pages/AMORAD-program.aspx) was the improvement of radionuclides dispersion and impact assessment modelling in the environment. My experience in forest contamination after Chernobyl was solicited to develop a program focusing on radiocaesium biogeochemistry in forested areas, contaminated on large surfaces in Fukushima region, while other programs looked at erosion via rivers and the transfers to/within marine ecosystems. We had our first field sampling in Japan in a cedar stand in autumn 2013 at a site equipped by the University of Tsukuba. Compared to post-Chernobyl projects, that fast cooperation was an exceptional opportunity to have a quick view on the early fate of contamination. Our study was facilitated thanks to additional exchanges with Japanese researchers, and a lot of supplementary information made available in the scientific literature by several Japanese institutes, including FFPRI. The importance of radioactive deposits interception by forest canopy and the further foliar uptake and recycling of radiocaesium by coniferous trees was rapidly confirmed. Nevertheless, it seems that the local climatic and

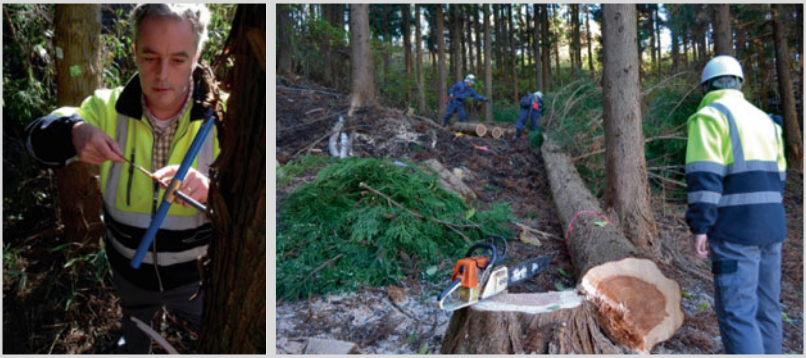
(continued)

edaphic conditions in the Fukushima area promoted the self-decontamination of soil and trees, compared to certain Chernobyl-affected forest. In my model TRIPS 2.0, initially developed for Scots pine in Belarus, I had to reduce the root uptake flux by a factor 4 in order the simulation agrees with measurement data in Japan. The recycling into deciduous trees remains more uncertain because of unclear foliar uptake and a root uptake still to be assessed. That is why continuous monitoring will be necessary for a couple of years. Overall, the calibration of our models of radiocaesium cycling in forest were consolidated thanks to the new data; those models are now being used to test different scenarios of forest management or countermeasures in cooperation with other Japanese researchers.

The contaminated areas are in a sort of convalescence now. A demanding task is to identify where and when a “normal” or adapted socio-economic situation may be developed, including the best safety conditions for the public and the workers. In highly contaminated zones where forest products contamination including wood will remain too high for a long time, we have to recognize that a recovery of a normal situation is difficult before several decades. It is depressing for local people to see great areas of forest excluded from their life habits. However, in most areas, less affected, there are still specific countermeasures to be tested to accelerate the self-decontamination of soil or trees and different processes of woody products’ valorisation still need to be investigated. For the future, I also expect a shift from individual/independent studies towards more integrated projects for a better control of the contamination fate at different interfaces e.g. the continuum forest-rivers-ocean. The forested watersheds have an essential role in stabilization of the contamination in Japan. Runoff and erosion of soil are primary vectors of possible long-term remobilization of the contamination, especially in Fukushima region due to local relief and climate; thus all that concerns the connectivity between forest and aquatic ecosystems must be carefully monitored and understood. That will also involve the effect of countermeasures that could degrade the contamination stabilization by forest, notably in steep hills regions. More generally, it is very important to consolidate an integrated vision and to have an interdisciplinary approach on the management of contaminated areas (from the soil to the waste repository) thanks to new insights in various disciplines: radiation protection, economical and social sciences in addition to environmental sciences. That is a very challenging task.

(continued)

In that perspective, the questionings of local public and forest workers are very important to clarify the expectations and to guide a future programme of forested area management in Fukushima region, not disconnected from real life.



Sampling in Fukushima. Yves Thiry is on the left (Courtesy of Yves Thiry)

Chapter 7
The Future of Forests in Fukushima: How Should We Face Radioactive Contamination of Forests

Abstract In this last chapter, we will discuss future measures, remaining issues, and better research methods based on the results of the research presented in this book to overcome radioactive contamination. Ten years have passed since the accident. As we have seen, a great deal of research has been conducted from the time of the accident to the present, and much has been learned about forests and radiocesium. Over the past 10 years, the amount of radiocesium in forests has decreased at a certain rate due to radioactive decay, and the distribution of radiocesium has also changed within forests, resulting in a change in the situation of forest contamination. As a result, the area of evacuation zones has been shrunk and restrictions on shipments of certain food items have been lifted. However, contaminated forests still remain, and many residents and stakeholders are still suffering. In this chapter, we will discuss how we should face radioactive contamination of forests, based on the results of the surveys introduced in this book.

Keywords Countermeasure · Technology based · Management based · Remaining challenges · Lesson learned · Preparation · Future

7.1 Key Points on Radioactive Contamination of Forests

To begin with, let's summarize some of the important points when dealing with radioactive contamination of forests. The general behavior of radiocesium, not only in forests, requires an understanding of the effects of radioactive decay.

- Radiation from the major radionuclides, radiocesium, decreases according to its physical half-life due to radioactive decay.
- Ten years after the accident, the ratio of cesium-134 has become very small, and cesium-137 has become more important.
- The physical half-life of cesium-137 is as long as 30 years, but the lifespan of trees and the cutting cycle of planted forests is longer than this.

We have understood many things about the behavior of radiocesium deposited on forests by this accident. We also need to take into account the condition of the forests in Japan when considering countermeasures.

S. Hashimoto et al., *Forest Radioecology in Fukushima*,
https://doi.org/10.1007/978-981-16-9404-2_7

- In Fukushima, forests cover a large area, accounting for about 70% of the total area.
- Radiocesium was largely trapped in trees immediately after the accident, but now most of it has migrated to mineral soil, especially the surface layer.
- Radiocesium is expected to remain in the soil surface layer for a long time.
- Radiocesium does not run off much from forests.
- Absorption of radiocesium from soil to trees has been occurring. It is not reported to be particularly high, as was observed in Europe during the Chernobyl nuclear accident, probably due to differences in the soil environment.
- The radiocesium concentration in trees varies depending on the species, site, and environment.
- Some non-wood forest products and wildlife, such as mushrooms and wild plants, continue to have high levels of radiocesium.

Many countermeasures were considered and tested based on the various findings from the surveys and studies.

- If decontamination is to be carried out, it would be more efficient to remove trees and the soil surface organic layer immediately after the accident, or to remove the soil surface organic layer at a time when most of the radiocesium has been transferred to the organic layer.
- Decontamination generates a huge amount of waste.
- Decontamination is more effective when it is conducted close to the place where air dose rates are to be reduced. Even if the range of forest decontamination is extended beyond 20 m from the forest edge, the effect of decontamination will reach a ceiling, and the reduction effect of air dose rates outside of the forest will be small.
- Given the large area and complex topography, there is a limit to the amount of radiocesium that can be reduced in the environment through treatments and practices such as decontamination and potassium fertilization in forests.
- Forests have the property of retaining radiocesium inside while letting almost no radiocesium flow out of the forest, and the decontamination area is limited to 20 m from the forest edge. As a result, air dose rates in forests are higher than those in residential areas and farmland in the same area.

It is also important to understand the following points from the perspective of radiation protection.

- There are internal exposure and external exposure, and we need to prevent both.
- The radiation dose is determined by multiplying the intensity of the radiation received by the time it is received.
- Therefore, reducing either or both of them can reduce exposure dose.

In consideration of the above, as stated in the ICRP publication 111, it is necessary for residents and the government to communicate sufficiently while being aware of the balance between the advantages and disadvantages of radiation protection measures. As more time passes, not only the situation of radioactive materials and radiation, but also the situation of forests and society will change. It is also important to understand that the best way to deal with the situation is to constantly review and change the evaluation accordingly over time.

7.2 A Guide to Understanding and Dealing with the Contamination

There are two important points to consider when dealing with radioactive contamination. The first one is, of course, that the stronger the contamination (higher air dose rate and higher radiocesium concentration), the more serious the problem becomes, and the second one is that the severity of the problem differs depending on the target of use (e.g. wood, mushrooms, wild plants, forestry, recreation, etc.) even in areas with the same level of contamination. The first point is that, from the perspective of countermeasures against radioactive contamination, as we have seen in Chaps. 2 and 5, it is necessary to take different measures for each level of contamination to reduce exposure to radiation. The second point can be attributed to the fact that the uptake, distribution, and temporal changes of radiocesium vary depending on the target, as seen in Chaps. 3 and 6, as well as the fact that the reference values related to the effects on humans may also differ. In this way, dealing with the contamination tends to be complicated due to the complex involvement of two different factors, the contamination level and the target, but from the perspective of radiation protection, it is necessary to understand the current situation for each contamination level and target and determine how to deal with it.

Based on these two points and the characteristics of each target that have been clarified in previous studies, we would like to propose the following classification of the relationship between the degree of contamination, and the activities in forests and the use of forest products in the forest 10 years after the accident.

Low Contaminated Areas (0.5 μSv/h or Less at the Time of the Accident, 0.1 μSv/h or Less in 2020)

- No problems with entry, recreation, or wood use as building materials.
- With regard to the use of broadleaf trees as mushroom logs and firewood, wildlife, wild mushrooms, and wild plants, the radiocesium concentration may exceed the criteria that restrict their use, or the standard limit for food, depending on the environment and type.

Moderately Contaminated Areas (2 μSv/h or Less at the Time of the Accident, About 0.5 μSv/h or Less in 2020)

- No problems with entry, recreation, or wood use as building materials.
- Broadleaf trees, wild mushrooms, and wild plants are likely to exceed the criteria in many areas.

Highly Contaminated Areas (10 μSv/h or Less at the Time of the Accident, About 2.5 μSv/h or Less in 2020)

- Temporary entry into forests is not a problem, but since external exposure above the criteria for the general public is received even in the vicinity of decontaminated residential areas, it is necessary to control the accumulated exposure dose when continuously entering forests for work or daily use.
- When carrying out forest maintenance and decontamination work, it is necessary to control exposure dose by using the radiocesium concentration in the soil as a simple indicator.
- Wood can be used for building materials, but the bark may exceed the criterion for designated waste.
- Broadleaf trees, wild mushrooms, and wild plants are expected to exceed the criteria for the long term, regardless of the type.

Difficult-to-Return Areas as of December 2020 (10 μSv/h or More at the Time of the Accident, About 2.5 μSv/h or More as of 2020)

- Entry into the forests is restricted except for special operations such as decontamination.
- It is recommended to continue to restrict access to the site until the air dose rate drops to around 2.5 μSv/h or less.
- Since the main radioactive material remaining even in 2020 is cesium-137 with a half-life of 30 years, the decrease in air dose rates and radiocesium concentration in forest products in the future will be very slow.
- Particularly in most-highly contaminated areas, it is expected to take several decades to more than 100 years for forests and forest products to become available.

In the above classification, for the sake of clarity and simplification, the air dose rate is used as indicators for classifying responses to contamination. The basis for above classification is the criteria set by governmental and international organizations, but some criteria are set for radiocesium concentrations and not for air dose rates. The classification based on air dose rates alone is therefore not strict; however, there are some reasons why we dared to propose rough guidelines for action based on air dose rate. One reason is that it is difficult to optimize the adaptation for the various status of contaminations in areas because the criteria are uniformly determined. Therefore, we believe that it is useful to use the air dose rate, which is an easy-to-understand indicator of the level of contamination in the region, to have an overview and understanding of the whole picture to prevent excessive exposure. What is important in using the air dose rate as a guide is that the measures to be taken according to the level of contamination will change with the passage of time on a yearly basis. Especially in the first few years after the accident, the distribution of radioactive materials in the forest changes significantly. In addition, the effect of cesium-134, which emits more intense radiation at the same concentration than cesium-137, rapidly decreases by a factor of ten in 7 years. Now that knowledge has been accumulated through 10 years of research and monitoring, this book proposes to review the criteria set immediately after the accident based on the distribution and dynamics of radiocesium, and to help to reorganize them from the viewpoint of how to deal with radioactive contamination of forests. In addition, we would like you to keep in mind that this kind of guideline should be checked and reviewed at each milestone in time, for example, 10 or 20 years.

7.3 Future Measures

So, now that we are in the tenth year of the Fukushima nuclear accident, and the rate of reduction in radioactive contamination is slowing down, what further measures can be taken? Let us first consider the two axes that are important for considering countermeasures (Fig. 7.1). The first axis is "countermeasures through the application of technology (technology based countermeasures)" and "countermeasures through management (management based countermeasures)". The former can be also called mainly dynamic measures or hardware measures, while the latter can be called static measures or software measures. However, measures cannot be clearly divided into two, and all measures have both aspects. The second axis is countermeasures against "air dose rate" and countermeasures against "radiocesium concentration". The former are measures to reduce the air dose rate or to keep enough distance from radioactive materials, which are mainly measures for external exposure. The latter are measures to reduce the radiocesium concentration in trees and forest products, for example, and to prevent people from eating contaminated food, which are mainly measures to prevent internal exposure. It is important to be aware that there are advantages (benefits) and disadvantages (risks) to each measure, and it is desirable to maximize the advantages while being aware of both. Let's consider the following specific measures.

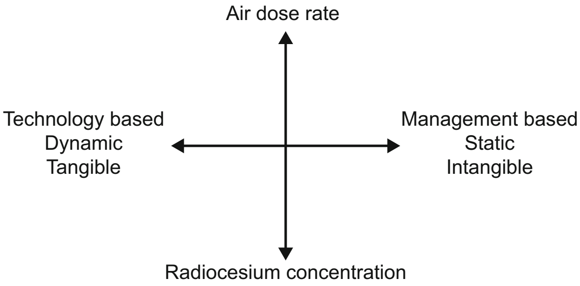


Fig. 7.1 Two axes for considering countermeasures

Technology Based Measures Against High Air Dose Rate

Decontamination of forests by removal of the organic layer is currently the only measure that can be taken (Sect. 6.1). However, 10 years have passed since the accident, and most of the radiocesium has migrated from the organic layer to the surface mineral soil below it, so removal of the organic layer is not expected to substancially reduce air dose rates. In addition, removal of the organic layer not only reduces the air dose rate, but also changes the soil environment, which may affect the multi functions of forests. The secondary effects of forest decontamination, other than reduction of radiocesium, need to be verified in the future. Since the forest area in Japan is as large as 70% of the land area, the possibility that the effect will not be worth the cost should always be considered. If decontamination is to be carried out in the future, priority should be given to *satoyama* forests (managed forests in mountain villages, which are close to farmlands and residential areas), which are frequently used and have a high public need for exposure dose reduction.

Management Based Measures Against High Air Dose Rate

Mapping of air dose rates for each forest is necessary for people in areas where forests are used to avoid exposure to radiation as much as possible (Sects. 5.2 and 6.1). A map that clearly shows the approximate possible exposure doses received from the environment for each type of people's activities will help people make decisions when they resume various activities in contaminated areas. In forests, it is expected that air dose rates will generally continue to decrease in accordance with radioactive decay (Sects. 3.6 and 6.1). Now that cesium-137 is the major radioactive material, it may take 100–200 years for the dose to be sufficiently reduced in some places.

Technology Based Measures Against High Radiocesium Concentration

Potassium fertilization, which has been implemented as an all-round measure in croplands, is also effective in reducing the radiocesium concentration in forest trees. Nonetheless, there are still some issues that need to be considered. Potassium fertilization in forests is more costly than in farmland, and it is not yet known how long the fertilization effect will last in forests; these problems should be solved before it can be put to practical use. However, even in cases where it is difficult to actively apply potassium, it has been shown that the radiocesium concentration is low in broadleaf trees used for mushroom logs that grow on land with high soil potassium concentration (Sect. 6.5). As a countermeasure using this property, the use of abandoned farmland, which has been increasing in Japanese mountain villages since before the accident, can be considered. Abandoned land that was used as farmland is expected to have high potassium concentration due to fertilizer application over the years. Although the area of such abandoned land may be limited, the potassium concentration in the soil varies depending on the soil type and topography, even in forest land that was originally used as forest. If we can efficiently find forest areas with high soil potassium concentrations, we may be able to partially restart producing logs for mushroom cultivation.

Management Based Measures Against High Radiocesium Concentration
One option would be delaying the harvest of trees. It takes a long time to grow trees. If we take advantage of this, it is possible that the concentration of cesium-137 will be sufficiently low due to radioactive decay by the time the trees are harvested. For this reason, it is necessary to improve the accuracy of prediction so that reliable information about future cesium-137 concentration in trees can be provided. It is not only trees that need to be predicted for future concentrations. It is also necessary to predict the concentrations of forest products such as mushrooms and wild plants. The question of "when?" is one of the biggest concerns we have when talking to people who work and live in forestry and forest products industries in the affected areas. It would also be useful to learn about the differences in the radiocesium concentration in different species of mushrooms and wild plants, as well as how to cook them in a way that reduces the radiocesium concentration in wild plants. In addition, among the criterion for general foods that have been uniformly applied since April 2012, it is possible to consider a new criterion for local consumption of minor foods such as mushrooms and wild plants (Sect. 6.4). After estimating the exposure dose through food intake based on the data, it may be possible to examine the benefits of mountain bounties from the standpoint of radiation protection and reconsider the optimization of preventing exposure and protecting the food culture of mountain villages. If people who choose to live in contaminated areas are able to think about the risks of exposure and make decisions for themselves, they will be able to live with peace of mind.

In the above, we have presented several specific measures to deal with radioactive materials related to the use of forests and forest products. It does not mean that any one of these measures is definitively effective. What is important is to understand the dynamics of radiocesium in forests and the characteristics of air dose rates, and to use the characteristic that "radiation from radiocesium decreases according to its half-life", and to gradually restore our relationship with forests while avoiding unnecessary exposure by taking a good mixture of various measures. This is what we think we should do. In the early days of the accident, there was limited information on the actual situation of radioactive contamination and the exposure to radiation. By using the data accumulated during the past 10 years, it has become possible to more accurately estimate the exposure doses from activities in the forest and from eating forest products. The basic idea is to maximize the benefits by accepting the situation and weighing the advantages of using forests and forest products against the disadvantages of exposure. To determine whether the newly selected measures are effective, it is necessary to continue monitoring the contamination status and exposure dose through repeated trial and error, and to take action based on the data. To do this, it is important for researchers to have more dialogues with local residents and governments to deepen their understanding of the essence of what the local people and society want.

7.4 Challenges Remaining for Researchers

As we sort out what we have learned from the past 10 years of research and study, and the actual efforts being made in the forest, it has become clear that while the results of our research to date have been useful, there are also things that need to be explored further in terms of research in the future.

Continue Monitoring
The half-life of cesium-137 is 30 years, and it is necessary to continue monitoring in the forest. Continuing surveys at the same sites where we have been conducting surveys for the past 10 years will maintain the continuity of data and provide better data. We also need multi-point data such as surveys and monitoring by government agencies because there is variation by location and tree species. Research in the forests of Europe contaminated by the Chernobyl nuclear accident was active for about 10 years after the accident, but was eventually halted and then restarted after the Fukushima accident. It is important to continue the monitoring that has been conducted since the immediate aftermath of the accident to avoid such interruptions in Fukushima.

Predict the Future with Accuracy
The behavior of radiocesium in the forest is gradually shifting from the quasi-equilibrium to the equilibrium phase. Even in equilibrium, some of the radiocesium will continue to move in the forest. If we can accurately predict the future of radiocesium, it will be easier to take countermeasures against contamination and provide residents, businesses, and governments with a highly accurate forecast. To improve the accuracy of predictions, we need to (1) understand the concentration characteristics of each species and the factors that cause differences among the species, (2) understand the factors that cause variations in concentration among and within individuals, and (3) determine the sustainability of the effects of artificial measures such as potassium fertilization.

Select Trees Suitable for Conversion (Replacement of Trees)
If it is clear that the current forest cannot be used for its original purpose for a long time, it will be necessary to consider conversion. To do so, it is necessary to select trees that are useful alternatives and do not absorb radiocesium easily, or trees whose use is not affected by radiocesium contamination. Researchers from not only environmental sciences but also breeding and economic perspectives will be required to collaborate.

Develop More Efficient Decontamination and Radiation Dose Reduction Methods
Forest decontamination is one of the few methods to reduce air dose rates. Although it is known that there are limitations in terms of cost and effectiveness, as described in the previous sections (Sect. 6.1), it is important to continue working on the development of more efficient decontamination methods and methods of radiation dose reduction. In addition, we can now effectively organize and prepare for the best

measures to be taken in forests in the event of another large-scale nuclear accident in Japan or elsewhere in the world in the future. Preparedness is essential if we are to continue using nuclear power plants.

Deepen Communication Among Government, Residents, and Researchers
It is important for researchers to return the results of their research to the local residents and businesses. Radioactive contamination is a complex issue, and there is no single answer, as it depends not only on the level of contamination in the area, but also on the living and economic conditions of the community. Now that we have a basic understanding of the situation and the future course of radioactive contamination, it will be more important than ever for researchers to deepen the dialogue and collaboration with the government and local residents, to consider various measures and options together, and to take a continuous and combined response.

How to Deal with Forests in Difficult-to-Return Areas
Since the occurrence of the Fukushima Daiichi Nuclear Power Plant accident, people in various organizations have been making efforts to lift the evacuation order for all areas. However, it is inevitable that some areas of forests that cannot be fully decontaminated will remain difficult to use in the long term, and we need to consider how to use such forests in the future. Forests in difficult-to-return areas have higher air dose rates than the residential areas, depending on the location, and it will be necessary to plan for a period of 100 years until the air dose rates are reduced to the target level for exposure protection. For example, if it is not possible to enter the area for a long period of time, it could be used as a mega-plant for renewable energy, or as a base for long-term observation of environmental changes caused by the nuclear power plant accident by conducting periodic ecological surveys while maintaining the natural state with no alteration, as is the case around the Chernobyl Nuclear Power Plant. It is also necessary to conduct research to maintain the forest health ecosystems that have been and will continue to be abandoned for a long time.

7.5 What Should Researchers Do in the Event of a Similar Accident?

The Fukushima nuclear accident has been compared to the Chernobyl nuclear accident, but in the Fukushima accident, data collection began earlier than in the Chernobyl accident, and the data collected are more comprehensive, and the results of the investigation were published in a more open manner. This was probably due to the fact that the Chernobyl accident took place in a country in the former Eastern bloc, the current emphasis on transparency, and the widespread use of the Internet. In addition, very early data were obtained in the forest, since observation systems for the dynamics of water and trace elements in the forest had been set up before the accident, and some of them could be used directly for radiocesium research. In addition, we were able to predict the approximate dynamics of radiocesium in the forest based on the results of research on the Chernobyl accident published in papers and reports, so we were able to quickly set up surveys and observations in preparation for this. Nevertheless, as a researcher, we still have some points to reflect on. To prepare for the future, we have compiled a list of lessons learned on how to conduct effective surveys, including our own reflections as researchers.

Use of existing observation systems

- In the immediate aftermath of the accident, the distribution of radiocesium in the forest changed in a matter of hours to days. To capture such fast changes, it is effective to use existing systems for sampling, such as the observation system used to observe the movement of water in the forest.

How to capture data over time and space

- The dynamics of radiocesium in the forest change from time to time. Contamination is widespread, and the extent of contamination varies. The types of forests and soils are also diverse. Therefore, it is necessary to have a survey method and a system that enables wide and long observation in time and space.

How to collect data to capture cycling

- In forests, unlike farmland, trees are perennially growing (there for decades while growing), and radiocesium circulates in the forest ecosystem. It will be necessary to analyze various parts of the forest, including trees and soil, and to acquire data with an awareness of cycling.

The season in which the accident occurs may have a significant impact on the process from deposition to transfer to soil and subsequent internal cycling through tree phenology (biological seasonality), precipitation patterns and timing, etc.

- Both the Chernobyl and Fukushima nuclear accidents occurred in early spring, before the deciduous broadleaf trees started to leaf out. In Japan, it is also the time of spring rains. What would have happened if the accident had occurred when the deciduous broadleaf trees already had leaves (e.g., summer)? What if it had happened during a dry season when there is no rain? What if it had happened during the rainy season? The mode of deposition and the initial dynamics of radionuclides in the forest would have been very different.

The possibility that, although the phenomena are generally similar, the speed of change over time may not necessarily be the same as in the past

- The behavior of radiocesium in the forest that was observed in the Fukushima accident was approximately similar to that in Chernobyl. However, the speed at which radiocesium transfers from the tree canopy and organic layer to the mineral soil was not necessarily the same. Also, due to the different topography and precipitation, there were different points to watch such as runoff. While referring to past results, it is necessary to conduct surveys according to the location and season in which the accident occurred.

How to get data for various components of the forest (e.g. wood, mushroom, soil) and species

- In addition to the basic components of trees (leaves, branches, and other parts) and soil (organic layer, and mineral soil layers at different depths), forests are ecosystems that contain many species of living things, such as mushrooms, wild plants, insects, and large animals. It is difficult to cover all of them, but it is necessary to conduct as wide a sampling as possible.

Use of geographic information systems (GIS) and models to understand and forecast large areas

- In general, radioactive contamination covers a wide area. It is essential to visualize the spatial extent of contamination by using geographic information systems.
- Rapid and regular air dose rate surveys from aircraft and basin-scale surveys using unmanned aerial vehicles (UAVs) are also effective.
- The behavior of radiocesium in forests is dynamic and shifts over time. In such a case, model-based analysis is more powerful. For more accurate model analysis, it is essential to adjust and verify the model with data.

Observations based on periods of rapid movement and slower movement of radioactive materials

- The key transfer processes are different during the period of faster and larger transfer just after and in the early phases of radioactive deposition, and during the period of entering a quasi-equilibrium phase after several years. It will be necessary to adjust the focus of observations and their frequency according to the situation.

Fixed-point monitoring during normal times, use of archived soil and wood samples from before the accident

- We do not know when an accident will occur. Information about the situation before the accident, such as what the radiocesium concentration was in normal times and how the effects of global fallout were reduced, will help us to better analyze the situation after the accident.

Long-term measures on a multi-decade scale after initial emergency measures

- Because of the half-life of cesium-137 and the perennial nature of forests, it is necessary to consider research and countermeasures over the long term.
- In the long term, major environmental changes, such as climate change, will also occur.
- Poorly managed forests are susceptible to disease, insects, and fires, and trees may expand their growing range, causing the forest area itself to expand.

Interdisciplinary collaboration among research institutes and universities, collaboration among experts in diverse fields, and sharing of accurate analytical techniques

- Researchers from many institutions and universities were involved in the survey. In addition, the fields of study varied. It is important to cooperate with each other, for example, by sharing roles in areas of expertise.
- Techniques for accurately measuring air dose rates and radiocesium concentrations are essential, and they need to be deployed quickly. It is necessary to share the techniques among experts and government research organizations as soon as possible after the accident.
- In addition to analysis, sampling techniques are important. Proper sampling of various parts of the forest (e.g. wood, stream water) requires sound knowledge and skills in forest research. It is necessary to collaborate and share these techniques as well.

Collaboration between government and researchers

- In the Fukushima nuclear accident, a huge amount of data was obtained by the government. If anything, researchers were good at taking detailed data at a limited number of points, while the government was good at taking data from wide areas.
- By sharing data, more comprehensive and useful data can be obtained, which can be used for countermeasures.
- For this purpose, it is necessary for the government and researchers to cooperate technically and exchange information.

Unified data format, data sharing, and rapid data release

- Information on radioactive contamination is of great interest to residents, businesses, and governments. The usual process in the scientific community of "observation, analysis, and publishing a paper" is not enough to provide information quickly, on time as required. It is necessary to release information and data quickly and carefully.
- With the spread of the Internet and the promotion of open data in the scientific community, data release and compilation has become easier and faster than it was during the Chernobyl accident.
- Formatting the data will make it easier to consolidate the data.
- However, there is a question of permanence, for example, will materials published on the Web be accessible in 10 years? It is necessary to have a system to ensure the permanence of materials on the Web.
- The whole world has been watching this accident closely. Overseas researchers are also studying Fukushima. It is necessary to disseminate information and provide data for Japan and overseas.

Information that balances overview, detailed process, and variability

- Because of the interest of residents and the government, researchers are required to communicate with people outside the scientific community. Therefore, it is necessary to communicate overview, details, scientific limitations, and uncertainties in a balanced and easy-to-understand manner.

7.6 Toward the Future

In the past 10 years, most of the radiocesium that fell on the forests due to the Fukushima nuclear accident, cesium-134, has physically decayed to negligible levels. However, cesium-137 will remain in the forest ecosystem, mostly in the surface layer of the soil, but some of it will circulate in the forest. Cesium-137 will also decrease slowly but surely due to radioactive decay, and air dose rates will decrease accordingly. Trees have a long life span, and forests have been nurtured in a slower time than other ecosystems. We, Japanese, have been enjoying various blessings from these forests. Forests not only function as a place for timber production and water source, but also have a strong cultural and psychological connection with us. Fortunately, the radiation level caused by the accident was not strong enough to destroy the functioning of the forest ecosystem itself. Although contaminated, the forests are still alive and strong as ever.

However, as we have seen in this book, the radioactive contamination has changed the lives of people working in forests. Some effective measures have been proposed to deal with radioactive forests, but there is no definitive solution. While we can successfully incorporate various countermeasures, fundamentally we can live with the forest by avoiding radiation exposure through the natural reduction of radiation levels and by making good use of the long time scale of the forest and its ability to retain radiocesium. In recent years, we have received encouraging news that the forests around Chernobyl have become like a nature reserve with living creatures running around. The creatures of the forest are not defeated. We believe that we, too, can continue to live together with the forests, based on accurate scientific information and taking measures to avoid radiation exposure, without giving up. We hope this book will help people to do so.

Bibliography

References

1. Ministry of the Environment (2020) BOOKLET to Provide Basic Information Regarding Health Effects of Radiation. http://www.env.go.jp/chemi/rhm/basic_data.html (in Japanese) (Accessed 27 Nov 2020), https://www.env.go.jp/en/chemi/rhm/basic-info/ (in English) (Accessed 27 Nov 2020)
2. Aoyama M, Yamazawa H, and Nagai H (2018) Current state of atmospheric and oceanic environmental researches on the Fukushima Daiichi nuclear accident: What is known about/from the accident. Journal of the Atomic Energy Society of Japan ATOMO∑ 60: 46–50. https://www.jstage.jst.go.jp/article/jaesjb/60/1/60_46/_article/-char/en (in Japanese)
3. Nuclear Regulation Authority (2021) Airborne Monitoring. In: Monitoring Information of Environmental Radioactivity Level. https://radioactivity.nsr.go.jp/en/list/278/list-1.html (Accessed 25 Oct 2021)
4. Saenko V, Ivanov V, Tsyb A, et al. (2011) The Chernobyl accident and its consequences. Clinical Oncology 23: 234–243. https://doi.org/10.1016/j.clon.2011.01.502
5. Katata G, Chino M (2017) Source term, atmospheric dispersion, and deposition of radionuclides during the Fukushima Daiichi Nuclear Power Station accident. Earozoru Kenkyu 32: 237–243. https://www.jstage.jst.go.jp/article/jar/32/4/32_237/_article/-char/en (in Japanese with English abstract)
6. Katata G, Ota M, Terada H, et al. (2012) Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi Nuclear Power Plant accident. Part I: Source term estimation and local-scale atmospheric dispersion in early phase of the accident. Journal of Environmental Radioactivity 109: 103–113. https://doi.org/10.1016/j.jenvrad.2012.02.006
7. Fukushima Prefecture, Agriculture, Forestry and Fisheries Department (2018) Fukushima Prefecture Forest and Forestry Statistics FY2018. https://www.pref.fukushima.lg.jp/uploaded/attachment/384590.pdf (in Japanese) (Accessed 2 Jun 2020)
8. Ministry of Land, Infrastructure, Transport and Tourism (2020) Digital National Land Information. https://nlftp.mlit.go.jp/ksj/index.html (in Japanese) (Accessed 27 Nov 2020)
9. Hashimoto S, Komatsu M, Imamura N, et al. (2020) Forest Ecosystems. In: Environmental Transfer of Radionuclides in Japan Following the Accident at the Fukushima Daiichi Nuclear Power Plant. IAEA, Vienna, pp. 129–178. https://www.iaea.org/publications/14751/environmental-transfer-of-radionuclides-in-japan-following-the-accident-at-the-fukushima-daiichi-nuclear-power-plant (Accessed 27 Oct 2021)
10. Ministry of the Environment (2020) Radioactive Waste Management Information Website. http://shiteihaiki.env.go.jp/ (in Japanese) (Accessed 28 Nov 2020)

S. Hashimoto et al., *Forest Radioecology in Fukushima*,
https://doi.org/10.1007/978-981-16-9404-2

11. Reconstruction Agency (2020) Basic Information Regarding Health Effects on Radiation. https://www.reconstruction.go.jp/topics/main-cat1/sub-cat1-1/20140603102608.html (in Japanese) (Accessed 28 Nov 2020)
12. ICRP (2007) The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37(2–4). https://www.icrp.org/publication.asp?id=ICRP%20Publication%20103 (Accessed 27 Oct 2021)
13. Kato H, Onda Y, Gomi T (2012) Interception of the Fukushima reactor accident-derived ^{137}Cs, ^{134}Cs and ^{131}I by coniferous forest canopies. Geophysical Research Letters 39: 2012GL052928. https://doi.org/10.1029/2012GL052928
14. Gonze MA, Calmon P (2017) Meta-analysis of radiocesium contamination data in Japanese forest trees over the period 2011–2013. Science of the Total Environment 601–602: 301–316. https://doi.org/10.1016/j.scitotenv.2017.05.175
15. Komatsu M, Kaneko S, Ohashi S, et al (2016) Characterization of initial deposition and behavior of radiocesium in forest ecosystems of different locations and species affected by the Fukushima Daiichi Nuclear Power Plant accident Journal of Environmental Radioactivity 161: 2–10. https://doi.org/10.1016/j.jenvrad.2015.09.016
16. Nishikiori T, Watanabe M, Koshikawa MK, et al. (2019) ^{137}Cs transfer from canopies onto forest floors at Mount Tsukuba in the four years following the Fukushima nuclear accident. Science of the Total Environment 659: 783–789. https://doi.org/10.1016/j.scitotenv.2018.12.359
17. Kato H, Onda Y, Saidin ZH, et al. (2019) Six-year monitoring study of radiocesium transfer in forest environments following the Fukushima nuclear power plant accident. Journal of Environmental Radioactivity 210: 105817. https://doi.org/10.1016/j.jenvrad.2018.09.015
18. Itoh Y, Imaya A, Kobayashi M (2015) Initial radiocesium deposition on forest ecosystems surrounding the Tokyo metropolitan area due to the Fukushima Daiichi Nuclear Power Plant accident. Hydrological Research Letters 9: 1–7. https://www.jstage.jst.go.jp/article/hrl/9/1/9_1/_article/-char/en
19. Endo I, Ohte N, Iseda K, et al. (2015) Estimation of radioactive 137-cesium transport by litterfall, stemflow and throughfall in the forests of Fukushima. Journal of Environmental Radioactivity 149: 176–185. https://doi.org/10.1016/j.jenvrad.2015.07.027
20. Imamura N, Komatsu M, Ohashi S, et al. (2017) Temporal changes in the radiocesium distribution in forests over the five years after the Fukushima Scientific Reports 7: 8179. https://doi.org/10.1038/s41598-017-08261-x
21. Forestry Agency (2020) Result of FY2019 Survey on Radioactive Cesium Distribution in Forests. https://www.rinya.maff.go.jp/j/kaihatu/jyosen/R1_jittaihaaku.html (in Japanese) (Accessed 27 Nov 2020), https://www.maff.go.jp/e/policies/forestry/attach/pdf/Regeneration-29.pdf (Relating report of FY2020, in English) (Accessed 27 Oct 2021)
22. Yamaguchi N, Takada Y, Hayashi K, et al. (2012) Behavior of radiocaesium in soil-plant systems and its controlling factor. Bulletin of National Institute for Agro-Environmental Sciences 31: 75–129. https://doi.org/10.24514/00002996 (in Japanese with English abstract)
23. Yamaguchi N (2014) Adsorption mechanism of radiocesium on soil. Japanese Journal of Soil Physics 126: 11–21. https://www.jstage.jst.go.jp/article/jssoilphysics/126/0/126_11/_article/-char/en (in Japanese)
24. Delvaux B, Kruyts N, Cremers A (2000) Rhizospheric mobilization of radiocesium in soils. Environmental Science and Technology 34: 1489–1493. https://doi.org/10.1021/es990658g
25. Toriyama J, Kobayashi M, Hiruta T, Shichi K (2018) Distribution of radiocesium in different density fractions of temperate forest soils in Fukushima. Forest Ecology and Management 409: 260–266. https://doi.org/10.1016/j.foreco.2017.11.024
26. Manaka T, Imamura N, Kaneko S, et al (2019) Six-year trends in exchangeable radiocesium in Fukushima forest soils. Journal of Environmental Radioactivity 203: 84–92. https://doi.org/10.1016/j.jenvrad.2019.02.014
27. Komatsu M, Hirai K, Nagakura J, Noguchi K (2017) Potassium fertilisation reduces radiocesium uptake by Japanese cypress seedlings grown in a stand contaminated by the

Fukushima Daiichi nuclear accident. Scientific Reports 7: 15612. https://doi.org/10.1038/s41598-017-15401-w

28. Kobayashi R, Kobayashi NI, Tanoi K, et al (2019) Potassium supply reduces cesium uptake in Konara oak not by an alteration of uptake mechanism, but by the uptake competition between ions. Journal of Environmental Radioactivity 208–209: 106032. https://doi.org/10.1016/j.jenvrad.2019.106032
29. Kabata-Pendias A (2010) Trace Elements in Soils and Plants, 4th Edition. CRC Press, Boca Raton
30. Kaneko N, Huang Y, Nakamori T (2015) Decontamination of radio Cs from forest soils using biodiversity and the functioning of soil organisms. Journal of the Japanese Forest Society 97: 75–80. https://www.jstage.jst.go.jp/article/jjfs/97/1/97_75/_article/-char/en (in Japanese with English abstract)
31. Fukuyama T, Takenaka C (2004) Upward mobilization of ^{137}Cs in surface soils of *Chamaecyparis obtusa* Sieb. et Zucc. (hinoki) plantation in Japan. Science of the Total Environment 318: 187–195. https://doi.org/10.1016/S0048-9697(03)00366-8
32. Thiry Y, Garcia-Sanchez L, Hurtevent P (2016) Experimental quantification of radiocesium recycling in a coniferous tree after aerial contamination: field loss dynamics, translocation and final partitioning. Journal of Environmental Radioactivity 161: 42–50. https://doi.org/10.1016/j.jenvrad.2015.12.017
33. Imamura N, Watanabe M, Manaka T (2021) Estimation of the rate of ^{137}Cs root uptake into stemwood of Japanese cedar using an isotopic approach. Science of the Total Environment 755: 142478. https://doi.org/10.1016/j.scitotenv.2020.142478
34. von Fircks Y, Rosén K, Sennerby-Forsse L (2002) Uptake and distribution of ^{137}Cs and ^{90}Sr in *Salix viminalis* plants. Journal of Environmental Radioactivity 63: 1–14. https://doi.org/10.1016/S0265-931X(01)00131-X
35. Calmon P, Thiry Y, Zibold G, et al. (2009) Transfer parameter values in temperate forest ecosystems: a review. Journal of Environmental Radioactivity 100: 757–766. https://doi.org/10.1016/j.jenvrad.2008.11.005
36. Ipatyev V, Bulavik I, Baginsky V, et al. (1999) Forest and Chernobyl: forest ecosystems after the Chernobyl nuclear power plant accident: 1986–1994. Journal of Environmental Radioactivity 42: 9–38. https://doi.org/10.1016/S0265-931X(98)00042-3
37. Ohashi S, Kuroda K, Takano T, et al. (2017) Temporal trends in ^{137}Cs concentrations in the bark, sapwood, heartwood, and whole wood of four tree species in Japanese forests from 2011 to 2016. Journal of Environmental Radioactivity 178–179: 335–342. https://doi.org/10.1016/j.jenvrad.2017.09.008
38. Harada H, Sato H (1966) On the dry matter and nutrient contents of the stem of mature *Cryptomeria* trees, and their distribution to the bark, sapwood and heartwood. Journal of the Japanese Forestry Society 48: 315–324. https://www.jstage.jst.go.jp/article/jjfs1953/48/8/48_8_315/_article (in Japanese with English summary)
39. IAEA (2006) Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience. IAEA, Vienna. https://www.iaea.org/publications/7382/environmental-consequences-of-the-chernobyl-accident-and-their-remediation-twenty-years-of-experience (Accessed 15 Sep 2021)
40. IAEA (2010) Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments. IAEA, Vienna. https://www.iaea.org/publications/8201/handbook-of-parameter-values-for-the-prediction-of-radionuclide-transfer-in-terrestrial-and-freshwater-environments (Accessed 15 Sep 2021)
41. Iwagami S, Tsujimura M, Onda Y, et al. (2019) Dissolved ^{137}Cs concentrations in stream water and subsurface water in a forested headwater catchment after the Fukushima Dai-ichi Nuclear Power Plant accident. Journal of Hydrology 573: 688–696. https://doi.org/10.1016/j.jhydrol.2019.04.019
42. Sakuma K, Nakanishi T, Yoshimura K, et al. (2019) A modeling approach to estimate the ^{137}Cs discharge in rivers from immediately after the Fukushima accident until 2017. Journal of

Environmental Radioactivity 208–209: 106041. https://doi.org/10.1016/j.jenvrad.2019.106041

43. Iwagami S, Onda Y, Tsujimura M, Abe Y (2017) Contribution of radioactive ^{137}Cs discharge by suspended sediment, coarse organic matter, and dissolved fraction from a headwater catchment in Fukushima after the Fukushima Dai-ichi Nuclear Power Plant accident. Journal of Environmental Radioactivity 166: 466–474. https://doi.org/10.1016/j.jenvrad.2016.07.025
44. Shinomiya Y, Tamai K, Kobayashi M, et al. (2014) Radiocesium discharge in stream water from a small watershed in forested headwaters during a typhoon flood event. Soil Science and Plant Nutrition 60: 765–771. https://doi.org/10.1080/00380768.2014.949852
45. Shinomiya Y, Tamai K, Kobayashi M, et al. (2013) The behavior of radioactive materials in stream water from a forested watershed. Kanto Journal of Forest Research 64: 53–56. http://www.kantoforest.jp/papers/pdf/64-2-A14.pdf (in Japanese with English Abstract)
46. Nishikiori T, Hayashi S, Watanabe M, Yasutaka T (2019) Impact of clearcutting on radiocesium export from a Japanese forested catchment following the Fukushima nuclear accident. PLOS ONE 14: e0212348. https://doi.org/10.1371/journal.pone.0212348
47. Evangeliou N, Balkanski Y, Cozic A, et al. (2015) Fire evolution in the radioactive forests of Ukraine and Belarus: future risks for the population and the environment. Ecological Monographs 85: 49–72. https://doi.org/10.1890/14-1227.1
48. Evangeliou N, Zibtsev S, Myroniuk V, et al. (2016) Resuspension and atmospheric transport of radionuclides due to wildfires near the Chernobyl Nuclear Power Plant in 2015: An impact assessment. Scientific Reports 6: 26062. https://doi.org/10.1038/srep26062
49. Yoschenko VI, Kashparov VA, Protsak VP, et al. (2006) Resuspension and redistribution of radionuclides during grassland and forest fires in the Chernobyl exclusion zone: part I. Fire experiments. Journal of Environmental Radioactivity 86: 143–163. https://doi.org/10.1016/j.jenvrad.2005.08.003
50. Ager AA, Lasko R, Myroniuk V, et al. (2019) The wildfire problem in areas contaminated by the Chernobyl disaster. Science of the Total Environment 696: 133954. https://doi.org/10.1016/j.scitotenv.2019.133954
51. UK Centre for Ecology & Hydrology (2017) Red Fire: Radioactive Environment Damaged by Fire. https://www.ceh.ac.uk/redfire (Accessed 28 Nov 2020)
52. Kaneko S, Goto Y, Tabuchi R, et al. (2018) The effect of forest fire on the radiocesium inventory of tree bark and surface soil in ‘difficult-to-return zone’. Bulletin of FFPRI 17: 259–264. https://www.jstage.jst.go.jp/article/ffpri/17/3/17_259/_article/-char/en (in Japanese with English abstract)
53. Fukushima Prefectural Centre for Environmental Creation (2017) Results of Survey to Understand the Environmental Impact of Radioactive Materials Associated with the Namie Town Forest Fire (Interim Report). http://www.pref.fukushima.lg.jp/uploaded/attachment/241494.pdf (in Japanese) (Accessed 28 Nov 2020)
54. Fukushima Prefecture (2018) Results of Radiation Monitoring Around the Site of a Forest Fire in Ide District, Namie Town. https://www.pref.fukushima.lg.jp/site/namie-rinyakasai-201704-05/ (in Japanese) (Accessed 28 Nov 2020)
55. Kurikami H, Sakuma K, Malins A, et al. (2019) Numerical study of transport pathways of ^{137}Cs from forests to freshwater fish living in mountain streams in Fukushima, Japan. Journal of Environmental Radioactivity 208–209: 106005. https://doi.org/10.1016/j.jenvrad.2019.106005
56. Nishina K, Hashimoto S, Imamura N, et al. (2018) Calibration of forest ^{137}Cs cycling model “FoRothCs” via approximate Bayesian computation based on 6-year observations from plantation forests in Fukushima. Journal of Environmental Radioactivity 193–194: 82–90. https://doi.org/10.1016/j.jenvrad.2018.09.002
57. Hashimoto S, Matsuura T, Nanko K, et al. (2013) Predicted spatio-temporal dynamics of radiocesium deposited onto forests following the Fukushima nuclear accident. Scientific Reports 3: 2564. https://doi.org/10.1038/srep02564

58. Nishina K, Hayashi S (2015) Modeling radionuclide Cs and C dynamics in an artificial forest ecosystem in Japan —FoRothCs ver1.0—. Frontiers in Environmental Science 3: 61. https://doi.org/10.3389/fenvs.2015.00061
59. Ota M, Nagai H, Koarashi J (2016) Modeling dynamics of ^{137}Cs in forest surface environments: Application to a contaminated forest site near Fukushima and assessment of potential impacts of soil organic matter interactions. Science of the Total Environment 551–552: 590–604. https://doi.org/10.1016/j.scitotenv.2016.02.068
60. Calmon P, Gonze M-A, Mourlon Ch (2015) Modeling the early-phase redistribution of radiocesium fallouts in an evergreen coniferous forest after the Chernobyl and Fukushima accidents. Science of the Total Environment 529: 30–39. https://doi.org/10.1016/j.scitotenv.2015.04.084
61. Shaw G, Avila R, Fesenko S, et al. (2003) Chapter 11 Modelling the Behaviour of Radiocaesium in Forest Ecosystems. In: Scott EM (ed) Radioactivity in the Environment. Elsevier, pp 315–351. https://doi.org/10.1016/S1569-4860(03)80067-0
62. Linkov I, Schell WR (eds) (1999) Contaminated Forests: Recent Developments in Risk Identification and Future Perspectives. Kluwer Academic Publishers, Amsterdam.
63. IAEA (2002) Modelling the Migration and Accumulation of Radionuclides in Forest Ecosystems, Report of the Forest Working Group of the Biosphere Modelling and Assessment (BIOMASS), Theme 3. IAEA, Vienna. https://www.iaea.org/publications/6625/modelling-the-migration-and-accumulation-of-radionuclides-in-forest-ecosystems (Accessed 27 Oct 2021)
64. Hashimoto S, Imamura N, Kaneko S, et al. (2020) New predictions of ^{137}Cs dynamics in forests after the Fukushima nuclear accident. Scientific Reports 10: 29. https://doi.org/10.1038/s41598-019-56800-5
65. Shaw G, Venter A, Avila R, et al. (2005) Radionuclide migration in forest ecosystems — results of a model validation study. Journal of Environmental Radioactivity 84: 285–296. https://doi.org/10.1016/j.jenvrad.2003.09.006
66. Forestry and Forest Products Research Institute (2020) Collection of Research results 2020 fiscal year. https://www.ffpri.affrc.go.jp/pubs/seikasenshu/2020/index.html (in Japanese) (Accessed 28 Nov 2020)
67. Fukushima Prefecture (2020) Results of Radioactive Materials Survey in Forests. https://www.pref.fukushima.lg.jp/site/portal/ps-shinrinhousyasei.html (in Japanese), https://www.pref.fukushima.lg.jp/uploaded/attachment/393608.pdf (pdf in Japanese) (Accessed 27 Nov 2020)
68. Kinase S, Takahashi T, Saito K (2017) Long-term predictions of ambient dose equivalent rates after the Fukushima Daiichi nuclear power plant. Journal of Nuclear Science and Technology 54: 1345–1354. https://doi.org/10.1080/00223131.2017.1365659
69. Kaneko N. (2004) Soil formation and soil animals. Kagaku To Seibutsu 42: 408–415. https://www.jstage.jst.go.jp/article/kagakutoseibutsu1962/42/6/42_6_408/_article/-char/en (in Japanese)
70. Shang H, Wang P, Wang T, et al. (2013) Bioaccumulation of PCDD/Fs, PCBs and PBDEs by earthworms in field soils of an E-waste dismantling area in China. Environment International 54: 50–58. https://doi.org/10.1016/j.envint.2013.01.006
71. Yasuda M, Yamada F (2006) Accumulation and behavior of POPs in terrestrial ecosystems: A case study of a lake and a mountain in the eastern Kanto area. Chemical Substances and Environment 76: 13–15. (in Japanese)
72. Forestry and Forest Products Research Institute (2014) Radiocesium Concentration in Earthworms is Lower than that in Leaf Litter. Environmental Report. pp. 15–16. https://www.ffpri.affrc.go.jp/kankyou/documents/kankyouhoukokusho2014.pdf (in Japanese) (Accessed 27 Oct 2021)
73. Hasegawa M, Kaneko S, Ikeda S, et al. (2015) Changes in radiocesium concentrations in epigeic earthworms in relation to the organic layer 2.5 years after the 2011 Fukushima Dai-ichi Nuclear Power Plant accident. Journal of Environmental Radioactivity 145: 95–101. https://doi.org/10.1016/j.jenvrad.2015.03.015

74. Hasegawa M, Ito MT, Kaneko S, et al. (2013) Radiocesium concentrations in epigeic earthworms at various distances from the Fukushima Nuclear Power Plant 6 months after the 2011 accident. Journal of Environmental Radioactivity 126: 8–13. https://doi.org/10.1016/j.jenvrad.2013.06.006
75. Fujiwara K, Takahashi T, Nguyen P, et al. (2015) Uptake and retention of radiocaesium in earthworms cultured in soil contaminated by the Fukushima nuclear power plant accident. Journal of Environmental Radioactivity 139: 135–139. https://doi.org/10.1016/j.jenvrad.2014.10.011
76. Tanaka S, Adati T, Takahashi T, et al. (2018) Concentrations and biological half-life of radiocesium in epigeic earthworms after the Fukushima Dai-ichi Nuclear Power Plant accident. Journal of Environmental Radioactivity 192: 227–232. https://doi.org/10.1016/j.jenvrad.2018.06.020
77. Yoshimura M, Akama A (2014) Radioactive contamination of aquatic insects in a stream impacted by the Fukushima nuclear power plant accident. Hydrobiologia 722: 19–30. https://doi.org/10.1007/s10750-013-1672-9
78. Murakami M, Ohte N, Suzuki T, et al. (2014) Biological proliferation of cesium-137 through the detrital food chain in a forest ecosystem in Japan. Scientific Reports 4: 3599. https://doi.org/10.1038/srep03599
79. Steiner M, Linkov I, Yoshida S (2002) The role of fungi in the transfer and cycling of radionuclides in forest ecosystems. Journal of Environmental Radioactivity 58: 217–241. https://doi.org/10.1016/S0265-931X(01)00067-4
80. Strand P, Sundell-Bergman S, Brown JE, Dowdall M (2017) On the divergences in the assessment of environmental impacts from ionising radiation following the Fukushima accident. Journal of Environmental Radioactivity 169–170: 159–173. https://doi.org/10.1016/j.jenvrad.2016.12.005
81. Tamaoki M (2016) Studies on radiation effects from the Fukushima nuclear accident on wild organisms and ecosystems. Global Environmental Research 20: 73–82. http://www.airies.or.jp/journal_GlobalEnvironmentalResearch_201705291027585.html (Accessed 27 Oct 2021)
82. Beresford NA, Adam-Guillermin C, Bonzom J-M, et al. (2012) Comment on “Abundance of birds in Fukushima as judged from Chernobyl” by Møller et al. (2012). Environmental Pollution 169: 136. https://doi.org/10.1016/j.envpol.2012.05.011
83. Mousseau TA, Møller AP, Ueda K (2012) Reply to “Comment on ‘Abundance of birds in Fukushima as judged from Chernobyl’ by Møller et al. (2012)”. Environmental Pollution 169: 137–138. https://doi.org/10.1016/j.envpol.2012.05.012
84. Mousseau TA, Møller AP (2012) Reply to response regarding “Abundance of birds in Fukushima as judged from Chernobyl” by Møller et al. (2012). Environmental Pollution 169: 141–142. https://doi.org/10.1016/j.envpol.2012.05.014
85. Copplestone D, Beresford N (2014) Questionable Studies won’t Help Identify Fukushima’s Effects. In: The Conversation. http://theconversation.com/questionable-studies-wont-help-identify-fukushimas-effects-26772 (Accessed 1 Dec 2020)
86. Beresford NA, Scott EM, Copplestone D (2020) Field effects studies in the Chernobyl Exclusion Zone: Lessons to be learnt. Journal of Environmental Radioactivity 211: 105893. https://doi.org/10.1016/j.jenvrad.2019.01.005
87. Watanabe Y, Ichikawa S, Kubota M, et al. (2015) Morphological defects in native Japanese fir trees around the Fukushima Daiichi Nuclear Power Plant. Scientific Reports 5: 13232. https://doi.org/10.1038/srep13232
88. Yoschenko V, Nanba K, Yoshida S, et al. (2016) Morphological abnormalities in Japanese red pine (*Pinus densiflora*) at the territories contaminated as a result of the accident at the Fukushima Dai-Ichi Nuclear Power Plant. Journal of Environmental Radioactivity 165: 60–67. https://doi.org/10.1016/j.jenvrad.2016.09.006
89. Quantum Science and Technology Research Organization, Quantum Medicine and Medical Care Division (2020) Effects on environmental organisms (Q&A related to the accident at

TEPCO's Fukushima Daiichi Nuclear Power Station). https://www.qst.go.jp/site/qms/39510.html (in Japanese) (Accessed 1 Dec 2020)

90. Ishihara M, Tadono T (2017) Land cover changes induced by the great east Japan earthquake in 2011. Scientific Reports 7: 45769. https://doi.org/10.1038/srep45769
91. Okuda K, Onuma M, Oi T, et al. (2018) A report on the workshop "Direct/Indirect effects on wild mammals caused by radioactive contamination" at the Annual Meeting of the Mammal Society of Japan 2017. Mammalian Science 58: 113–114. https://www.jstage.jst.go.jp/article/mammalianscience/58/1/58_113/_pdf/-char/en (in Japanese)
92. Sekizawa R, Ichii K, Kondo M (2015) Satellite-based detection of evacuation-induced land cover changes following the Fukushima Daiichi nuclear disaster. Remote Sensing Letters 6: 824–833. https://doi.org/10.1080/2150704X.2015.1076207
93. Lyons PC, Okuda K, Hamilton MT, et al. (2020) Rewilding of Fukushima's human evacuation zone. Frontiers in Ecology and the Environment 18: 127–134. https://doi.org/10.1002/fee.2149
94. Garnier-Laplace J, Beaugelin-Seiller K, Della-Vedova C, et al. (2015) Radiological dose reconstruction for birds reconciles outcomes of Fukushima with knowledge of dose-effect relationships. Scientific Reports 5: 16594. https://doi.org/10.1038/srep16594
95. Perino A, Pereira HM, Navarro LM, et al. (2019) Rewilding complex ecosystems. Science 364: eaav5570. https://doi.org/10.1126/science.aav5570
96. Forestry and Forest Products Research Institute (2015) How to Reduce the Damage Caused by Japanese Oak (*Quercus mongolica* var. *japonica*) — New Development —. https://www.ffpri.affrc.go.jp/pubs/chukiseika/documents/3rd-chuukiseika26.pdf (in Japanese) (Accessed 26 Oct 2021)
97. Aoyama M, Hirose K, Igarashi Y (2006) Re-construction and updating our understanding on the global weapons tests ^{137}Cs fallout. Journal of Environmental Monitoring 8: 431. https://doi.org/10.1039/B512601K
98. Nuclear Regulation Authority (2021) Environmental Radiation Database. https://www.kankyo-hoshano.go.jp/ (Accessed 26 Oct 2021)
99. Ito E, Miura S, Aoyama M, Shichi K (2020) Global ^{137}Cs fallout inventories of forest soil across Japan and their consequences half a century later. Journal of Environmental Radioactivity 225: 106421. https://doi.org/10.1016/j.jenvrad.2020.106421
100. Fukuyama T, Onda Y, Takenaka C, Walling DE (2008) Investigating erosion rates within a Japanese cypress plantation using Cs-137 and Pb-210_{ex} measurements. Journal of Geophysical Research 113: F02007. https://doi.org/10.1029/2006JF000657
101. Collins AL, Blackwell M, Boeckx P, et al. (2020) Sediment source fingerprinting: benchmarking recent outputs, remaining challenges and emerging themes. Journal of Soils and Sediments 20: 4160– 4193. https://doi.org/10.1007/s11368-020-02755-4
102. Kuroda K, Yamane K, Itoh Y (2020) Radial movement of minerals in the trunks of standing Japanese cedar *Cryptomeria japonica* D. Don trees in summer by tracer analysis. Forests 11: 562. https://doi.org/10.3390/f11050562
103. ICRP (2009) Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas after a Nuclear Accident or a Radiation Emergency. ICRP Publication 111. Ann. ICRP 39(3). https://www.icrp.org/publication.asp?id=icrp%20publication%20111 (Accessed 27 Oct 2021)
104. ICRP (2009) Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations. ICRP Publication 109. Ann. ICRP 39(1). https://www.icrp.org/publication.asp?id=icrp%20publication%20109 (Accessed 27 Oct 2021)
105. ICRP 111 Commentary Editorial Committee (2015) ICRP 111 for Talking Together: Hometown Life and Radiation Protection. Japan Radioisotope Association, Tokyo.
106. IAEA (2015) The Fukushima Daiichi Accident — Technical Volume 4/5, Radiological Consequences. Vienna. https://www.iaea.org/publications/10962/the-fukushima-daiichi-accident (Accessed 27 Oct 2021)

107. Ogino H, Hamada N, Sugiyama D (2013) Application of reference levels in the existing exposure situations: Towards stepwise reduction of radiation dose depending on situations of contamination. Journal of the Atomic Energy Society of Japan ATOMOΣ 55: 106–110. https://www.jstage.jst.go.jp/article/jaesjb/55/2/55_106/_article/-char/en (in Japanese), https://www.aesj.net/document/fukushima_vol1/1-256_263.pdf (Translated version) (Accessed 27 Oct 2021)
108. Ministry of the Environment (2020) Decontamination Information Website. http://josen.env.go.jp (in Japanese) (Accessed Oct 25, 2021), http://josen.env.go.jp/en/ (in English) (Accessed Oct 25, 2021)
109. Forestry Agency (2018) Considerations for Prevention of Radiation Hazards in Operations in Forests and Other Areas (Q&A). https://www.rinya.maff.go.jp/j/routai/anzen/sagyou.html (in Japanese) (Accessed 21 Nov 2020)
110. Safety and Health Information Center (2012) Pamphlet on Work Under Specific Radiation Doses (for Workers). In: Related to the Great East Japan Earthquake. https://www.jaish.gr.jp/information/tokuteipamph_sagyou.pdf (in Japanese) (Accessed 28 Nov 2020)
111. Consumer Affairs Agency (2020) Food and Radiation Q and A, 14th Edition. https://www.caa.go.jp/disaster/earthquake/understanding_food_and_radiation/material/ (in Japanese) (Accessed 28 Nov 2020), https://www.caa.go.jp/disaster/earthquake/understanding_food_and_radiation/material/pdf/130902_food_qa_en.pdf (translated pamphlet in English) (Accessed 20 Feb 2022)
112. Ministry of Education, Culture, Sports, Science and Technology (2011) Technical Standard for Prevention of Radiation Hazards Under the Provisions of the Act on Special Measures Concerning the Handling of Contamination by Radioactive Materials. https://warp.ndl.go.jp/info:ndljp/pid/3193671/www.mext.go.jp/b_menu/shingi/housha/shiryo/1313892.htm (in Japanese) (Accessed 21 Nov 2020)
113. Imamura N, Kobayashi M, Kaneko S (2018) Forest edge effect in a radioactivity contaminated forest in Fukushima, Japan. Journal of Forest Research 23: 15–20. https://doi.org/10.1080/13416979.2017.1396417
114. Yasuda Y (2017) Air dose rate in forests and its temporal changes for the past five years. Water Science 61: 102–130. https://www.jstage.jst.go.jp/article/suirikagaku/61/5/61_102/_article/-char/en (in Japanese)
115. Nuclear Regulation Authority (2016) 2015 Fiscal Year Report on the Results of the Project for Consolidating Distribution Data of Radioactive Substances Associated with the Accident at TEPCO's Fukushima Daiichi Nuclear Power Station. In: Monitoring Information of Environmental Radioactivity Level. https://radioactivity.nsr.go.jp/ja/list/564/list-1.html (in Japanese) (Accessed 21 Nov 2020) https://www.nsr.go.jp/data/000067236.pdf (related information in English) (Accessed 29 Oct 2021)
116. Fukushima Prefecture (2020) Changes in Evacuation Zones. In: Fukushima Revitalization Station https://www.pref.fukushima.lg.jp/site/portal/cat01-more.html (in Japanese) (Accessed 2 Jun 2020)
117. Ministry of Economy, Trade and Industry (2020) Information on Evacuation Orders to Date. In: Disaster Related Information. https://www.meti.go.jp/earthquake/nuclear/hinan_history.html (in Japanese) (Accessed 27 Oct 2021), https://www.meti.go.jp/english/earthquake/nuclear/roadmap/index.html (related information in English) (Accessed 20 Oct 2021)
118. Kimura K (2019) The influence of the nuclear disaster on the wood supply and demand and the present situation of forestry and wood industry in Fukushima Prefecture. Journal of the Japanese Forest Society 101: 7–13. https://www.jstage.jst.go.jp/article/jjfs/101/1/101_7/_article/-char/en (in Japanese with English abstract)
119. Ministry of Agriculture, Forestry and Fisheries (2012) FY2011 Annual Report on Food, Agriculture and Rural Areas in Japan, Contamination of Agricultural Land and Soil by Radioactive Substances and Response. https://www.maff.go.jp/j/wpaper/w_maff/h23/index.html (in Japanese) (Accessed 28 Oct 2021), https://www.maff.go.jp/j/wpaper/w_maff/h23/pdf/e_all.pdf (summary in English) (Accessed 4 Apr 2022)

120. Ministry of the Environment (2020) Decontamination of Forests. In: Decontamination Information Website. http://josen.env.go.jp/about/efforts/forest.html (in Japanese) (Accessed 27 Nov 2020)
121. Forestry Agency (2011) Results of the Demonstration Test for Decontamination of Forest (2nd Report). Forestry Agency Press Release. https://www.rinya.maff.go.jp/j/kaihatu/jyosen/attach/pdf/index-12.pdf (in Japanese) (Accessed 30 Nov 2020)
122. Reconstruction Agency (2020) Satoyama Restoration Model Project. https://www.reconstruction.go.jp/topics/main-cat1/sub-cat1-4/forest/20170113183504.html (in Japanese) (Accessed 21 Nov 2020)
123. Forestry Agency (2019) Results of the Validation and Development Project for Countermeasures Against Radioactive Substances in Forests. https://www.rinya.maff.go.jp/j/kaihatu/jyosen/201228.html (in Japanese) (Accessed 21 Oct 2021)
124. Yasutaka T, Naito W (2016) Assessing cost and effectiveness of radiation decontamination in Fukushima Prefecture, Japan. Journal of Environmental Radioactivity 151: 512–520. https://doi.org/10.1016/j.jenvrad.2015.05.012
125. Fukushima Prefecture Forestation Division (2020) On the Situation and Future Prediction of Radioactive Substances in Forests. https://www.pref.fukushima.lg.jp/uploaded/attachment/393610.pdf (in Japanese) (Accessed 21 Nov 2020)
126. Forestry Agency (2018) The Current State of Radioactive Substances in Forests and Regeneration of Forests and Forestry 2018 Edition (Pamphlet). https://www.rinya.maff.go.jp/j/kaihatu/jyosen/houshasei_panfu.html (Accessed 28 Nov 2020)
127. Fukushima Prefecture (2014) Guidelines for Felling and Moving Trees from Private Forests of Fukushima Prefecture. (in Japanese)
128. Fukushima Minpo (2016) 90% of Privately Owned Forests Can be Cut Down, Below Prefectural Radiation Standards. https://www.minpo.jp/pub/topics/jishin2011/2016/01/post_12901.html (in Japanese) (Accessed 2 Jun 2020)
129. Forestry Agency (2012) Establishment of Index Values for Mushroom Logs and Cultivars, and Firewood and Charcoal for Cooking and Heating. In: Sectoral Information. https://www.rinya.maff.go.jp/j/tokuyou/shihyouti-index.html (in Japanese) (Accessed 2 Jun 2020)
130. Ministry of the Environment (2012) Exposure Assessment of Ash Generated by the Use of Wood Stoves. http://www.env.go.jp/jishin/rmp/attach/no120119001_eval.pdf (in Japanese) (Accessed 24 Sep 2020)
131. Ministry of Agriculture, Forestry and Fisheries (2012) Provisional Permissible Values for Fertilizers, Soil Conditioning Materials, Culture Soil and Feed Containing Radiocesium. https://www.maff.go.jp/j/syouan/soumu/saigai/supply.html (in Japanese) (Accessed 2 Jun 2020)
132. Forestry Agency (2020) Forest and Forestry Statistics Handbook 2019. https://www.rinya.maff.go.jp/j/kikaku/toukei/youran_mokuzi2019.html (in Japanese) (Accessed 28 Nov 2020)
133. Japan Atomic Energy Agency (2014) Management of Removed Materials. In: Cleanup Navi. https://fukushima.jaea.go.jp/c-navi/ja/resources/waste-managment-kernel.html (in Japanese) (Accessed 4 Apr 2022)
134. Otsuka Y, Navarro RR, Nakamura M, Magara K (2018) Methane Fermentation of Woody Biomass: A New Technology Applicable to Radioactively Contaminated Biomass. https://www.ffpri.affrc.go.jp/pubs/seikasenshu/2018/documents/p26–27.pdf (in Japanese) (Accessed 21 Oct 2021)
135. Ministry of Health, Labour and Welfare (2020) Restriction of Distribution and/or Consumption of Contaminated Food. https://www.mhlw.go.jp/stf/kinkyu/2r9852000001dd6u.html (in Japanese) (Accessed 28 Oct 2021), https://www.mhlw.go.jp/english/topics/2011eq/index_food_press.html (related page in English) (Accessed 20 Oct 2021)
136. Tsujino R, Ishimaru E, Yumoto T (2010) Distribution patterns of five mammals in the Jomon period, middle Edo period, and the present, in the Japanese archipelago. Mammal Study 35: 179–189. https://doi.org/10.3106/041.035.0304

137. Ministry of the Environment (2010) Guidelines for the Preparation of Specific Wildlife Protection and Management Plans (Wild Boar Edition). Protection and Management of Wild Birds and Animals. https://www.env.go.jp/nature/choju/plan/plan3-2a/index.html (in Japanese) (Accessed 24 Sep 2020)
138. Fukushima Prefecture (2019) Wild Boar Management Plan in Fukushima Prefecture (Phase 3). https://www.pref.fukushima.lg.jp/uploaded/life/609103_1687969_misc.pdf (in Japanese) (Accessed 4 Apr 2022)
139. Ministry of the Environment (2019) Statistics on Birds and Animals. In: Protection and Management of Wild Birds and Animals. https://www.env.go.jp/nature/choju/docs/docs2.html (in Japanese) (Accessed 28 Nov 2020)
140. Ueda G, Takahashi MA, Sasaki C, et al. (2018) Effects of radioactive contamination by Fukushima nuclear accident on hunting and wildlife management, with emphasis on wild boar management. Wildlife and Human Society 6: 1–11. https://www.jstage.jst.go.jp/article/awhswhs/6/1/6_1/_article/-char/en (in Japanese with English abstract)
141. Tagami K, Howard BJ, Uchida S (2016) The time-dependent transfer factor of radiocesium from soil to game animals in Japan after the Fukushima Dai-ichi nuclear accident. Environmental Science and Technology 50: 9424–9431. https://doi.org/10.1021/acs.est.6b03011
142. Nemoto Y, Saito R, Oomachi H (2018) Seasonal variation of cesium-137 concentration in Asian black bear (*Ursus thibetanus*) and wild boar (*Sus scrofa*) in Fukushima Prefecture, Japan. PLOS ONE 13: e0200797. https://doi.org/10.1371/journal.pone.0200797
143. Steiner M, Fielitz U (2009) Deer truffles — the dominant source of radiocaesium contamination of wild boar. Radioprotection 44: 585–588. https://doi.org/10.1051/radiopro/20095108
144. Kodera Y, Kanzaki N, Ishikawa N, Minagawa A (2013) Food habits of wild boar (*Sus scrofa*) inhabiting Iwami District, Shimane Prefecture, western Japan. Mammalian Science 53: 279–287. https://www.jstage.jst.go.jp/article/mammalianscience/53/2/53_279/_article/-char/en (in Japanese with English abstract)
145. Ministry of Agriculture, Forestry and Fisheries (2013) Recommended Measures Against Wild Boar Damage: Advanced Approaches Focusing on Trapping, March 2013. https://www.maff.go.jp/j/seisan/tyozyu/higai/manyuaru/taisaku_inosisi_hokaku/inosisi_hokaku.html (in Japanese) (Accessed 24 Sep 2020)
146. Fukushima Environmental Creation Center, National Institute for Environmental Studies (2018) Technical Data on the Proper Treatment of Captive Wild Boars Containing Radiocesium in Fukushima Prefecture. http://www.pref.fukushima.lg.jp/uploaded/attachment/294342.pdf (in Japanese) (Accessed 24 Sep 2020)
147. Japan Forest Products Association (2005) Sansai (Edible Wild Plants): Science of Their Relationship with Health. https://nittokusin.jp/sansai/index.html (in Japanese) (Accessed 23 Mar 2020)
148. Saito H (2017) Forest culture in sansai and mushrooms (Special issue on the blessings of forest and biocultural diversity). Forest Environment 2017: 12–21. https://www.shinrinbunka.com/publish/shinrin/6707.html (in Japanese) (Accessed 27 Oct 2021)
149. Saito H (2015) Report 1: Special Forest products and forest societies (forest and food renaissance: Creating, enjoying, and using mountains-consideration of a new vocation, the 2014 Symposium Supported by National Land Afforestation Promotion Organization). Forest Economy 67: 2–6. https://www.jstage.jst.go.jp/article/rinrin/67/12/67_KJ00009961763/_article/-char/en (in Japanese)
150. Matsuura T, Hayashi M, Sugimura K, et al. (2013) Ecosystem services valuation of harvesting edible wild plants/mushrooms − A case study in Tadami Town, Fukushima Prefecture−. Japan Society of Forest Planning 47: 55–81. https://www.jstage.jst.go.jp/article/jjfp/47/2/47_KJ00010028725/_article/-char/en (in Japanese with English abstract)
151. Kawarazaki SH, Sugimura K (2012) Estimation of frequency and locality of collection of wild mushroom and wild vegetables by internet search. Journal of Japanese Forest Society 94: 95–99. https://www.jstage.jst.go.jp/article/jjfs/94/2/94_95/_article/-char/en (in Japanese with English abstract)

152. Ministry of Health, Labour and Welfare (2020) Levels of Radioactive Materials in Foods Tested in Respective Prefectures. In: Information on the Great East Japan Earthquake. https://www.mhlw.go.jp/english/topics/2011eq/index_food_radioactive.html (Accessed 20 Oct 2021)
153. Forestry Agency (2020) Status of Shipment Restrictions on Mushrooms and Wild Plants. https://www.rinya.maff.go.jp/j/tokuyou/kinoko/syukkaseigen.html (in Japanese) (Accessed 24 Nov 2020)
154. Komatsu M, Nishina K, Hashimoto S (2019) Extensive analysis of radiocesium concentrations in wild mushrooms in eastern Japan affected by the Fukushima nuclear accident: Use of open accessible monitoring data. Environmental Pollution 255: 113236. https://doi.org/10.1016/j.envpol.2019.113236
155. Kiyono Y (2018) What we have learned about the concentration of radiocesium in wild vegetables: To avoid picking wild vegetables with high concentration. Quarterly Journal of FFPRI 40: 12–13. https://www.ffpri.affrc.go.jp/pubs/kikan/documents/kikanffpri40-research1.pdf (in Japanese) (Accessed 27 Oct 2021)
156. Kiyono Y, Akama A, Iwaya M, Yoshida Y (2019) Transfer of radiocesium released in the 2011 Fukushima Daiichi Nuclear Power Station accident to *Eleutherococcus sciadophylloides*, a wild tree that produces edible sprouts. Bulletin of FFPRI 18: 195–211. https://www.jstage.jst.go.jp/article/ffpri/18/2/18_195/_article/-char/en (in Japanese with English abstract)
157. Yamaji K, Nagata S, Haruma T, et al. (2016) Root endophytic bacteria of a ^{137}Cs and Mn accumulator plant, *Eleutherococcus sciadophylloides*, increase ^{137}Cs and Mn desorption in the soil. Journal of Environmental Radioactivity 153: 112–119. https://doi.org/10.1016/j.jenvrad.2015.12.015
158. Shigematsu Y, Sugimura K, Sakai M (2018) The trends in the outdoor recreation activities in Fukushima Prefecture: exploring the effects of the East Japan Earthquake. Journal of Environmental Studies, Nagasaki University 21: 43–54. https://nagasaki-u.repo.nii.ac.jp/?action=pages_view_main&active_action=repository_view_main_item_detail&item_id=1455&item_no=1&page_id=13&block_id=21 (in Japanese with English summary) (Accessed 27 Oct 2021)
159. Matsuura T (2021) Impact of the Fukushima nuclear accident on the life of mountain villages and prospects for recovery. Forest Science 91: 16–18. https://www.jstage.jst.go.jp/article/jjsk/91/0/91_16/_article/-char/en (in Japanese), https://researchmap.jp/tm50jp/misc/31757839/attachment_file.pdf (pdf) (Accessed 28 Oct 2021)
160. Kiyono Y, Akama A (2019) Cesium-137 food-processing factors and food-processing retention factors of 11 organs and 10 edible wild plant species from Japan: recipes for long-term preservation reduced the radiocesium mass the most. Bulletin of FFPRI 18: 369–380. https://www.jstage.jst.go.jp/article/ffpri/18/4/18_369/_article/-char/en (in Japanese with English abstract)
161. Nabeshi H, Tsutsumi T, Uekusa Y, et al. (2016) Effects of cooking process on the changes of concentration and total amount of radioactive caesium in beef, wild plants and fruits. Radioisotopes 65: 45–58. https://www.jstage.jst.go.jp/article/radioisotopes/65/2/65_650201/_article/-char/en (in Japanese with English abstract)
162. Forestry Agency (2019) Annual Report on Forest and Forestry in Japan, 2018 Fiscal Year. https://www.rinya.maff.go.jp/j/kikaku/hakusyo/30hakusyo_h/all/index.html (in Japanese) (Accessed 22 Nov 2020), https://www.maff.go.jp/e/data/publish/attach/pdf/index-176.pdf (summary version in English) (Accessed 15 Sep 2021)
163. Forestry and Forest Products Research Institute (2012) Project Report on Measures for Stable Supply of Safe Mushroom Logs in 2011 Fiscal Year. https://www.ffpri.affrc.go.jp/pubs/various/documents/kinoko-genboku.pdf (in Japanese) (Accessed 22 Nov 2020)
164. Forestry Agency (2012) Approaches for Uncovering Information on the Availability of Mushroom Logs. https://www.rinya.maff.go.jp/j/tokuyou/genboku_jukyu.html (in Japanese) (Accessed 23 Nov 2020)

165. Tokyo Metropolitan Central Wholesale Market (2020) Market Statistics (Monthly and Annual Reports). http://www.shijou-tokei.metro.tokyo.lg.jp/ (in Japanese) (Accessed 15 Sep 2021)
166. Ministry of Agriculture, Forestry and Fisheries (2020) Statistical Survey on Production of Non-wood Forest Products. https://www.maff.go.jp/j/tokei/kouhyou/tokuyo_rinsan/ (in Japanese) (Accessed 23 Nov 2020)
167. Iwasawa M (2017) Relationship of the radioactive cesium concentration with bed-log each parts and the shiitake mushroom (*Lentinula edodes*), and influence of cultivation period on cesium concentration. Kanto Journal of Forest Research 68: 157–160. (in Japanese)
168. Sakata H, Toma H (2014) Research on radioactive materials in mushrooms (1) Decontamination of shiitake mushroom logs using a decontamination machine (2). Report of the Gunma Forestry Experiment Station. 58–59. https://www.pref.gunma.jp/07/p13700521.html (in Japanese) (Accessed 27 Oct 2021)
169. Ohashi Y, Ishikawa Y, Sugimoto E, et al. (2015) Effect of Prussian Blue for reduction of radiocesium content on bed-log cultivation of *Lentinula edodes*. Kanto Journal of Forest Research 66: 101–102. http://www.kantoforest.jp/papers/pdf/66-1-S13.pdf (in Japanese) (Accessed 27 Oct 2021)
170. Ito H, Ogawa H, Kumata A (2018) Investigation of techniques to reduce radiocesium in processed lumber and mushroom logs. Bulletin of the Fukushima Prefectural Forestry Research Centre 50: 9–19. https://www.pref.fukushima.lg.jp/uploaded/attachment/257016.pdf (in Japanese) (Accessed 27 Oct 2021)
171. Ohnuki T, Aiba Y, Sakamoto F, et al. (2016) Direct accumulation pathway of radiocesium to fruit-bodies of edible mushroom from contaminated wood logs. Scientific Reports 6: 29866. https://doi.org/10.1038/srep29866
172. Haraguchi M, Miyake S, Yoshida T, Ohno T (2016) Study of mitigation of environmental radiocesium pollution in the cultivated *Pholiota microspora* mushroom by using *Chamaecyparis obtusa* bed-log cultivation method. Journal of the Japanese Forest Society 98: 128–131. https://www.jstage.jst.go.jp/article/jjfs/98/3/98_128/_article/-char/en (in Japanese with English abstract)
173. Forestry Agency (2013) Guidelines for the Management of Log Mushroom Cultivation to Reduce Radioactive Materials. Forestry Agency Press Release. https://www.rinya.maff.go.jp/j/press/tokuyou/pdf/131016-01.pdf (in Japanese) (Accessed 2 Jun 2020)
174. Kanasashi T, Miura S, Hirai K, et al. (2020) Relationship between the activity concentration of ^{137}Cs in the growing shoots of *Quercus serrata* and soil ^{137}Cs, exchangeable cations, and pH in Fukushima, Japan. Journal of Environmental Radioactivity 220–221: 106276. https://doi.org/10.1016/j.jenvrad.2020.106276
175. Forestry and Forest Products Research Institute (2018) Resumption and Restoration of Use of Shiitake Mushroom Log Forests in Radioactively Contaminated Areas. https://www.ffpri.affrc.go.jp/rad/documents/20181206shiitake.pdf (in Japanese) (Accessed 29 Nov 2020)

Key Review Papers

First analysis of spatial distribution of forest contamination

Hashimoto S, Ugawa S, Nanko K, Shichi K (2012) The total amounts of radioactively contaminated materials in forests in Fukushima, Japan. Scientific Reports 2: 416. https://doi.org/10.1038/srep00416

Comprehensive monitoring of radiocesium distribution within forests in the early phase

Imamura N, Komatsu M, Ohashi S, et al. (2017) Temporal changes in the radiocesium distribution in forests over the five years after the Fukushima Daiichi Nuclear Power Plant accident. Scientific Reports 7: 8179. https://doi.org/10.1038/s41598-017-08261-x

Comprehensive monitoring of radiocesium transfer within forests in the early phase

Kato H, Onda Y, Saidin ZH, et al. (2019) Six-year monitoring study of radiocesium transfer in forest environments following the Fukushima Nuclear Power Plant accident. Journal of Environmental Radioactivity 210: 105817. https://doi.org/10.1016/j.jenvrad.2018.09.015

Model prediction by 6 forest models

Hashimoto S, Tanaka T, Komatsu M, et al. (2021) Dynamics of radiocaesium within forests in Fukushima—results and analysis of a model inter-comparison. Journal of Environmental Radioactivity 238–239: 106721. https://doi.org/10.1016/j.jenvrad.2021.106721

Extensive analysis of mushroom contamination

Komatsu M, Nishina K, Hashimoto S (2019) Extensive analysis of radiocesium concentrations in wild mushrooms in eastern Japan affected by the Fukushima nuclear accident: Use of open accessible monitoring data. Environmental Pollution 255: 113236. https://doi.org/10.1016/j.envpol.2019.113236

Extensive analysis of game meat contamination

Tagami K, Howard BJ, Uchida S (2016) The time-dependent transfer factor of radiocesium from soil to game animals in Japan after the Fukushima Dai-Ichi Nuclear accident. Environmental Science and Technology 50: 9424–9431. https://doi.org/10.1021/acs.est.6b03011

Database for radioactivity in tree, soil, and mushroom

Hashimoto S, Imamura N, Kawanishi A, et al. (2020) A dataset of ^{137}Cs activity concentration and inventory in forests contaminated by the Fukushima accident. Scientific Data 7: 431. https://doi.org/10.1038/s41597-020-00770-1

Fate of cesium-137 in forest

Ito E, Miura S, Aoyama M, Shichi K (2020) Global ^{137}Cs fallout inventories of forest soil across Japan and their consequences half a century later. Journal of Environmental Radioactivity 225: 106421. https://doi.org/10.1016/j.jenvrad.2020.106421

Review on radionuclides in terrestrial environment

Onda Y, Taniguchi K, Yoshimura K, et al. (2020) Radionuclides from the Fukushima Daiichi Nuclear Power Plant in terrestrial systems. Nature Reviews Earth & Environment 1: 644–660. https://doi.org/10.1038/s43017-020-0099-x

Estimation of cost/benefit of decontamination

Yasutaka T, Naito W (2016) Assessing cost and effectiveness of radiation decontamination in Fukushima Prefecture, Japan. Journal of Environmental Radioactivity 151: 512–520. https://doi.org/10.1016/j.jenvrad.2015.05.012

Collection of relating papers published in Atomic Energy Society of Japan

Insights concerning the Fukushima Daiichi Nuclear accident (Atomic Energy Society of Japan) https://www.aesj.net/publish/fukushima_insights_intro

Key Reports from International Agencies

International Atomic Energy Agency (IAEA)

Comprehensive compilation of transfer of radionuclides observed in Fukushima

IAEA (2020) Environmental Transfer of Radionuclides in Japan Following the Accident at the Fukushima Daiichi Nuclear Power Plant. IAEA, Vienna. https://www.iaea.org/publications/14751/environmental-transfer-of-radionuclides-in-japan-following-the-accident-at-the-fukushima-daiichi-nuclear-power-plant

Comprehensive report about Fukushima accident

IAEA (2015) The Fukushima Daiichi accident. IAEA, Vienna. https://www.iaea.org/publications/10962/the-fukushima-daiichi-accident

Comprehensive report about effects of radiation exposure in Fukushima

UNSCEAR (2021) Sources, Effects and Risks of Ionizing Radiation UNSCEAR 2020/2021 Report, Scientific ANNEX B: Levels and Effects of Radiation Exposure due to the Accident at the Fukushima Daiichi Nuclear Power Station: Implications of Information Published Since the UNSCEAR 2013 Report. http://www.unscear.org/unscear/en/publications/2020_2021_2.html

Overview of twenty years of Chernobyl studies

IAEA (2006) Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience. IAEA, Vienna. https://www.iaea.org/publications/7382/environmental-consequences-of-the-chernobyl-accident-and-their-remediation-twenty-years-of-experience

International Commission on Radiological Protection (ICRP)

Recommendations on protection by experts

ICRP (2007) The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2–4). https://www.icrp.org/publication.asp?id=ICRP%20Publication%20103

ICRP (2009) Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations. ICRP Publication 109. Ann. ICRP 39(1). https://www.icrp.org/publication.asp?id=icrp%20publication%20109

ICRP (2009) Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas after a Nuclear Accident or a Radiation Emergency. ICRP Publication 111. Ann. ICRP 39(3). https://www.icrp.org/publication.asp?id=icrp%20publication%20111

Informative Web Pages

Informative Web Pages Prepared by Japan's Government or Agencies (in English)

About Forest

Regeneration of Forests and Forestry (Ministry of Agriculture, Forestry and Fisheries). https://www.maff.go.jp/e/policies/forestry/Regeneration.html

The Current State of Radioactive Substances and the Regeneration of Forests and Forestry, 2018 edition (Forestry Agency). https://www.maff.go.jp/e/policies/forestry/attach/pdf/Regeneration-18.pdf

Comprehensive Efforts toward Regeneration of Forests and Forestry in Fukushima (Ministry of the Environment). https://www.env.go.jp/en/chemi/rhm/basic-info/1st/09-01-07.html

About Food

Information on the Great East Japan Earthquake: Food (Ministry of Health, Labour and Welfare). https://www.mhlw.go.jp/english/topics/2011eq/index_food.html

General Information on Health

BOOKLET to Provide Basic Information Regarding Health Effects of Radiation (Ministry of the Environment). https://www.env.go.jp/en/chemi/rhm/basic-info/index.html

General Information

Assistance of Residents Affected by the Nuclear Incidents (Ministry of Economy, Trade and Industry). https://www.meti.go.jp/english/earthquake/nuclear/roadmap/index.html

Transition of Evacuation Designated Zones (Fukushima Prefecture). https://www.pref.fukushima.lg.jp/site/portal-english/en03-08.html

Environmental Remediation (Ministry of the Environment). http://josen.env.go.jp/en/policy_document/

Reconstruction Agency. https://www.reconstruction.go.jp/english/

Database

Hashimoto S, Imamura N, Kawanishi A, et al. (2020) Cs-137 in forests ecosystems contaminated by the Fukushima Daiichi Nuclear Power Plant Accident. Zenodo. https://doi.org/10.5281/zenodo.4268843

Noguchi H, Chayama S, Japan Forest Technology Association, et al. (2021) Grasp of the impact of litter removal and logging on the amount of eroded radioactive materials: precipitation data at testing slope frames at the Kawauchi testing sites. ERAN Database. https://doi.org/10.34355/Forest.Agency.00049

Noguchi H, Chayama S, Japan Forest Technology Association, et al. (2021) Verification of the impact of litter removal and logging on air dose rates: measurement data of radiocesium concentration by tree parts at the Kawauchi testing sites. ERAN Database. https://doi.org/10.34355/Forest.Agency.00050

Database for Radioactive Substance Monitoring Data (Japan Atomic Energy Agency). https://emdb.jaea.go.jp/emdb/

Informative Web Pages (in Japanese)

About Forest

Current Status of Radioactive Substances and Regeneration of Forests and Forestry (pamphlet prepared by the Forestry Agency). https://www.rinya.maff.go.jp/j/kaihatu/jyosen/houshasei_panfu.html

Forest and Radioactivity (Forestry and Forest Products Research Institute). http://www.ffpri.affrc.go.jp/rad/

Results of Radioactive Materials Survey in Forests (Fukushima Prefecture). https://www.pref.fukushima.lg.jp/site/portal/ps-shinrinhousyasei.html

Decontamination Information Website, Decontamination of Forests, etc. (Ministry of the Environment). http://josen.env.go.jp/about/efforts/forest.html

About Agricultural Products

Test Results of Radiocesium Concentration in Agricultural Products (Ministry of Agriculture, Forestry and Fisheries). https://www.maff.go.jp/j/kanbo/joho/saigai/s_chosa/

General Information on Health

BOOKLET to Provide Basic Information Regarding Health Effects of Radiation (Ministry of Environment). https://www.env.go.jp/en/chemi/rhm/basic-info/

Basic Information on Radiation Risk (Reconstruction Agency). https://www.reconstruction.go.jp/topics/main-cat1/sub-cat1-1/20140603102608.html

General Information

Base Information Q&A Site: About Fukushima NOW and FUTURE (Japan Atomic Energy Agency). https://fukushima.jaea.go.jp/QA/

Radioactive Waste Disposal Information Site - What is the Difference Between Radioactive Materials, Radioactivity, and Radiation? (Ministry of the Environment). http://shiteihaiki.env.go.jp/radiological_contaminated_waste/basic_knowledge/how_different.html

Application of the Commission's Recommendations to the Protection of People Living in Long-Term Contaminated Areas after a Nuclear Accident or Radiological Emergency (Prepared by the International Commission on Radiological Protection, translated by the Japan Radioisotope Association). http://www.icrp.org/docs/P111_Japanese.pdf

About Chernobyl

Environmental impact of the Chernobyl nuclear accident and its remediation—20 years of experience (International Atomic Energy Agency) (prepared by the Subcommittee to Review the Investigation on Environmental Contamination Caused by the Nuclear Accident, in Section III (Science and Engineering) of the Science Council of Japan). https://www.scj.go.jp/ja/member/iinkai/kiroku/3-250325.pdf

Index

S. Hashimoto et al., *Forest Radioecology in Fukushima*,
https://doi.org/10.1007/978-981-16-9404-2