Progress in Environmental Emergency Research after the Great East Japan Earthquake and Fukushima Nuclear Disaster
Editorial

It is our great pleasure to issue our journal ‘Global Environmental Research’ which aims to disseminate the results of studies on global environmental issues, studies conducted not only in Japan but also in other parts of the world. Many scientists monitor research in their own fields, but communications between scientists are not always easy, because the ranges of their fields are so diverse, and reports may not be written in an internationally spoken language. This journal is intended to help to fill these gaps.

In recent years, many reports, publications, and other forms of information have been released relating to Japanese studies on global environmental issues. The main purpose of ‘Global Environmental Research’ is to provide information on Japanese research results to scientists internationally and in a timely manner. We also hope that ‘Global Environmental Research’ will encourage exchanging information among such as the Asian and Pacific regions where local language barriers and limited opportunities exist.

International Geosphere-Biosphere Programme (IGBP), International Human Dimensions Programme of Global Environmental Change (IHDP) and other international and interdisciplinary programmes have produced a lot of important results. A new global research platform ‘Future Earth’ will provide the knowledge required to face risks posed by global environmental changes and to seize opportunities for global sustainability. The results of these studies need to be distributed worldwide. We hope this journal will also make a contribution to this end.

It was said that the title of the third scientific symposium of the IHDP ‘Global Change, Local Challenge’ recognizes that global changes are the results of a variety of local activities shaped by particular cultures, histories, political boundaries, and national policies. We are certain that our ‘Global Environmental Research’ will serve as a transmitter of information on local activities about global change.

Teiji WATANABE

---

Editorial Board

Chairperson : Teiji WATANABE  Professor, Hokkaido University

Members :
Naoki KACHI  Designated Professor, Tokyo Metropolitan University
Hiroyasu TOKUDA  Executive Director, Association of International Research Initiatives for Environmental Studies

Guest editor :
Toshimasa OHARA  Fellow, National Institute for Environmental Studies
Seiji HAYASHI  Research Manager, Fukushima Branch, National Institute for Environmental Studies
Kazuki IJIMA  Division Head, Fukushima Environmental Evaluation Research Division, Japan Atomic Energy Agency

Editorial Secretary : Association of International Research Initiatives for Environmental Studies
Ryoko MORIMOTO  Editorial Administrator
Patricia ORMSBY  English Editor
Global Environmental Research
Vol.24 No.2/2020

Progress in Environmental Emergency Research after the Great East Japan Earthquake and Fukushima Nuclear Disaster
CONTENTS

Progress in Environmental Emergency Research after the Great East Japan Earthquake and Fukushima Nuclear Disaster

083  Preface .............................................................. Toshimasa OHARA, Seiji HAYASHI and Kazuki IIJIMA

I. Environmental assessment

085  Overview of Environmental Impact Assessment Studies on Radioactive Contamination after the Fukushima Daiichi Nuclear Power Plant Accident ................................................................. Kazuki IIJIMA, Seiji HAYASHI and Masanori TAMAI

095  Overview of Open Biodiversity Data around the Fukushima Disaster Area and the Nuclear Power Plants in Japan ................................................................. Akira YOSHIOKA, Nao KUMADA, Yui OGAWA and Keita FUKASAWA

105  Role and Effect of a Dam on Migration of Radioactive Cesium in a River Catchment after the Fukushima Daiichi Nuclear Power Plant Accident ............................... Seiji HAYASHI and Hideki TSUJI

115  Dynamics of $^{137}$Cs in Water and Phyto- and Zooplankton in a Reservoir Affected by the Fukushima Daiichi Nuclear Power Plant Accident ........................................ Hideki TSUJI, Megumi NAKAGAWA, Kazuki IIJIMA, Hironori FUNAKI, Kazuya YOSHIMURA, Kazuyuki SAKUMA and Seiji HAYASHI

129  $^{137}$Cs Outflow from Forest Floor Adjacent to a Residential Area: Comparison of Decontaminated and Non-decontaminated Forest Floor ........................................ Tadafumi NIIZATO and Takayoshi WATANABE

II. Waste management and removed soil

137  Summary of Radioactive Cs Dynamics Studies in Coastal Areas and Assessment of River Impacts ................................................................. Toshiharu MISONOU, Tadahiko TSURUTA, Takahiro NAKANISHI and Yukihisa SANADA

145  Case History: Decontamination Challenge of Iitate Village ........................................ Yuuzou MAMPUKU

159  Experimental Study on the Mechanism of Cs Removal from Contaminated Soil and Incineration Ash by Pyroprocessing .......................... Kazuo YAMADA, Kazuhiko TOKYOYODA, and Masahiro OSAKO

173  Insolubilization of Cesium Contained in Fly Ash by Co-heating with Potassium Feldspar ................................................................. Yasumasa TOJO

181  A Study on the Durability of Covering Sheets Used at Temporary Storage Sites in Fukushima Prefecture ........................................................ Yusuke TAKAHASHI and Masahiro KOISO

III. Environmental renovation

191  Promoting Local Revitalization to Solve Issues on Degraded Forests in Japan: A Case Study in Oku-Aizu, Fukushima .......................... Makoto OBA, Shogo NAKAMURA and Takuya TOGAWA

199  Smart Community Recovering from the Tsunami-Disaster: Case Study of the Community Energy Supply Project in Shinchi Town, Fukushima Yuijiro HIRANO, Shogo NAKAMURA, Takaya TOGAWA, Tsuyoshi FUJITA and Kenichi ADACHI
Longitudinal Evaluation of Energy-saving Effects and Their Implication Using Electricity Monitoring Data in Shinchi Town, Fukushima

Ayami OTSUKA, Yujiro HIRANO, Shogo NAKAMURA, Tsuyoshi FUJITA and Daisuke NARUMI

Impact of TEPCO Nuclear Accident and Associated Evacuation to the Demography in Fukushima

Kei GOMI

A Study on Sustainable Energy Systems for Small Villages in Fukushima

Takuya TOGAWA, Yi DOU, Shogo NAKAMURA and Makoto OObA

Survey on Household Wood Biomass Use and Energy Consumption in the Oku-Aizu Region

Shogo NAKAMURA and Takuya TOGAWA

Community Governance in Decontamination Policy after the Fukushima Nuclear Accident: Two Case Studies from the Naka-dori Region, Fukushima, Japan

Takashi TSUJI, Shogo NAKAMURA and Makoto OObA

IV. Environmental management

Overview of the Environmental Emergency Management Studies in National Institute for Environmental Studies (NIES)

Ryo TAJIMA and Masahiro OSAKO

Systematic Analysis of Environmental Release Process and Emergency Response in Chemical Accident

Yosuke KOYAMA, Yoshitaka IMAIZUMI and Noriyuki SUZUKI

Strategy to Promote Residents’ Behaviors for Appropriate Disaster Waste Management

Tomoko MORI and Ryo TAJIMA

Expanding the Scope of Environmental Emergency Research towards Disaster-resilience and Environmental Sustainability

Toshimasa OHARA, Ryo TAJIMA, Yujiro HIRANO, Shigenori INO and Seiji HAYASHI
Preface

Just ten years ago, the world witnessed the Great East Japan Earthquake (GEJE), the subsequent Fukushima Daiichi nuclear power plant (FDNPP) accident and the severe impacts these had on the society and environment of eastern Japan. A wide range of research related to the nuclear accident has been conducted, with the results already released in many cases regarding the environmental impacts of the large amounts of radioactive substances emitted into the environment during that event. In addition, research is being carried out on sustainable community development, including the establishment of sustainable regional environments, reconstruction according to environmentally conscious principles and creation of disaster resilient regions. Such environmental emergency research has contributed greatly to environmental recovery in areas affected by the GEJE and nuclear accident and also to environmental emergency management for natural disasters after the GEJE.

This special issue focuses on the progress in environmental emergency research after the GEJE and nuclear accident, and provides an integrated body of relevant scientific knowledge. The articles in this issue cover a wide range of studies addressing environmental emergency aspects such as post-disaster environmental impacts of pollutants, environmental recovery and management of disaster waste. Many articles have been provided by researchers of the National Institute for Environmental Studies, Japan Atomic Energy Agency, and other organizations. We are profoundly grateful for their contribution of valuable scientific knowledge and technical expertise toward environmental restoration, and strongly hope that this information will be utilized in efforts towards disaster-resilience and environmental sustainability worldwide.

Guest Editors
Toshimasa OHARA
Seiji HAYASHI
Kazuki IIJIMA
Overview of Environmental Impact Assessment Studies on Radioactive Contamination after the Fukushima Daiichi Nuclear Power Plant Accident

Kazuki Iijima¹, Seiji Hayashi²* and Masanori Tamaoki²

¹Fukushima Environmental Evaluation Research Division, Japan Atomic Energy Agency
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
²Fukushima Branch, National Institute for Environmental Studies
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
*E-mail: shayashi@nies.go.jp

Abstract

The radioactive environmental contamination that resulted from the Fukushima Daiichi nuclear power plant accident has clearly been declining during the nearly 10 years that have passed since the accident. Many studies, however, have indicated prolongation of radioactive contamination in natural ecosystems, probably arising from non-decontaminated forested areas, so a more detailed examination is needed on the environmental dynamics of bioavailable radiocesium and its transfer to ecosystems. Also, regarding the influences of radiation on organisms, the effects on wild organisms of the evacuation of humans have been more pronounced than the direct effects from radiation, especially in the Fukushima evacuation zones.

Key words: dissolved Cs, radiation effect, transfer to ecosystem, wild organism

1. Introduction

As shown by the time change in radiation air dose rates measured by airborne surveys (Nuclear Regulation Authority, 2020), serious environmental radioactive contamination occurred widely as a result of the Fukushima Daiichi nuclear power plant (FDNPP) accident. The air dose rate has clearly been declining during the nearly 10 years that have passed since the accident thanks to decontamination operations in the living sphere of the affected areas as well as the natural decay of Cs-134, the half-life of which is 2.0 years, and weathering of radiocesium.

On the other hand, the forested areas that cover over 80% of the evacuated zones remain mostly non-decontaminated. Considering the reported behavioral properties of radiocesium in forests such as its high adsorption in clay particles in the soil (Takahashi et al., 2019) and limited runoff ratios even during rain events (Tsuji et al., 2016; Iwagami et al., 2017a), it is assumed that large amounts of the deposited radiocesium will be retained in the surface soil layer over a long period of time. Serious radioactive contamination of forested areas and subsequent long-term contamination of natural ecosystems were reported after the Chernobyl nuclear power plant (CNPP) accident in 1986 in the former Soviet Union (Belli & Tikhomirov, 1996; Bulgakov et al., 2002). The same situation is of increasing concern in the area affected by the FDNPP accident. Additionally, since long-term retention of radiocesium in the forest floor means prolonged conditions of high dose rates in the part of the forest environment near the ground, we cannot overlook the effects of radiation doses on organisms over the mid to long term.

In this paper, we focus especially on radiocesium transfer to natural ecosystems and the various effects of radiation on organisms in an attempt to assess the environmental effects of the FDNPP accident through the accumulated scientific knowledge from previous research papers. Concretely, we first give an overview of the behavioral properties of dissolved radiocesium with high bio-availability, which plays an important role in its transfer to ecosystems in forests and river systems. Then we describe the state of radiocesium transference to forest trees, freshwater fish and wild animals. In addition, the actual state of radiation doses’ influence on organisms and the influence on biota of the absence of humans due to evacuation are described respectively as direct and indirect effects of serious environmental radioactive contamination.
2. Migration Behavior of Dissolved Cs in Terrestrial Areas

In a previous review (Hayashi, 2016), the following points were indicated as future issues regarding the behavior of Cs in the environment around Fukushima:

- Organization of scientific knowledge on managing radiocesium runoff from forests based on many case studies,
- Detailed investigations of dissolved radiocesium in river systems in terms of generation mechanisms, particularly the contribution of highly contaminated organic matter (leaf litter) and seasonal fluctuations in concentrations,
- Investigations on the behavior of sediments with high concentrations of radiocesium through direct deposition and initial inflow to clarify the actual state of bottom sediment contamination in dam reservoirs, and
- Investigations on the possibility of dam reservoirs acting as a source of dissolved radiocesium.

In this chapter, we review recent investigations on the behavior of dissolved radiocesium in river systems and forests, which are considered to be two sources.

2.1 Sources of Dissolved Cs in River Systems

Highly contaminated organic litter, such as leaf litter, is considered one of the possible sources of dissolved radiocesium in river systems. This possibility is supported by both seasonal fluctuation, with high levels in summer and low in winter (Tsuji et al., 2016; Nakanishi & Sakuma, 2019), and a rapid but extremely temporary increase in concentration immediately after rainfall starts (Tsuji et al., 2016; Iwagami et al., 2017b; Sakuma et al., 2019). According to phenomenological model calculations, these trends in dissolved radiocesium concentration cannot be expressed by traditional adsorption-desorption distribution models, so it is thought that the kinetically controlled dissolution of radiocesium during the decomposition of organic matter might contribute (Sakuma et al., 2019). Dissolved radiocesium concentrations are correlated with water temperature (Nakanishi & Sakuma, 2019), dissolved organic carbon (DOC) and potassium (K) concentrations (Tsuji et al., 2016), also suggesting contribution of organic matter decomposition. However, since the width of fluctuation decreases with time (Nakanishi & Sakuma, 2019), the contribution of this process might be decreasing.

Desorption from forest soil or river sediments is another possible source. In the case of forest streams, the declining trend of dissolved radiocesium in stream water is similar to that in groundwater (Iwagami et al., 2017b). The level of radiocesium dissolved in water contained in soil layers was found to be quite high in July 2011 and declined after that, and could be fit with a two-component exponential model (Iwagami et al., 2017c). The faster decline rate showed a good correlation with the radiocesium interception potential (RIP), suggesting that desorption from clay minerals contributed to generation of dissolved radiocesium in forest soil. In the case of river sediments, the cation exchange capacity (CEC) is influenced by both clay minerals and organic matter content (Tachi et al., 2020a). The adsorption behavior at 10⁻⁹ M of the initial concentration of radiocesium can be expressed by a first-order reaction, but the rate constant decreases with an increase in organic matter content, indicating that organic matter inhibits radiocesium access to frayed edge sites (FESs) (Tachi et al., 2020b). In particular, the dissolved radiocesium concentration in output water from one of the dam reservoirs in Fukushima has shown slightly higher concentrations and slower decline than that of the input water (Funaki et al., 2020). It is thought that radiocesium that has accumulated in the reservoir sediments may partly be desorbed by ammonium ions, dissolving into the reservoir’s water. The conditions in the reservoir sediment are likely to remain in a reducing condition under which ammonium ions are easily generated and can desorb cesium ions.

2.2 Behavior of Cs in the Forest Floor

Most of the radiocesium deposited in forests has moved from the canopy to the forest floor. Throughfall is the dominant pathway of radiocesium transfer in the first year, and the contribution of litterfall gradually increases with time (Kato et al., 2017). The trend of radiocesium decreasing in the canopy is expressed by a double exponential field-loss model. In the six months after the accident, 82% of the initially deposited radiocesium was present on the forest floor in mixed forests and broad-leaved forests, and 78-56% in the case of cedar forests (Komatsu et al., 2016). The ratio of radiocesium on the cedar forest floors to the initially deposited amount was also reported to be 80% three years after the accident (Gonze et al., 2017) and 94% four years after it (Yoschenko, 2017).

On the forest floor, radiocesium in the litter layer migrates to the lower mineral layer, and is strongly adsorbed by the minerals. It has been reported that the radiocesium concentration in the mineral layer located a few centimeters below the surface gradually increased and became higher than that in the litter layer after two or three years (Takahashi et al., 2019). The exchangeable fraction of radiocesium was of 10% in the organic layer and 6% in mineral layer after five months, and constant at 2-4% in two to four years in both layers, showing that radiocesium could not easily move to deeper parts (Manaka et al., 2019). Throughfall dominates as the source of radiocesium migrating downward from the litter layer in the case of cedar forests, while decomposition of litter dominates in the case of broad-leaved forests (Kurihara et al., 2018).
Overview of environmental impact assessment studies

Litter from forests and elution from the litter/organic soil layer are likely contributors to the dissolved radiocesium concentrations in river systems. Based on a compartment model analysis, Kurikami et al. (2019) reported that the origination of dissolved radiocesium concentration in river water and freshwater fish could be explained by a combination of these three sources. Further investigations to clarify the dissolution mechanism and behavior of radiocesium in forests are desired, which would enable the establishment of models for estimating future concentrations.

3. Radiocesium Transfer to Natural Ecosystems

Most of the radiocesium emitted in large quantities into the environment by the FDNPP accident was deposited in the mountainous forested areas of Fukushima Prefecture and its surroundings. Many studies after the accident suggest that although most of the deposited radiocesium remains in the surface soil layer because it is strongly bound with clay particles in the soil, the runoff ratio from forest catchments is limited to less than 1.0% annually even when large storms occur (Tsujii et al., 2016; Iwagami et al., 2017a). Therefore, forested areas would not be involved with re-contamination in the downstream catchment area as the source of radiocesium migration. However, this situation implies that radiocesium deposited on the forest floor, especially Cs-137 with a long half-life (30.1 yrs.) stays nearly retainable in the surface soil layer, which is biologically active (Takahashi et al., 2019). Therefore, understanding radiocesium transfer in natural ecosystems is essential for inferring future trends.

In this chapter, we outline the current state of radiocesium distribution and properties of its transfer in the natural ecosystems of forested areas, freshwater bodies and wild animals, based on reports from previous studies after the FDNPP accident.

3.1 Forest Ecosystems

As for the state of radiocesium transfer into forest products, which is of most concern regarding radioactive contamination of forest ecosystems, the main research that has been conducted has targeted evergreen needle-leaved trees like Japanese cedar and cypress which have been utilized as timber products (Kanasashi et al., 2015; Kajimoto et al., 2015; Kato et al., 2017; Nishikiori et al., 2019). Since uptake followed by translocation from the above-ground parts, mainly foliage, where it was deposited soon after the accident, and root uptake are assumed as the transfer processes of radiocesium to wood, this is of most interest. Several attempts have been made to quantitatively evaluate the respective contributions (Mahara et al., 2014; Nishikiori et al., 2015; Yoschenko et al., 2018). Imamura et al. (2020) conducted a source analysis utilizing the ratio of Cs-137 activity concentration to stable cesium (Cs-133) concentration in several components of Japanese cedar and soil pore water. They estimated that root uptake had contributed to about 50% of the increment in Cs-137 in the stemwood of a 40-year-old tree from Jul. 2011 to Aug. 2017 at a maximum, although the size of this contribution was highly uncertain. Thiry et al. (2020) applied their comprehensive modeling of radiocesium cycling in forests to pine trees in Belarus and Ukraine after the CNPP accident using the observed data. They proved that root uptake contributed to the transfer of Cs-137 to wood more strongly than uptake from foliage for periods of 10 years after the accident. Even in Fukushima, continuous observation will be needed to see if the contribution of root uptake to the Cs -137 transfer to the wood of Japanese cedar and Japanese cypress increases in the future, although it will depend on how much bio-available Cs-137 is generated in the soil, corresponding to forest environment conditions.

Based on a five-year study starting from Aug. 2011, five months after the FDNPP accident, Imamura et al. (2017) estimated the initial deposition of Cs-137 onto the above-ground parts of konara oak to be less than one-third of those of Japanese cedar or Japanese cypress, due to lack of foliage at the time of the accident in the case of deciduous broad-leaved trees. Surprisingly, Cs-137 activity concentrations in deciduous konara oak leaves did not change over the five years, although the Cs-137 activity concentrations in the wood significantly increased year by year. Kanasashi et al. (2020) showed that Cs-137 activity concentrations in growing coppiced shoots of konara oak have had a significant positive correlation with exchangeable Cs-137 in soil in Fukushima after the FDNPP accident. It may be necessary to examine the contribution of root uptake as one of the main controlling factors in determining Cs-137 activity concentrations in the leaves and stemwood of deciduous broad-leaved trees as well as translocation from the deposited bark and branches. Generally, many deciduous broad-leaved trees have shallower root systems than Japanese cedars and Japanese cypresses, suggesting that they may be able to take up exchangeable Cs-137 in soil supplied by leaching from litter more easily.

Since radiocesium cycling caused by transfer to deciduous broad-leaved trees via root uptake will be a strong concern regarding long-term radioactive contamination of forest ecosystems, countermeasures to this issue should be considered in future research.

3.2 Freshwater Ecosystems

Since radioactive contamination of fish is a big concern from the viewpoint of inland water fisheries and the leisure industry in freshwater ecosystems, the Ministry of the Environment; Ministry of Agriculture, Forestry and Fisheries; and Fukushima Prefecture have been conducting respective monitoring projects to
elucidate the state of radiocesium concentrations in fish. By utilizing these monitoring data, Ishii et al. (2020) showed that the state of Cs-137 transfer to fish clearly differed by habitat (river or lake) or feeding habit of fish using the concentration factor (CF: \( CF = \frac{\text{Cs-137 activity concentration in fish}}{\text{Cs-137 in water}} \)), which serves as an indicator of the present state of radiocesium transfer from the aqueous environment to aquatic organisms. It has also been confirmed that larger fish show higher radiocesium concentrations than smaller ones even in the same habitat or among the same species (Wada et al., 2019; Ishii et al., 2020). Freshwater fish usually supplement cations including radiocesium through feeding and have a lower excretion rate during osmoregulation compared to marine fish (Wada et al., 2019). Consequently, since their radiocesium activity concentration varies depending largely on what they eat, clarifying the flow of radiocesium via the food-web is clearly essential to understanding the mechanism of transfer to fish.

Generally, radiocesium activity concentrations in omnivorous or carnivorous fish are higher than that in herbivorous or planktrophic fish (Wada et al., 2016; Ishii et al., 2020), so how radiocesium is transferred to fish by the detritus food chain via insects feeding on forest litter is being examined. As an example, it has been confirmed that differences in radiocesium concentrations in litter, which is the basal food of forest and stream ecosystems, are reflected in radiocesium concentrations in communities of aquatic organism (Sakai et al., 2016). Factors inhibiting lower of radiocesium activity concentrations in fish need to be investigated and effective countermeasures to prevent radiocesium from transfer to fish need to be examined as much as possible based on scientific knowledge obtained from an evaluation of transfer properties through the food web in order to promote the recovery of industries related to freshwater fish.

### 3.3 Wild Animals

As for the transfer of radiocesium originating from the FDNPP accident to wild animals, the current and transition states have been examined mainly with regard to game animals from the viewpoint of food-safety. From the reported Cs-137 activity concentrations in game meat data from Asian black bears (\( \text{Ursus thibetanus} \)), wild boars (\( \text{Sus scrofa} \)), sika deer (\( \text{Cervus nippon} \)), green pheasants (\( \text{Phasianus versicolor} \)), copper pheasants (\( \text{Syrmaticus soemmerringii} \)), and wild ducks (\( \text{Anas poecilorhynchos} \) and \( \text{Anas platyrhynchos} \)) in more than 10 prefectures after the FDNPP accident between 2011 and 2015, Tagami et al. (2016) confirmed that the concentrations in wild boars were the highest of all, but were lower than those reported after the CNPP accident. Also from a comparison between Cs-137 activity concentrations in the meat of Asian black bears or wild boars between 2011 and 2016 and Cs-137 inventories in the areas where they had been trapped, estimated by airborne surveys (Nuclear Regulation Authority 2020), Nemoto et al. (2018) reported that each concentration was proportional to the inventory and the concentration in wild boars was higher than in Asian black bears if they had been trapped in the same area.

As for the aggregated Cs-137 transfer factor (Tag = activity concentration in meat (Bq/kg-fw)/inventory in soil (Bq/m³)), which is an indicator of transfer properties from radioactive contaminated land to game animals, the geometric means (GM) for green pheasant and wild duck remained on the order of \( 10^{-3} \) during the monitoring period, while those for Asian black bear, wild boar, sika deer and copper pheasant were one order higher (Tagami et al., 2016; Nemoto et al., 2018). Compared with the Tag after the CNPP accident, directly comparable data obtained for wild boars were in the same range of the GM value \( (4 \times 10^{-3} \text{ to } 6.7 \times 10^{-3}) \) collected within five years after the CNPP accident by International Atomic Energy Agency (IAEA; Howard et al., 1996).

The annual change in Tag depends on the species. While it decreases slightly in some species (wild boar, green pheasant and wild duck), no significant change has been found in other species (Asian black bear, sika deer and copper pheasant). Although clear seasonal changes in Cs-137 activity concentration were found in wild animals after the CNPP accident (Semizhon et al., 2009), a uniform opinion has yet to be formed in the case of the FDNPP accident. While Tagami et al. (2016) concluded that no seasonal trends could be found in any species from the collected data, Nemoto et al. (2018) stated that muscle Cs-137 varied seasonally and that this seasonal variation also differed between Asian black bears and wild boars. It might be necessary to conduct more successive sample collections and detailed analyses considering differences in feeding among species or differences in environment between the areas affected by the FDNPP and CNPP accidents to gain a clearer understanding of the properties. Concretely, progress will be needed in studies focused on gastric contents of wild animals to elucidate increases in concentrations according to when and what they eat (Saito et al., 2020). This pertains especially to the most contaminated wild boars whose numbers are confirmed to have increased due to the effects of evacuation orders affecting seriously contaminated areas (Lyons et al. 2020). More detailed research on ranging behavior, dietary habits and the long-term behavior of radiocesium in forest ecosystems will be needed in Fukushima Prefecture and surrounding areas (Hinton et al., 2015).

### 4. Effects of Radiation and Human Evacuation on Wild Organisms and Ecosystems in Fukushima

As a result of the FDNPP accident, all of the wild
animals and plants have been left behind in high radiation-dose areas, so they are still exposed to radiation in Fukushima. It is, therefore, of high concern whether any adverse effects have been found in wild organisms in the Fukushima area resulting from long-term, low-dose exposures to radiation. In the first half of this chapter, we focus on radiation effects in wild organisms found in Fukushima, where small but serious adverse effects of radiation have been detected. However, the risks from radiation on wild organisms will diminish because radiation doses in Fukushima have been decreasing through natural decay, weathering and efforts for decontamination. The area covered by the evacuation zones has been steadily decreasing, from 1,150 km² in August 2013 to 340 km² in April 2019, as air dose rates have decreased. With the lifting of evacuation orders, about 58,000 former residents of the evacuation zones, have been permitted to return to their hometowns, but the area’s population is only 28% of its total before the accident. Thus, changes in land use with the cessation of daily life activities, such as agricultural and horticultural work, continue, and these significantly affect the wild organisms and ecosystems in the evacuation zones. In the Fukushima evacuation zones, because the air dose rates are gradually decreasing with time, it will be necessary to pay more attention to the effects of the evacuation on wild organisms and ecosystem rather than direct effects from radiation hereafter. Therefore, the impacts of rapid changes in human activities on wild organisms and ecosystems are also described in the second half of this chapter.

4.1 Estimated Levels of Exposure of Wild Organisms to Radiation

Levels of contamination with radioactive materials and estimated radiation exposure doses in marine and terrestrial organisms living in Fukushima were initially predicted to exceed the derived consideration reference levels (DCRLs) determined by ICRP and reported during first month after the accident (ICRP, 2008; Garnier-Laplace et al., 2011; Strand et al., 2014). According to the prediction, marine organisms including seaweed, benthic invertebrates and benthic flatfish were expected to have suffered severe effects from radiation categorized as “reduction in life span” in ICRP’s DCRLs (Tamaoki, 2016). However, very few adverse effects were found in marine organisms living in Fukushima. The only exception was reported by Horiguchi et al. (2015), in which the abundance and diversity of intertidal species decreased significantly with decreasing distance from the FDNPP in 2012, and no rock shells (Thais clavigera) were observed within a radius of 20 km of the FDNPP. Unfortunately, whether the decrease or disappearance of these species was caused directly by the increase of radiation doses or not remains unclear at this moment.

4.2 Radiation Effects in Wild Organisms in Fukushima

In contrast to marine organisms, only rodents were expected to suffer from radiation at the level categorized as “reduced production” in ICRP’s DCRLs for terrestrial organisms (Tamaoki, 2016). Onuma et al. (2020) calculated exposure dose rates for large Japanese field mice (Apodemus speciosus) captured in the “difficult-to-return zones” in Fukushima Prefecture from 2012 to 2016, and they found that the total dose rate (sum of internal and external dose rates) was estimated at less than 1.0 mGy/day. Exposure exceeding 1.0 mGy/day could reduce fertility in male and female field mice according to ICRP’s DCRLs, indicating that the present dose rates of the field mice living in the capture sites were lower than the dose rates that would reduce fertility. Accordingly, no significant differences in apoptotic cell frequencies or frequencies of morphologically abnormal sperm were observed in field mice captured in Fukushima as compared to the results from two control sites, in Aomori and Toyama prefectures, in 2013 and 2014 (Okano et al., 2016).

Among organisms living in Fukushima, morphological abnormalities were detected in some species such as the pale grass butterfly (Pseudozeeria maha) (reviewed by Hiyama et al., 2015), gall-forming aphids (Tetraneura sorini and T. nigrifiedinalis) (Akimoto 2014) and conifer tree species (Japanese fir tree; Watanabe et al., 2015, Japanese red pine; Yoschenko et al., 2016). It is noteworthy that no abnormal morphologies in the butterfly and aphid have been observed since 2013 (Akimoto, 2014; Hiyama et al., 2015). This indicates that the abnormal phenotypes in these small insects only occurred within two years after the FDNPP accident, and severely malformed individuals were eliminated by natural selection.

In addition, there is no evidence of genetic mutations causing abnormal morphologies. Further studies are needed to obtain positive proof that these abnormal phenotypes occurred due to radiation, and reproductive experiments such as irradiation of butterflies, aphids and conifer tree species for long periods at low doses would also be effective for advancing our knowledge on radiation effects in wild organisms.

4.3 Effects of Radiation on Abundance of Wild Populations in Fukushima

Radiation effects on population sizes in insect and birds were also investigated in the Fukushima evacuation zones. Möller et al. (2013) took a census of spiders, grasshoppers, dragonflies, butterflies, bumblebees and cicadas at 300 sites in forested areas of the evacuation zones. They found that the abundance of butterflies and cicadas declined significantly with increasing levels of radiation doses. Interestingly, the abundance of spiders showed a positive correlation to the radiation doses at the sites where they were collected. Such positive
correlations observed in spiders were not observed in particular in the case of Chernobyl, where all of the arthropods showed negative correlations between their abundance and radiation dose rates.

The effects of radiation on the abundance of common birds were also studied in Fukushima and the results obtained were compared to those in Chernobyl (Møller et al., 2012). Fourteen bird species common to both Fukushima and Chernobyl showed abundance negatively correlated to radiation doses at the two sites, but the tendency toward negative effects differed between Fukushima and Chernobyl. Interestingly, the negative correlation between the abundance of these 14 common bird species and radiation doses was more pronounced in Fukushima than in Chernobyl. The reasons for these differences in radiation-dose-dependent change in abundance of spiders and bird species between Fukushima and Chernobyl are unclear. Some research evidence indicates that wild organisms living in Chernobyl have already finished undergoing adaptation to and/or selection for high radiation environments because the investigations in the area started 20 years after the Chernobyl accident. Thus, it will be very important to study whether adaptation and/or selection is occurring in the Fukushima evacuation zones.

### 4.4 Effects of Human Non-residence by Evacuation on Population Size in Wild Organisms

To clarify the effect of evacuation on wild organisms, biota monitoring targeting mammals, birds, frogs and flying insects inside and outside the evacuation zones in Fukushima has been undertaken since 2014 (Yoshioka et al., 2016). As reviewed previously, the abundance of carpenter bees (Xylocopa appendiculata) was lower in the evacuation zone than outside it (Yoshioka et al., 2015; Tamaokı 2016). Moreover, some small bees, wasps and beetles were more common inside the evacuation zone. The causes of these population changes in some insect species are unclear, but changes in human activities such as abandonment of cultivation and/or gardening may affect them. Among frogs, eight species have been observed during the monitoring, but the frequency of observation of each frog species has not yet been compared inside and outside of the evacuation zones. The two-year data sets (2014–2015) obtained were published as a data paper for enabling its use by other researchers (Yoshioka et al., 2020).

Mammals have been monitored at 46 sites in nine municipalities inside and outside the evacuation zones (locations can be seen at http://www.nies.go.jp/biowm/map/en_mafu.html). Infrared camera traps were employed, which automatically respond to infrared radiation from homothermic animals. Sixteen different mammal species have been observed through camera trapping (Fukasawa et al., 2016). Among these, wild boars (Sus scrofa) were caught on camera most often and at the largest number of sites (78% of the monitored sites). A statistical analysis showed that wild boars were more abundant in the evacuation zone than outside it, indicating that decreased human activity may help the wild boar population increase. The same tendency was also found to a lesser extent in other species such as badgers (Meles meles), Japanese macaques (Macaca fuscata) and Japanese hares (Lepus brachyurus). The same result was also reported by Lyons et al. (2020) in which they found no evidence of impact on population size in mammals or gallinaceous birds, and showed that several species were most abundant in the evacuation zones, despite the presence of high radiation doses.

Among them, increased wild boar populations in Fukushima have resulted in damage to agricultural operations and require control by state-funded hunting programs. Radioesium levels in wild boar meat often exceed government guidelines for food consumption, not only in and around the evacuation zones but also in the Aizu area in western Fukushima Prefecture, more than 100 km from the FDNPP. Moreover, wild boars are considered a pest animal in farmland, and are a major mediator of classical swine fever which can seriously damage the pork industry. Indeed, about half of the animal damage to crop yields in Fukushima is due to wild boars, and wild boars infected by swine fever virus have been found in Aizu-Wakamatsu City as of September 2020. Thus, it is important to clarify the population dynamics and migratory movements of wild boars in Fukushima to develop an efficient plan for helping residents return to the evacuation zones.

### 5. Summary

In this paper, we have provided an overview of recent progress in investigations of the environmental impact induced by the FDNPP accident, focusing especially on radioesium transfer to natural ecosystems and the effects of deposited radioactive materials on organisms.

Litter from forests and desorption from the litter/organic soil layer are likely contributors to dissolved radioesium concentrations in river systems. The origins of the dissolved radioesium will evolve with time in accordance with the source of radioesium migrating downward from the litter layer to the mineral layer. In forest ecosystems, radioesium is thought to migrate into wood by root uptake and/or uptake from deposits on above-ground parts followed by translocation. The contribution of root uptake, however, has not been evaluated as of this time. As a source of dissolved radioesium affecting river systems and forest ecosystems, the behavior of litter decomposing and leading to the dissolution of radioesium in forests is a key issue to be investigated in the future.

The transfer of Cs-137 to freshwater fish is affected
by habitat (river or lake), feeding habit, body size and so on. It has also been pointed out that the concentration of radioactive cesium in litter is related to that in communities of aquatic organisms. Among wild animals, wild boars showed relatively higher radioactive cesium concentrations, but the tendencies of concentrations to evolve, such as through seasonal variation, are still under discussion. To predict future concentrations in these ecosystems, it would be desirable to clarify dominant pathways of transfer of radioactive cesium via the food-web through continuous systematic sample collection and detailed analysis.

Direct effects of increased radiation doses have not been clearly observed among marine organisms, while morphological abnormalities have been detected in some species of terrestrial organisms, such as small insects and coniferous trees. However, further investigation will be needed to obtain evidence as to whether or not genetic mutations caused these abnormalities. Negative effects of radiation on population size in insects and birds have also been observed in areas affected by the FDNPP and CNPP accidents, respectively, though the tendencies differed in some cases. Conversely, the decrease in human activities caused by conditions of high radiation are thought to lead to increased wild boar populations. In future work, it will be important to investigate whether adaptation and/or selection occur in the Fukushima evacuation zones and to elucidate the population dynamics and migratory movements of wild boars.

References
Kanasashit, S., Sugiiura, Y., Takenaka, C., Hiji, N. and Umemura,


Overview of environmental impact assessment studies


Kazuki Iijima

Kazuki Iijima heads the Fukushima Environmental Evaluation Research Division at the Collaborative Laboratories for Advanced Decommissioning Science, Japan Atomic Energy Agency (JAEA). He is interested in how radionuclides behave in the environment, especially the interactions of trace amounts of radionuclides with minerals and organic matter of natural origins. Previously, he investigated the behavior of radionuclides under conditions deep underground (stable and static for long periods). After the Fukushima Daiichi nuclear power plant accident, he started studying their behavior at the earth’s surface. (He says it is so unstable and too dynamic!)

Seiji Hayashi

Seiji Hayashi is a research group manager at the Fukushima Branch of the National Institute for Environmental Studies. He serves as project leader for research on radioactive substance behavior in multimedia environments. His energetic research activities are contributing to the environmental recovery of Fukushima Prefecture and its surrounding region.

Masanori Tamaoki

Masanori Tamaoki is principal researcher at the Fukushima Branch of the National Institute for Environmental Studies (NIES). Has also been appointed associate professor at the University of Tsukuba. He has studied plant responses to oxidative stress, especially to air-pollutant ozone. Ozone is known to generate reactive oxygen species (ROS) in leaves, harming vegetation. ROS is also produced in organisms exposed to radiation; hence he launched an investigation into the effects of radiation on plants in 2011. He transferred to the Fukushima Branch of NIES from June 2016 and is investigating the impacts of radiation on wild organisms in Fukushima with his colleagues as project leader.

(Received 17 December 2020, Accepted 28 December 2020)
Overview of Open Biodiversity Data around the Fukushima Disaster Area and the Nuclear Power Plants in Japan

Akira YOSHIOKA¹, Nao KUMADA², Yui OGAWA² and Keita FUKASAWA²

¹Fukushima Branch, National Institute for Environmental Studies
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
²Center for Environmental Biology and Ecosystem Studies, National Institute for Environmental Studies
16-2 Onogawa, Tsukuba-shi Ibaraki, 305-8506, Japan
*E-mail: yoshioka.akira@nies.go.jp

Abstract
Examining the comprehensive impacts of the nuclear accidents in Fukushima on biodiversity continues to be a challenge. Data availability may be one problem. Previous studies have used hardly any ecological data from before the accidents. Furthermore, raw data from the previous studies have been not adequately released for re-analysis and integration into new analyses. To examine the current status and problems with open biodiversity data and monitoring systems related with nuclear plants, we surveyed (1) datasets registered in GBIF (the Global Biodiversity Information Facility) around the Fukushima evacuation zone (including the “difficult to return zone,” Fig. 1) and (2) monitoring sites of the Monitoring Sites 1000 Project and JaLTER (Japan Long-Term Ecological Research Network) around Japan’s nuclear power plants. The GBIF database shows that few datasets on wild organisms exist covering periods both before and after the Fukushima accident around the evacuation zone, except on birds. The present monitoring sites near the nuclear power plants are shown mainly to target wild birds and sites targeting other taxa are limited. In addition, the monitoring surveys have been highly dependent on citizen scientists. To enhance biodiversity data availability in preparation for evaluating impacts of nuclear emergencies, it would be desirable to improve monitoring systems and technologies for integrating monitoring by citizen scientists in normal times with monitoring by scientists belonging to institutes in times of emergency.

Key words : citizen science, ecology, monitoring, nuclear power plant, open science

1. Introduction
The Fukushima Daiichi nuclear power plant (FDNPP) accident in 2011 following the Great East Japan Earthquake and Tsunami resulted in increased radiation levels over a large area owing to radioactive materials released from the FDNPP. Many studies have examined the ecological and biological impacts of that radiation on biodiversity from the genetic to the population level (Tamaoki, 2016; UNSCEAR, 2017). Some studies have suggested remarkable negative effects on wild plants and animals (e.g., Hiyama et al., 2012; Möller et al., 2012, 2013; Akimoto, 2014; Ochiai et al., 2014; Watanabe et al., 2015; Horiguchi et al., 2016), while others have not (e.g., Matsushima et al., 2015; Yoshioka et al., 2015; Okano et al., 2016; Lyons et al., 2020). It is difficult to explain some of the remarkable negative results only from direct radiation dose effects considering the spatial distribution of the air dose in the disaster area (Garnier-Laplace et al., 2011; UNSCEAR, 2017). Wild organisms and environments not only interact with each other in complicated ways, but can also be affected by interruption of anthropogenic activities as a result of evacuation orders (Yoshioka et al., 2015; Lyons et al., 2020). Although United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2017) concluded that any radiation effects would have been constrained to a limited area and that the potential for effects on biota beyond that area was insignificant, the long-term impacts of the nuclear disaster on biodiversity and ecosystems remain to be seen.

One difficulty in evaluating the impacts on biodiversity may be limited availability of data. First, studies based on data covering periods both before and after the accident are limited. Murase et al. (2015) compared the data on reproductive performance of the goshawk Accipiter gentilis before and after the Fukushima accident and suggested that the reproductive rate was negatively affected by the radiation doses. The study site, however, was more than 100 km from the FDNPP and the air dose rate was quite low (0.27–0.85 µSv/h) compared to the derived consideration reference
level (DCRL) for birds: 0.1–1 mGy/day by International Commission on Radiological Protection (ICRP, 2008). Please note that the air dose rate measured using a dosimeter (TERRA-P, Sparing-Vist Center, Lviv, Ukraine) in Murase et al. (2015) was considered to correspond to a gamma-ray dose equivalent rate and we assumed that 1µSv ≒ 1µGy (Morishita, 2007). Comparing data around the FDNPP and the evacuation zone before and after the accidents would provide more comprehensive inferences on the direct and indirect effects of the radiation. Although no one desires a nuclear accident, preparation in advance for evaluating the impact is desirable.

The second problem with data availability is openness and transparency of the data. The biological impacts of the nuclear accidents are of interest not only to scientists in multiple fields, but also to citizens. Among scientists, lack of underlying data makes appropriate interpretation difficult (Beresford et al., 2012). Citizens have become skeptical of science and technology as a result of the nuclear accident (Ministry of Education, Culture, Sports, Science and Technology, Japan, 2012). To meet their expectations with limited information, accumulating and sharing raw data in the most open and transparent manner as possible would be helpful. In addition, considering serious nuclear accidents have been relatively infrequent (e.g., the Fukushima accident happened about 25 years after that in Chernobyl) and the impacts can continue for a long time, contacting corresponding authors of papers on past accidents is not always easy. Sharing data in an open manner (e.g., using data repositories) would be desirable for integrating past data and novel data. Therefore, the concept of open science and citizen science (Silvertown, 2009) would be suitable as a research theme (Fukasawa et al., 2017a).

Out of 20 papers on the biological and ecological impacts of the Fukushima accident that Tamaoki (2016) reviewed, however, only two papers (Murase et al., 2015 and Yoshioka et al., 2015) published the raw data they had used for statistical analysis, which is a basic component of ecological research (Okland, 2007). After 2016, some research groups that had reported remarkable results immediately after the accident published related studies presenting raw analyzed data (Morelli et al., 2017; Hiyama et al., 2017; Akimoto et al., 2018), but that’s not always the case (e.g., Hayama et al., 2017; Møller & Mousseau, 2019). Thus, open data has not been a standard assumption under this research theme.

Interdisciplinarity may be one reason open data have been uncommon in this area. Differences in the culture of data sharing and access between different disciplines, and the lack of obvious, public, community repositories can pose a significant barrier to public data deposition (Nature Research, 2016). Nevertheless, leading scientific journals are working to improve the situation. Nature Research (2019) stated that sharing of data in earth, space and environmental sciences will be required through data repositories at Nature and the related Nature Research journal; and Scientific Data, a nature research group journal for data papers, will be updating its list of recommended data repositories to help authors from these fields comply with these new policies. This movement may encourage researchers studying environmental impacts of radiation to publish their raw data as well.

As matters stand, there is room for improvement in data availability and openness in research on the biological and ecological impacts of the nuclear accident. To improve the situation from the viewpoint of ecologists, we have published ecological datasets collected inside and around the Fukushima evacuation zone in the form of data papers (Fukasawa et al., 2016; Fukasawa et al., 2017b; Ishiniwa et al., 2019; Yoshioka et al., 2020). Likewise, compiling open data collected in the past regardless of the FDNPP may be useful for evaluating the impact of the accident. Furthermore, current ecological monitoring systems not related to the nuclear disaster could potentially play an important role in evaluating the ecological risks of nuclear accidents in the future. In this paper, we examine open data and related projects regarding the distribution and population dynamics of wild organisms that can potentially play a role in biodiversity monitoring in the event of nuclear accidents via two approaches: (i) datasets collected around the FDNPP and registered in GBIF (the Global Biodiversity Information Facility), which is one of the largest worldwide platforms for open data on biodiversity, are examined, and (ii) monitoring sites around nuclear power plants in Japan and the monitoring targets of the “Monitoring Sites 1000 Project,” a national project for monitoring biodiversity, are examined as indicators of preparation for future emergencies. Based on these results, the characteristics and limitations of data availability on biodiversity data in Japan from the viewpoint of nuclear accidents are discussed.

2. GBIF Data around the FDNPP

GBIF is an international network and research infrastructure funded by governments around the world and aimed at providing anyone, anywhere, open access to data about all types of life on Earth (GBIF, 2020). Through the GBIF website, datasets on biological specimens and species distribution data registered by research institutes and scientists worldwide are available for free. Using the filter function of the website, we extracted datasets within a rectangular area enclosing the evacuation zone of Fukushima registered through June 30, 2020 (Fig. 1, GBIF.org, 2020). The latitudes and longitudes of the corners of the area are (N37.2402°, E140.61826°), (N37.2402°, E141.04526°), (N37.76172°, E141.04526°), (N37.76172°, E140.61826°). Please note that the filter function on the GBIF web site is able to
extract only simple polygonal regions.

Based on “occurrences” (records of when and where a species existed, used as a unit in GBIF data), 75,556 occurrence records were extracted. Among them, however, 137 records lacked information on the year of sampling. Most of data had been obtained after 2011 (only 2,891 occurrence records had been obtained before 2011, see Fig. 2 also) and consisted of birds (Fig. 3). Actually, a large part of the data set on birds was obtained by NIES (National Institute for Environmental Studies, Japan) for monitoring the evacuation zone starting from 2014 (Fukasawa et al., 2016; Fukasawa et al., 2017b; Fig. 4). Excluding avian and mammalian data sets obtained by NIES for its biodiversity monitoring project after the accident (66,226 and 5,267 records, respectively), the volume of the remaining data decreased to about 5%. The remaining data consisted mainly of data on waterfowl populations and plant specimens (Fig. 3(c)). The waterfowl population data were based on a continuous census conducted by the Ministry of the Environment, Japan, and the abundance data were also published through the national government’s website (Biodiversity Center of Japan, 2020a). Thus, the dataset may give some inferences through ecological analysis. On the other hand, the dataset on plant specimens was obtained in the context of natural history and most of the data had been obtained before the accident. Several assumptions are needed and additional data may be required to analyze the dataset from an ecological viewpoint. The specimen data do not always show that the species were absent or rare in locations where specimens were not recorded. There are some ecological analysis methods for presence-only data such as Maxent (Phillips et al., 2006), so inferences of the results should be carefully conducted. Results of such an analysis will be biased due to spatial heterogeneity of the monitoring effort. Anyway, the taxa in the species distribution data available from GBIF are highly biased toward birds as matters stand. In particular, data before the nuclear accident are limited conspicuously.

Fig. 1 Spatial distribution of ecological data registered in GBIF (Global Biodiversity Information Facility) near the FDNPP (Fukushima Daiichi nuclear power plant) through 30th June 2020. The sky blue circles and deeper blue circles show locations where the data were obtained before and after 2011, respectively. The latitudes and longitudes of the corners of the data-extracted area are (N37.2402º, E140.61826º), (N37.2402º, E141.04526º), (N37.76172º, E141.04526º) and (N37.76172º, E140.61826º). Please note that GBIF data outside the region were not extracted. The background map was obtained from National Land Numerical Information (Ministry of Land, Infrastructure, Transport and Tourism, 2014). The green, yellow and red zones correspond to the “areas preparing for the lifting of the evacuation order,” “restricted residential areas” and “areas to which it is difficult to return” sub-zones, respectively. The evacuation zone classification was based on conditions in October 2013 (Cabinet Office, Government of Japan, 2013).

Fig. 2 Number of GBIF occurrence records registered by NIES (National Institute for Environmental Studies, Japan) and other institutes near the FDNPP per year as of 30 June 2020.
Including decommissioned plants such as the FDNPP, there are 17 nuclear plant location points in Japan as of 2020 (Table 1). Although no nuclear accident should ever happen again, the existing biodiversity monitoring systems around the nuclear power plants are expected to be useful in evaluating the status of biodiversity and ecosystems at normal times and the data from them to contribute to analysis of changes in status if nuclear emergencies should happen.

The Monitoring Sites 1000 Project is a long-term nationwide project for monitoring biodiversity and ecosystems that has been conducted by the Ministry of the Environment, Japan since 2003 (Watanabe et al., 2012; Kobori et al., 2015). To cover Japan’s wide variety of ecosystems, the monitoring data are collected not only by scientists belonging to research institutes, but also trained citizen scientists associated with the Wild Bird Society of Japan and the NACS-J (Biodiversity Center of Japan, 2019, 2020b). In long-term and broad-area biodiversity monitoring projects, citizens’ cooperation has often
played quite an important role (Silvertown, 2009; Bonney et al., 2009). The compiled dataset has been available from the project’s website and partly from the GBIF website, though some parts of the dataset are closed (e.g., data on species at risk from poaching and over-exploitation). Because this project aims to detect degradation of ecosystems at early stages through long-term continuous monitoring, the dataset is expected to contribute to evaluation of the state of biodiversity around nuclear plants now and in the future.

Here, we examine the spatial distribution of the monitoring sites (Fig. 5; Table 1; Table 2) based on the project’s website (Monitoring Site 1000 Project, 2020). We extracted the geographic coordinates of the

<table>
<thead>
<tr>
<th>Nuclear power plant</th>
<th>Prefecture</th>
<th>Monitoring Sites 1000 within 20km (focal ecosystem)</th>
<th>Monitoring Sites 1000 within 20–30km (focal ecosystem)</th>
<th>The number of sites per terrestrial area within 30 km (sites/km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomari</td>
<td>Hokkaido</td>
<td>n.a.</td>
<td>Nakoma (rural area)</td>
<td>5.26×10⁻⁴</td>
</tr>
<tr>
<td>Higashidori</td>
<td>Aomori</td>
<td>n.a.</td>
<td>Mutsuyokohama (forest and grassland)</td>
<td>6.82×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>North coast of Shimokita peninsula (lake and wetland)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Obuchinuma (lake and wetland)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>North part of Mutsu bay (lake and wetland)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Takasegawa-Mutsuogawara port (tidal flat)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bentenjima (small islet)</td>
<td></td>
</tr>
<tr>
<td>Onagawa</td>
<td>Miyagi</td>
<td>Ashijima (small islet)</td>
<td>Monomishiyama forest road (forest and grassland)</td>
<td>6.40×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Downstream of Kyu-Kitakami River (forest and grassland)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Haden-ya (rural area)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Shizugawa (seaweed bed)</td>
<td></td>
</tr>
<tr>
<td>Fukushima Daiichi</td>
<td>Fukushima</td>
<td>n.a.</td>
<td>Hirusone-Ohatake forest road (forest and grassland)</td>
<td>7.19×10⁻⁴</td>
</tr>
<tr>
<td>Fukushima Daini</td>
<td>Fukushima</td>
<td>n.a.</td>
<td>Hirusone-Ohatake forest road (forest and grassland)</td>
<td>1.44×10⁻³</td>
</tr>
<tr>
<td>Tokai &amp; Tokai Daini</td>
<td>Ibaraki</td>
<td>Namekawahama (rural area)</td>
<td>Tananobasandori (forest and grassland)</td>
<td>2.59×10⁻³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ibaraki-kenminnomori (forest and grassland)</td>
<td>Hinuma (lake and wetland)</td>
<td></td>
</tr>
<tr>
<td>Kashiwazaki Kariwa</td>
<td>Niigata</td>
<td>Koshijihara hill (rural area)</td>
<td>Tsukikosa forest road (forest and grassland)</td>
<td>1.96×10⁻³</td>
</tr>
<tr>
<td>Shiga</td>
<td>Ishikawa</td>
<td>Bepposhodake (forest and grassland)</td>
<td>Tokinoufurusato-Notomaruyama (rural area)</td>
<td>3.28×10⁻³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ochi (lake and wetland)</td>
<td>Chirihamada (tidal flat)</td>
<td></td>
</tr>
<tr>
<td>Tsuruga</td>
<td>Fukui</td>
<td>Nosaka-ikoinomori (forest and grassland)</td>
<td>Sanriyama (forest and grassland)</td>
<td>1.83×10⁻³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Kuroko forest road for Mikuniyama (forest and grassland)</td>
<td></td>
</tr>
<tr>
<td>Mihama</td>
<td>Fukui</td>
<td>Nosaka-ikoinomori (forest and grassland)</td>
<td>Kuroko forest road for Mikuniyama (forest and grassland)</td>
<td></td>
</tr>
<tr>
<td>Ohi</td>
<td>Fukui</td>
<td>Ashi (forest and grassland)</td>
<td>Ashiokamitani (forest and grassland)</td>
<td>2.06×10⁻³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Kannurujima &amp; Kutsujima (small islet)</td>
<td></td>
</tr>
<tr>
<td>Takahama</td>
<td>Fukui</td>
<td>Kammurujima &amp; Kutsujima (small islet)</td>
<td>Otagawasho-tokuhEnter (tidal flat)</td>
<td>1.31×10⁻³</td>
</tr>
<tr>
<td>Hamamako</td>
<td>Shizuoka</td>
<td>Ogasayama (forest and grassland)</td>
<td>Ashi (forest and grassland)</td>
<td>4.35×10⁻³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Omazaki coast (sandy shore)</td>
<td>Otagawashofujimotheru-Yaizushitajiri (tidal flat)</td>
<td></td>
</tr>
<tr>
<td>Shimane</td>
<td>Shimane</td>
<td>Lake Nakaumi (lake and wetland)</td>
<td>Hoshikamiyama (forest and grassland)</td>
<td>4.55×10⁻³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lake Shinji (lake and wetland)</td>
<td>Estuary of Inashi River (tidal flat)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Estuary of Hii River (lake and wetland)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sagara coast (sandy shore)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ikata</td>
<td>Ehime</td>
<td>Suwazaki-shizenkyuyorin (forest and grassland)</td>
<td>Dogadani-tonbonosato (rural area)</td>
<td>3.79×10⁻³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sanctuary-donguri (rural area)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Genkai</td>
<td>Saga</td>
<td>n.a.</td>
<td>Ochi (forest and grassland)</td>
<td>9.96×10⁻¹</td>
</tr>
<tr>
<td>Sendai</td>
<td>Kagoshima</td>
<td>Shibisan (forest and grassland)</td>
<td>Urushinosato-oiyama (rural area)</td>
<td>1.65×10⁻¹</td>
</tr>
</tbody>
</table>

Mean ± SD 2.68×10⁻⁷ ± 1.90×10⁻³
Number of sites in Japan (24 June 2020) 1,014
Land area of Japan overall (sites/km²) 377,975.21
Density of monitoring sites in Japan (sites/km²) 2.68×10⁻⁷
examined areas within 30 km of each nuclear power plant as a buffer. In addition, areas 30 km from nuclear power plants usually correspond to “Urgent Protective Action Planning Zones” based on Japan’s Nuclear Emergency Response Guidelines (Nuclear Regulation Authority, 2019), in which precautionary sheltering and emergency monitoring of environmental radiation levels are required under nuclear emergency situations.

As a result, all nuclear power plants in Japan (including decommissioned plants) are located within 30 km of one or another of the monitoring sites, though six of the 17 nuclear power plants have no corresponding monitoring sites within 20 km. In particular, the number of monitoring sites in Hokkaido and Kyushu (Saga and Kagoshima prefectures) is likely to be small. The number of the monitoring sites near the nuclear power plants in Fukushima Prefecture is also small (three sites in total within 30 km). However, the mean density of sites within the 30 km zone (site number per terrestrial area) was 2.68×10^{-3} sites/km^2, almost equivalent to the site number

---

**Table 2** Relationships between focal ecosystems and monitoring targets (surveyed indicators) in the Monitoring Sites 1000 Projects. Please note that only cases within 30 km of a nuclear plant are shown.

<table>
<thead>
<tr>
<th>Focal ecosystem</th>
<th>Monitoring target</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest and grassland</td>
<td>Terrestrial birds, Vegetation</td>
<td>In addition, ground-dwelling beetles, litter and tree growth have also been surveyed in “Ashiu,” which is one of the core sites for forest monitoring. Targeting indicators of traditional agricultural landscapes in Japan, the so-called “satoyama.” Usually, more than one from the nine targets is surveyed by citizen scientists (see Table 3). In the core sites, multiple indicators are surveyed (only the “Urushinosatoyama” site in Kagoshima Pref. is a core site for rural area monitoring within 30 km of a nuclear power plant).</td>
</tr>
<tr>
<td>Rural area</td>
<td>Flora</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water environment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vegetation (Anthropogenic impacts)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Birds</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Large-middle size mammals</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Harvest mouse Micromys minutus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frogs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Butterflies</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fireflies</td>
<td></td>
</tr>
<tr>
<td>Lake and wetland</td>
<td>Waterfowl</td>
<td>At “Shinjiko” and “Nakaumi,” plankton, benthos and vegetation have been surveyed. At the other sites within 30 km of a nuclear plant, waterfowl has been surveyed.</td>
</tr>
<tr>
<td></td>
<td>Plankton, Benthos, Vegetation</td>
<td></td>
</tr>
<tr>
<td>Sandy shore</td>
<td>Turtles</td>
<td></td>
</tr>
<tr>
<td>Tidal flat</td>
<td>Shorebirds</td>
<td></td>
</tr>
<tr>
<td>Seaweed bed</td>
<td>Seaweed vegetation, Benthos</td>
<td></td>
</tr>
<tr>
<td>Small islet</td>
<td>Seabirds</td>
<td></td>
</tr>
</tbody>
</table>

---

Fig. 5 Spatial distribution of the monitoring points of the Monitoring Sites 1000 Project and nuclear power plants in the (a) eastern and (b) western part of Japan, respectively. The blue points indicate representative points of each monitoring site. The black points indicate nuclear power plants. The circles of solid and dotted grey lines indicate the areas within a 20 km and 30 km radius from the nuclear plant, respectively.
per land area of Japan overall (Table 1).

Considering focal ecosystems and monitoring targets, most sites have targeted birds (Tables 1 and 2). In addition, these bird monitoring surveys have been conducted by citizen scientists. Therefore, citizen science is essential to monitoring the current status of biodiversity and ecosystems around nuclear plants. Sites surveying taxa other than birds are quite scarce. Although the sites focusing on rural areas (so-called *satoyama*, a traditional heterogeneous agricultural landscape of Japan; Takeuchi, 2001; Kadoya & Washitani, 2011) have mainly surveyed flora as well as birds, the total number of these sites is less than 10 (Table 3). There are even fewer sites surveying mammals, frogs or insects.

Furthermore, we also examined JaLTER (Japan Long-Term Ecological Research Network) monitoring sites near the nuclear plants. JaLTER was established in November 2006 to provide scientific knowledge contributing to conservation, advancement and sustainability of the environment, ecosystem services, productivity and biodiversity for society by conducting long-term and interdisciplinary research in ecological science including human dimensions (JaLTER, 2020a). This scientific network became an official member of the ILTER (International Long-Term Ecological Research) project (Ohle et al., 2012), which along with GBIF plays an important role in ecological data archiving (Osawa et al., 2013). Monitoring of the sites has been mainly conducted by scientists belonging to research institutes (JaLTER, 2020b) and the datasets have been available from a database called JaLTER Metacat (JaLTER, 2020c). The 61 representative points of the JaLTER sites were extracted from a Google Maps map. The Ashiu Forest Research Station was located within 30 km of the Oi nuclear power plant, while the Maizuru Fisheries Research Station was located within 20 km of the Takahama nuclear power plant and within 30 km of the Oi nuclear power plant. The Lake Shinji and Lake Nakaumi sites were located within 20 km of the Shimane nuclear plant. The locations and associated institutes of the JaLTER site in Ashiu, Lake Shinji and Lake Nakaumi overlapped to some extent with the sites of the Monitoring Sites 1000 Project. Therefore, JaLTER’s sites may not adequately complement the Monitoring Site 1000 Project’s.

### 4. Discussion

In this study, we have obtained an overview of the ecological monitoring data/sites around Japan’s nuclear plants that could play an important role owing to their availability. The results suggest that datasets on bird dynamics are relatively abundant, while datasets on other taxa are inadequate. In addition, the datasets on birds have been collected by not only researchers, but also citizen scientists from NGOs such as the Wild Bird Society of Japan and NACS-J (Biodiversity Center of Japan, 2019, 2020b), though research institutes such as NIES play an important role in publishing data around the Fukushima evacuation zone. The waterfowl census data conducted by the Ministry of the Environment, Japan and registered in GBIF have also been based on considerable cooperation from environmental organizations such as the Wild Bird Society of Japan (Ministry of the Environment, Japan, 2020a). Therefore, availability of open biodiversity data is highly dependent on taxa, and interest among citizens will be important.

The caveat here is that our overview is not a complete review of open biodiversity datasets near nuclear power plants. We may have overlooked other freely available ecological datasets and long-term monitoring sites which were not registered in GBIF or the Monitoring Sites 1000 Projects, respectively. In addition, the datasets from these projects cannot cover certain types of biodiversity components. For example, detailed information on endangered species has usually not been released by these projects to avoid poaching and overexploitation. In addition, data based on hunting and fishing (i.e., economically important data) which have been compiled by national or local governments (or related organizations) are often not released. Some databases have been released, but not adequately integrated into these world-wide projects (e.g., Ministry of Land, Infrastructure, Transport and Tourism, 2007). Furthermore, it goes without saying that the biodiversity datasets and monitoring sites have not usually conducted

### Table 3 Monitoring targets of rural (*satoyama*) sites of the Monitoring Sites 1000 Project near nuclear power plants, based on Biodiversity Center of Japan (2019).

<table>
<thead>
<tr>
<th>Monitoring sites</th>
<th>Flora</th>
<th>Water environment</th>
<th>Vegetation</th>
<th>Birds</th>
<th>Large-middle size mammals</th>
<th>Harvest mouse</th>
<th>Frogs</th>
<th>Butterflies</th>
<th>Fireflies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nakoma</td>
<td>○</td>
<td></td>
<td>○</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haden-ya</td>
<td>○</td>
<td></td>
<td>○</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Namekawahama</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Koshijihara hill</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kashiwazaki-yumenomori park</td>
<td>○</td>
<td></td>
<td>○</td>
<td></td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tokinofurusato-Notomaru-ya</td>
<td>○</td>
<td></td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>Sanctuary-donguri</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dogadani-tonbonosato</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urushinosato-ya</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
surveys assuming nuclear accidents. Data and samples on internal exposure or mutation have not been monitored, though part of the data followed by preserved samples or specimens may make it possible to examine these biological effects later. Nevertheless, the biodiversity status should be rapidly assessed in emergent situations and easily available datasets representing normal situations will be required for comparison. GBIF and the Monitoring Sites 1000 Project are convenient and readily accessible to researchers and citizens. The open data provided by them will be important for rapid assessment of the status and dynamics of biodiversity.

From the viewpoint of improving preparation for future emergencies, what is needed is not only to maintain the current monitoring system, but also to provide a system for encouraging surveys of taxa diversity. Of course, the available manpower is usually limited, so indicator taxa should be well considered. If monitoring taxa other than birds is difficult, we should know how birds, which have often been assumed to be a good indicator of biodiversity (Greenwood, 2007), indicate or surrogate the status of other taxa in the event of nuclear accidents. Promoting registration of long-term data collected by local governments to GBIF or other available platforms may relieve the bias in monitored taxa in open biodiversity data. In principal, construction of nuclear power plants must accompany environmental surveys based on the Environmental Impact Assessment Act and the data associated with surrounding biodiversity should have been collected, though only summarized results were published for a limited period of time under the current system (Ministry of the Environment, 2020b). Furthermore, as our review shows, enhancing and maintaining participation of citizen scientists in ecological monitoring will be essential. The problem is that if a nuclear disaster happens, the citizens will not be able to collect data around the nuclear plants as before the accident. Therefore, methodology for follow-up of citizen scientists by scientists belonging to research institutes will also be important. In the case of the Fukushima accident, NIES has been conducting acoustic bird surveys using voice recorders and has set up opportunities to share their recordings of bird songs with local bird watchers (Fukasawa et al., 2017a). To prepare for future nuclear emergencies (or other disasters with movement restricted long term) appropriately and sustainably, a hybrid of surveys by citizen scientists and automated digital devices may be key. Ideally, a scheme that integrates monitoring by citizen scientists in normal times and that by scientists belonging to institutes in emergency times should be established from the viewpoint of both technologies and systems.

Acknowledgements
We would like to thank Dr. M. Tamaoki (National Institute for Environmental Studies, Japan) and two reviewers for their valuable comments.

References
Geospatial Information Authority of Japan (2020) *Statistical reports on the land area by prefectures and municipalities in Japan*, Geospatial Information Authority of Japan, Tsukuba. (in


Akira YoshioKA

Akira YoshioKA is a senior researcher at the Fukushima Branch of the National Institute for Environmental Studies, Japan. To evaluate the impacts of evacuation orders on biodiversity, since 2014, he together with the coauthors has been conducting biodiversity monitoring of the evacuation zones necessitated by the FDNPP accident. His main field of study has been flying insects in the evacuation zone and he is now developing original camera traps to monitor red dragonflies. He has also studied development of an index for satoyama, the traditional agricultural landscape of Japan, which plays an important role in biodiversity conservation but is threatened by increasingly prevalent land abandonment.

Nao Kumada

Nao Kumada is a specialist at the Center for Environmental Biology and Ecosystem Studies, National Institute for Environmental Studies, Japan. She has supported biodiversity monitoring of the Fukushima evacuation zone and her contributions range from data compilation to development of a novel method for estimating the population density of birds. She is also a member of the Japan Bird Research Association and has studied the ecology of cormorants vigorously.

Yui Ogawa

Yui Ogawa is a junior research associate at the Center for Environmental Biology and Ecosystem Studies, National Institute for Environmental Studies, Japan. She has studied citizen scientists' attitudes contributing to biodiversity data collection, especially on birds, and is now developing online training tools for assisting acoustic bird monitoring in the Fukushima evacuation zones.

Keita Fukasawa

Keita Fukasawa is a senior researcher at the Center for Environmental Biology and Ecosystem Studies, National Institute for Environmental Studies, Japan. He has studied statistical modeling and population density estimation for various plants and animals from the viewpoint of managing wildlife and alien species, as well as biodiversity conservation in underused agricultural ecosystems.

(Received 4 September 2020, Accepted 21 December 2020)
Role and Effect of a Dam on Migration of Radioactive Cesium in a River Catchment after the Fukushima Daiichi Nuclear Power Plant Accident

Seiji HAYASHI* and Hideki TSUJI

Fukushima Branch, National Institute for Environmental Studies
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
*E-mail: shayashi@nies.go.jp

Abstract

Positive and negative roles of dam reservoirs in radiocesium behavior in a river catchment were examined based on the results of comprehensive, long-term hydrological monitoring from 2013 to 2017 at Matsugabou Dam on the upstream reaches of the Uda River, which is one of the main rivers in the northern coastal region of Fukushima Prefecture. An estimation of the annual mass balance of Cs-137 associated with suspended solids (SS) in the reservoir showed that Matsugabou Dam had the effect of reducing the migration of radiocesium associated with SS from the dam reservoir catchment to the downstream reaches by more than 85% by storing SS in the reservoir bed. Moreover, proactive discharge control for preventing flood inundation in the downstream region had the ability to make this storage function perform even more effectively. On the other hand, the estimated annual mass balance of dissolved Cs-137 in the reservoir showed that the amount in the water discharged clearly tended to exceed the amount in the inflow, suggesting that substantial amounts of dissolved radiocesium were presumably produced by dissolution/elution from the stored bottom sediments in the dam reservoir. This negative role of a dam producing dissolved radiocesium may contribute to long-term contamination of freshwater ecosystems in downstream water bodies.

Key words: bottom sediment, dam reservoir, discharge control, dissolution, runoff

1. Introduction

Most of the seriously radioactively contaminated areas resulting from the Fukushima Daiichi nuclear power plant (FDNPP) accident consisted of mountainous forests (Morino et al., 2011). Few forested areas have been decontaminated because decontamination operations have been limited to inhabited areas such as residential districts, farmland, roads and marginal forests near residential districts (Ministry of the Environment, 2019). Consequently, the remaining vast forested area is left as a potential source of radiocesium penetration into downstream regions. Therefore, there are concerns about recontamination of the downstream regions as well as prolonged contamination of freshwater ecosystems by runoff from forested areas. Meanwhile there are over 90 water supply dams in Fukushima Prefecture, where agriculture is well developed as one of the main industries. Although radiocesium runoff originating from the FDNPP accident has been confirmed to be limited to less than 0.3% annually in forest catchments (Shinomiya et al., 2014; Iwagami et al., 2017; Tsuji et al., 2016), it is also a fact that a successive inflow of radiocesium in dissolved or particulate forms has been occurring from dam reservoir catchments covered mainly by seriously contaminated forest. As for behaviors of radiocesium originating from the FDNPP accident in dam reservoirs, although it is assumed that radiocesium associated with suspended solids (SS) flowing into a reservoir tends to accumulate in the bed through the water storage function of the dams (Kurikami et al., 2014; Huon et al., 2018), a quantitative evaluation of that function has yet to be fully accomplished based on long-term monitoring. Additionally, research on the effects of the re-suspension or dissolution of radiocesium from bottom sediment is very limited (Funaki et al., 2020). There is a need to accumulate scientific knowledge from the viewpoint of not only understanding the behavior of radiocesium in a dam reservoir but also examining the roles of dam reservoirs in radiocesium dynamics in river catchments. An approach of clarifying radiocesium dynamics comprehensively in a significantly contaminated dam reservoir catchment would contribute to a detailed examination of radiation exposure risks via various
pathways in river catchments.

The objective of this paper is thus to present characteristics of radioesium dynamics in a dam reservoir catchment mainly covered with forest affected by the FDNPP accident that have been elucidated on the basis of the data from our observations since 2012. Moreover, based on these results, the positive and negative roles of dam reservoirs in radioesium behavior in a river catchment are discussed from the viewpoint of considering various pathways of radiation exposure.

2. Materials and Methods

2.1 Study Area

Matsugabou Dam constructed on the upstream reaches of the Uda River and completed in 1997 was selected as the objective of this study (Fig. 1). The Uda River is one of the main rivers in the northern coastal region of Fukushima Prefecture, about 50 km north-northwest of the FDNPP. Matsugabou Dam reservoir, which has a surface water area of 0.72 km$^2$ and total storage capacity of 9,710 × 10$^6$ m$^3$, is operated mainly to supply irrigation water to the developed paddy fields in the middle and lower reaches of the Uda River catchment. The dam reservoir catchment (DRC, catchment area: 25.4 km$^2$) consists mainly of forest (80%), with 7% paddy fields, 5% farmland and 3% built-up areas. The soil in the DRC is mainly brown soils or red-brown forest soil. A small forested catchment (SFC, catchment area: 0.34 km$^2$) was selected to study the radioesium runoff characteristics from a forested area. Additionally, to estimate the effect of dam storage functions on prevention of radioesium migration to downstream areas, an observation site was set in the downstream reaches of the Uda River (#1 in Fig. 1) to get an overview of the radioesium runoff characteristics of the whole Uda River catchment (WURC, catchment area: 95.6 km$^2$) consisting of 79% forest, 7% paddy fields, 5% farmland and 4% built-up areas. The spatially averaged deposition of Cs-137 from the FDNPP accident into the DRC, SFC and WURC was 260 kBq/m$^2$, 170 kBq/m$^2$ and 210 kBq/m$^2$, respectively, based on the third airborne survey conducted by the Ministry of Education, Culture, Sports, Science and Technology (2011).

2.2 Sampling and Monitoring

To elucidate temporal changes in radioesium activity concentration in the river and water discharged from the dam and evaluate the mass balance of radioesium in the Matsugabou Dam reservoir, automatic hydrological observation (2150 Area Velocity Module, Teledyne Isco, Lincoln, NE, USA) and turbidity observation (DTS-12, Forest Technology Systems Ltd., Victoria, British Columbia, Canada) were conducted in the stream to measure the flowrate at the outlet of the SFC (37°48’10.7”N 140°45’28.1”E, #2 in Fig. 1) from July 2012 with a time interval of 10 min. Turbidity was automatically measured at the chapter just downstream of the dam discharge point (37°47’44.3”N 140°46’23.2”E, #3 in Fig. 1) using TC-500 (OPTEX Co., Ltd., Otsu, Shiga, Japan) from May 2013 and at the observatory at the outlet of the WURC (37°47’23.6”N 140°54’42.8”E, #1 in Fig. 1) using an INFINITY-Turbi (JFE Advantech Co., Ltd., Nishinomiya, Hyogo, Japan) from July 2012 with a time interval of 10 min. Measured data with a time interval of 10 min. for the dam discharge volume and the flowrate at the downstream observatory were obtained from Soma City and Fukushima Prefecture, respectively.

Water samples were collected at the hydrological observation point in the SFC from Oct. 2012, the inflow chapter to the dam reservoir (37°47’44.6”N 140°44’43.7”E, #4 in Fig. 1) to get an overview of the radioesium runoff characteristics of the whole Uda River catchment (WURC, catchment area: 95.6 km$^2$) consisting of 79% forest, 7% paddy fields, 5% farmland and 4% built-up areas. The spatially averaged deposition of Cs-137 from the FDNPP accident into the DRC, SFC and WURC was 260 kBq/m$^2$, 170 kBq/m$^2$ and 210 kBq/m$^2$, respectively, based on the third airborne survey conducted by the Ministry of Education, Culture, Sports, Science and Technology (2011).
6712, Teledyne Isco, Lincoln, NE, USA) was used to collect 3 L of river water for every sample in addition to that taken in the same manner during low flow conditions to sample the stream water at 30–60 min intervals. Bottom sediment samples were collected using an undisturbed sediment core sampler (HR type, RIGO Co. Ltd, Tokyo, Japan) at a site near the dam every late autumn after the typhoon season from 2012 to 2016. In particular, three core samples were collected at almost the same point to get an understanding of the spatial variation in radiocesium accumulation properties in 2015 and 2016.

2.3 Measurement

Particulate and dissolved radiocesium in water sampled during low flow conditions were collected separately using two types of cartridge filters (Tsuji et al., 2014; Yasutaka et al., 2015) immediately after sampling. As for the samples collected during rain runoff events, either centrifuge separation (15,760×g, 25min) to extract suspended matter or the cartridge filters described above were adapted depending on the SS concentration after being brought back to the laboratory to measure particulate radiocesium concentration. After centrifuge separation, the extracted suspended matter was placed in 100-mL plastic containers, dried at 60°C, weighed and analyzed for Cs-134 and Cs-137. The SS concentration of all of the water samples was measured by a filtering method using glass fiber filter papers (pore size, 0.7 μm, GF/F; GE Healthcare, Tokyo, Japan) to develop an equation to estimate the respective SS concentration from turbidity data measured at each observatory site as well as to evaluate its association with the particulate radiocesium concentration.

The collected reservoir bottom sediment core samples were sliced at 1–2 cm intervals from the surface, and the sliced samples were placed in 100-mL plastic containers, dried at 60°C, weighed and analyzed for Cs-134 and Cs-137.

Cs-134 and Cs-137 activities in samples were measured using a coaxial or a well-type germanium detector (GC2518 or GCW7023; Canberra, Meriden, CT). A Spectrum Explorer (Canberra Japan, Tokyo, Japan) was used to analyze the γ-ray spectra. MX033U8PP (The Japan Radioisotope Association, Tokyo, Japan) was used to analyze the γ-ray spectra. CT). A Spectrum Explorer (Canberra Japan, Tokyo, Japan) was used as the standard source for the efficiency calibration. Estimates of the activities of samples trapped in the cartridge filters were geometrically corrected using the formula of (Tsuji et al., 2014; Yasutaka et al., 2015). The activities were decay-corrected to the sampling date, and then the activity concentration was determined on a dry weight basis. Since it was confirmed that the proportion of activity concentrations of Cs-134 and Cs-137 for each sample was almost 1.0 after decay correction to Mar. 11, 2011, only Cs-137 was used, as described in the Results and Discussion below, from the viewpoint of evaluating long-term radioactive contamination.

3. Results and Discussion

3.1 Particulate Radiocesium Runoff Properties from Forests and Entire River Catchments

The activity concentrations of dissolved Cs-137 were very low (less than 0.02 Bq/L) at the outlets of both the SFC and the WURC at the beginning of our observation period and have also been decreasing since then. Therefore, only particulate Cs-137 was considered in evaluating the amount of radiocesium migration at the river-catchment scale in this study because dissolved radiocesium contributes little to radiocesium flux during the rain runoff events that play an important role in transport and dispersion of radiocesium in river watersheds and coastal marine environments, as pointed out by Nagao et al. (2013). Figure 2 shows the temporal change in the activity concentration of Cs-137 associated with SS in the outlets of the SFC and WURC (#2 and #1 in Fig. 1). The temporal change of each respective decline in concentration was fitted using a single component exponential model represented by the following equation:

\[
^{137}\text{Cs}_\text{SS} = A \cdot e^{-\lambda_{\text{ss}} \cdot t}
\]

where \(^{137}\text{Cs}_\text{SS} (\text{Bq/kg-SS})\) represents the activity concentration of Cs-137 associated with SS, \(A\) (Bq/kg-SS) and the effective decay constant, \(\lambda_{\text{ss}}\) (1/y) are empirically determined constants, and \(t\) (y) is time elapsed since deposition. The statistical analysis used to determine these parameters was performed using Origin version 2020 data analysis and graphing software (OriginLab Corporation, Northampton, MA, USA). The concentrations at both sites fluctuated greatly until a huge rain event, tropical storm Etau, occurred in September 2015 with a large amount of rainfall over two days as is said only to occur every 50 to 100 years. It is especially curious that the concentrations at the SFC were relatively

**Fig. 2** Change over time in activity concentrations of Cs-137 associated with SS in the small forest catchment (SFC) and the whole Uda River catchment (WURC) after the FDNPP accident.
higher than those at the WURC, contrary to differences in the initial amount of Cs-137 deposited between the catchments. This may be due to the fact that decontamination operations in farmland and inhabited areas in the upper reaches of the WURC began in the autumn of 2012. Additionally, no significant decreasing trend in the activity concentration of Cs-137 associated with SS could be confirmed in the forest stream (Hayashi et al., 2016). However, the concentrations decreased with relatively small fluctuation after tropical storm Etau, which consequently brought about a significant decreasing trend exceeding natural decay at the both sites. The effective decay constant ($\lambda_{SS}$) in the SFC was estimated to be 0.20 (y$^{-1}$) which is in the range of the values (0.15 – 0.44 (y$^{-1}$)) estimated by Iwagami et al. (2019) based on monitoring from Apr. 2012 to Nov. 2016 in several small forest catchments in Yamakiya District, Kawamata Town, located around 35 km northwest of the FDNPP. Although no detailed analysis has been conducted to explain these decreases that are much faster than natural decay in the activity concentration of cesium-137 associated with SS in a forest stream, the extreme rain event of 2015 is assumed to have eroded fine surface mineral soils with high concentrations of radionuclides or washed highly contaminated forest organic matter out from the river banks and riparian zones which play a dominant role in sediment production (Sakuma et al., 2018). This might bring about the decreases shown in Fig. 2 in the concentration and fluctuation of the activity concentration of Cs-137 associated with SS since then. Also for the effective decay constant ($\lambda_{SS}$) in the WURC, the estimated value (0.26 (y$^{-1}$)) corresponds approximately to the reported values in other major rivers in the northern coastal region (0.06 – 0.41(y$^{-1}$); Taniguchi et al., 2019). Although the effects of land use or decontamination operations are indicated as a cause of the concentration clearly decreasing (Taniguchi et al. 2019), a detailed mechanism remains to be clarified by applying an SS source analysis.

Figure 3 shows the relationship between SS concentration and Cs-137 activity concentration associated with SS in the SFC and WURC. The plotted Cs-137 concentration values are decay-corrected to Mar. 11, 2011 to remove the effect of physical decay on the relationship. While increases in SS concentration easily exceeding 1,000 mg/L would obviously contribute to decreases in the activity concentration of Cs-137 associated with SS from huge rain events, resulting in sediment runoffs with larger amounts of sandy components, variations in SS concentration were not confirmed to have a significant effect on Cs-137 concentrations associated with SS at either site when relatively high rain events happened. Ratios of annual Cs-137 runoff associated with SS to the amount of Cs-137 deposited in the catchments are presented with annual rainfall amounts observed at the Matsugabou Dam maintenance facility (Fig.1; 37°47’46.5"N 140°46’13.7"E) in Table 1. Data from the third airborne survey (Ministry of Education, Culture, Sports, Science and Technology, 2011) were used to calculate the amount of Cs-137 deposited in each catchment. The annual amount of Cs-137 runoff was calculated using sequential data on flowsrates and SS concentrations and by applying the estimated Cs-137 concentration decay equation at each site (Fig. 2). The annual runoff ratio varies considerably whether huge rain events occur or not. In fact, in 2015 when tropical storm Etau hit in September, 90% of the annual Cs-137 runoff amount was produced during this rain event. Decay in Cs-137 concentrations associated with SS is also an important factor influencing the runoff ratio, because the ratio in 2016 was less than that in 2013 by half despite the annual rainfall amount in 2016 being larger than in 2013.

3.2 Role of Dam Reservoirs in Radiocesium Storage Functions

As a result of applying Eq. 1 to the time series data on Cs-137 radioactivity concentration associated with SS

![Graph showing relationship between SS and activity concentrations of Cs-137 associated with SS in the small forest catchment (SFC) and the whole Uda River catchment (WURC).](image)

Table 1 Ratio of annual Cs-137 runoff associated with SS to the amount of Cs-137 deposited, estimated from the third airborne survey data (MEXT, 2011) in the small forest catchment (SFC) and the whole Uda River catchment (WURC).

<table>
<thead>
<tr>
<th>Year</th>
<th>Cs-137 runoff ratio (%)</th>
<th>Annual rainfall* (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SFC</td>
<td>WURC</td>
</tr>
<tr>
<td>2013</td>
<td>0.081</td>
<td>0.25</td>
</tr>
<tr>
<td>2014</td>
<td>0.084</td>
<td>0.066</td>
</tr>
<tr>
<td>2015</td>
<td>0.15</td>
<td>0.47</td>
</tr>
<tr>
<td>2016</td>
<td>0.037</td>
<td>0.092</td>
</tr>
<tr>
<td>2017</td>
<td>0.027</td>
<td>0.023</td>
</tr>
</tbody>
</table>

*Observed at the Matsugabou Dam maintenance facility.
in the water discharged from Matsugabou Dam, the radioactivity concentration was found to decrease significantly faster than the physical decay rate (Fig. 4; \( \lambda_{SS} = 0.22 \ (1/y) \)), although it showed large variations among samples. Just as in the cases of the forest stream or downstream reaches, no SS concentration effects on Cs-137 associated with SS could be clearly distinguished. The Cs-137 concentration fluctuated considerably under low discharge conditions with less than 5 mg/L of SS concentration (\( R^2=0.03, \ p=21, \ N=63 \)). Additionally, it was not clear whether Cs-137 concentrations associated with SS were influenced by increased SS concentrations in discharged water from pronounced sediment inflows to the dam reservoir during rain runoff events because of insufficient sample numbers.

Figure 5 shows the vertical distribution of Cs-137 radioactivity concentration in undisturbed bottom sediment core samples collected around the deepest point near the dam itself each year in late autumn from 2012 to 2016. The samples for 2015 were collected in November after tropical storm Etau passed. Since the bottom sediment in this area with a water depth of more than 30 m is rarely disturbed by water flow, the vertical distribution of radiocesium in bottom sediment is formed only through settling and accumulation of inflow sediment. The most notable point is that the sediment layer with the highest concentration of Cs-137 had obviously migrated downward to deeper levels from 2014 to 2015. Hayashi (2017) suggested that the sediment layer with the highest peak in the Cs-137 concentration be assumed to have been influenced by direct deposition to the reservoir surface or the initial inflow to the reservoir after the accident. Those layers were located a little deeper from the surface of the bottom sediments in analyses using undisturbed bottom sediment core samples in the Matsugabou Dam reservoir in 2012 and 2013. They also suggested that the layer with the highest concentration apparently continues migrating downward due to intermittent sediment inflow from the dam reservoir catchment. From that observation, the settling and deposition of huge amounts of sediment inflow into the dam reservoir when tropical storm Etau hit in September 2015, are considered to be the main reason the layer with the highest concentration of Cs-137 moved downward remarkably in the bottom sediment. This may have been caused by spatial heterogeneity in the process of sedimentation and deposition of the inflowing sediment due to complex topography of the reservoir bed. The huge amounts of sediment inflow and their accumulation at the bottom are also confirmed by annual measurements of dam reservoir sedimentation conducted by the Soma Land Improvement District (not published). The measurement data show that the amount of sand accretion in Jan. 2016 (114,000 m³) increased by twice as much as that in Jan. 2015 (53,000 m³). Although the amount of Cs-137 accumulating in the bottom sediment samples showed an annual increasing trend, it was not significant (\( R^2=0.37, \ p=0.27 \)). In addition to insufficient sample numbers, this variation among the sampling points might be influenced by spatial heterogeneity in accumulation of Cs-137 on the reservoir bed.

Since the annual changes in the observed sedimentation and vertical distribution of Cs-137 activity concentrations in the bottom sediment showed that the dam acted to store radiocesium associated with SS pouring in from the reservoir catchment, an attempt to quantify the function was made by annually comparing

**Fig. 4** Change over time in activity concentrations of Cs-137 associated with SS in the water discharged from Matsugabou Dam after the FDNPP accident.

**Fig. 5** Annual changes in vertical distribution of Cs-137 activity concentrations in bottom sediment collected in the neighborhood of Matsugabou Dam itself. All of the samples were collected each late autumn after the typhoon season.
the amount of Cs-137 associated with SS between the inflow into the dam reservoir and the discharge from the dam. Each annual amount of Cs-137 inflow associated with SS was calculated by multiplying the estimated amount of Cs-137 deposition by each annual runoff ratio of Cs-137 associated with SS in the dam reservoir catchment. The annual runoff rate in the DRC was assumed equal to that of the watershed, which is the WURC minus the DRC. This is because the spatial distribution of land use in the catchment is similar to that of the DRC. Specifically, it was estimated by dividing the difference calculated by subtracting the annual amount of Cs-137 associated with SS discharged from the dam from the annual amount of runoff from the WURC, by the amount of Cs-137 deposited in the area, subtracting the DRC area from the WURC area. Table 2 presents the annually calculated runoff ratios, inflows and amounts of Cs-137 discharged associated with SS, and the effects the dam had on storing Cs-137 associated with SS and preventing its migration to the coastal area. Although the inflow and amount of Cs-137 discharged varied from year to year corresponding to the annual rainfall amount, i.e., the amount of sediment inflow from the dam reservoir catchment, the runoff ratio was confirmed to remain at more than 84% every year. The contribution of internal production to the concentration of Cs-137 associated with SS and its mass balance in the dam reservoir is not clear but may not be significant, as shown by Tsuji et al. (2020) in the Yokokawa Dam reservoir on the Ohta River in the northern coastal region of Fukushima Prefecture. It is especially curious that the retention ratio in 2015 (93%) when the huge storm event happened was higher than that in 2017 (84%), which was a typical dry year. Since the effective decay rate in the concentration of Cs-137 associated with SS in the WURC ($\lambda_{Cs}$: 0.26), which was faster than that in the SFC ($\lambda_{Cs}$: 0.20) or the dam discharged water ($\lambda_{Cs}$: 0.22), was applied in estimating the runoff ratio of Cs-137 associated with SS from the DRC, the runoff ratio of 2017 may have been underestimated. Moreover, as pointed out by Hayashi et al. (2016), active water storage management for preventing flood inundation downstream may have resulted in a larger retention ratio by promoting the settling and deposition of the amount of Cs-137 inflow associated with SS during the huge rain event, accounted for about 95% of the annual total inflow. When compared with the case without a dam, these high ratios also indicate that the dam plays a role in reducing the amount of Cs-137 inflow associated with SS into the coastal area (Matsukawaura Lagoon; Fig. 1) by about 30% every year through its storage function.

While huge amounts of sediment flowed into the reservoir, Hayashi et al. (2016) suggested that proactive dam discharge control for flood prevention downstream could have accelerated the accumulation of sediment on the reservoir bed. This is also supported by the sedimentation survey results described above. Additionally, in terms of usefulness of water storage management for storing radiocesium associated with SS in dam reservoirs, in a simulation of the Ogaki Dam reservoir Yamada et al. (2015) found that the amount of clay discharged, including large amounts of radiocesium from the reservoir, could be reduced by a factor of three by raising the height of the dam exit. These results clearly show that not only does a dam function to prevent migration and diffusion of radiocesium associated with SS by storing it in the reservoir, but also that proactive discharge control has the potential to help fulfill this function more effectively.

### 3.3 Effect of Dam Reservoirs as Sources of Dissolved Cs

Figure 6 shows the annual changes in dissolved Cs-137 activity concentration measured every two weeks or monthly in the dam reservoir inflow stretch and the dam discharge channel. Unlike Cs-137 associated with SS, the activity concentration of dissolved Cs-137 showed annual periodic variations at both sites. Moreover, since the amplitude as well as the activity concentration of the dissolved Cs-137 have been declining with time, the effective decay constant and efficiency half-life ($T_{ew}$) of the Cs-137 concentration could be estimated by fitting the data to the following exponential function equation consisting of the decay component and the periodical component using Origin version 2020 (OriginLab Corporation, Northhampton, MA, USA). The curves fitted by the equation have also been drawn in their respective graphs.

$$\text{Dissolved } ^{137}\text{Cs} = \exp\left(-\lambda_{Cs} \cdot t + b + e \cdot \sin \left(\frac{2\pi c(t + r)}{d}\right)\right)$$

<table>
<thead>
<tr>
<th>Year</th>
<th>Ratio of runoff from the DRC (%)</th>
<th>Amount of inflow from the DRC (10^9 Bq)</th>
<th>Amount discharged from the dam (10^9 Bq)</th>
<th>Ratio of storage in the dam reservoir (%)</th>
<th>Ratio of prevented migration to the outlet of the entire catchment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>0.097</td>
<td>6.4</td>
<td>0.33</td>
<td>95</td>
<td>31</td>
</tr>
<tr>
<td>2015</td>
<td>0.68</td>
<td>44</td>
<td>2.8</td>
<td>94</td>
<td>31</td>
</tr>
<tr>
<td>2016</td>
<td>0.13</td>
<td>8.6</td>
<td>0.89</td>
<td>90</td>
<td>29</td>
</tr>
<tr>
<td>2017</td>
<td>0.031</td>
<td>2.1</td>
<td>0.32</td>
<td>84</td>
<td>28</td>
</tr>
</tbody>
</table>
Where Dissolved $^{137}$Cs represents dissolved Cs-137 activity concentration (Bq/L) at the elapsed time $t$ (y) after the FDNPP accident and $\lambda_{in}$ represents the effective decay constant ($y^{-1}$). The constant $b$ representing the initial value, $e$ representing the amplitude (Bq/L), $c$ representing the phase difference and $d$ representing the period ($y^{-1}$) are empirically determined. The analytical result shows that the tendency of dissolved cesium-137 activity concentration in water discharged from the dam to decrease ($\lambda: 0.10 (y^{-1}) ; T_{eff}: 6.8 (y)$) was slower than that in the reservoir inflow river ($\lambda_{in}: 0.28 (y^{-1}) ; T_{eff}: 2.5 (y)$). Moreover, the fitted curves suggest that the temporal difference in the peaks of concentration, in which the peak in the discharged water emerges after a delay of about 100 days compared to that in the inflow water, was generated between them. By applying the equation respectively to the time-series data for the total inflow volume into the dam reservoir or the amount of water discharged from the dam, the annual balance of dissolved Cs-137 in the dam reservoir was calculated and the results are organized in Table 3. The trend of dissolved Cs-137 activity concentration decreasing (Fig. 6) resulted in a tendency of the annual flux of the dissolved Cs-137 to increase at both the inflow and outflow of the dam reservoir. Moreover, by reflecting differences in the rate of decrease in dissolved Cs-137 concentration, the annual amount discharged has exceeded the annual amount of inflow since 2015, as markedly shown in 2017 with little annual precipitation (Table 1). Based on long-term monitoring of dissolved radionuclides in the Ogaki Dam reservoir, Funaki et al. (2020) showed that the annual dissolved amount of Cs-137 in the dam discharge water was about 1.6 times higher than the annual amount of inflow into the dam reservoir and that the effective environmental half-life of dissolved Cs-137 in the output water was longer than in the main input water. He concluded from the measured vertical distribution of dissolved Cs-137 concentration in the dam reservoir that dissolution from the reservoir bed sediment played an important role as an internal source in increasing the amount of dissolved radionuclide in the water discharged from the dam. This result strongly suggests that a substantial amount of dissolved radionuclide is generated through the contribution of dissolution from the bottom sediment even in the Matsugabou Dam reservoir. How the dissolved radionuclide is produced in the bottom sediment and supplied to reservoir water, however, should be clarified in future work, considering that the radioactivity concentration of Cs-137 has been decreasing in the surface layer of the bottom sediment as a result of intermittent sediment inflow from the DRC.

Since the dissolved Cs-137 activity concentration has remained at less than 0.03 Bq/L for the last few years in water discharged from the Matsugabou Dam, a slowdown in the rate of dissolved Cs-137 decrease through internal production in the dam reservoir would have very small effects on water uses like drinking or irrigation. Additionally, no radiocesium activity concentration...
concentrations exceeding the shipping regulatory value (100 Bq/kg wet weight) have been detected in water bodies downstream since 2015 (Ministry of the Environment, 2020). If it is assumed, however, that dissolution of radioesium occurs naturally from dam reservoir bed sediments, there may be considerable concern about the effects of dam reservoirs on water use or contamination of freshwater ecosystems in more heavily contaminated areas. As for the transfer of radioesium into fresh water ecosystems in particular, the concentration ratio \( CR = \text{activity concentration in organisms (Bq/kg fresh weight/activity concentration in water (Bq/L)), which is an indicator useful for gaining an understanding of the state of transference of radioesium from water to aquatic organisms, shows values on the order of several hundreds to several thousands in many kinds of freshwater fish (Ishii et al., 2020). Therefore, radioesium activity concentrations in commercial fish could possibly exceed the specified regulatory value for shipment even if the radioesium activity concentration is around 0.1 Bq/L in the water. Storing huge amounts of radioesium in a dam reservoir bed for a long period happens to slow down the decrease in dissolved radioesium activity concentrations in the water discharged through dissolution from the bottom sediment. This might enhance long-term contamination of aquatic ecosystem in downstream water bodies.

The function of effectively storing radioesium associated with SS in a dam reservoir should be actively utilized to prevent its migration into downstream water bodies, particularly, the diffusion to urban areas in the downstream region by flood inundation during extreme storm events in the future. On the other hand, it may be necessary to pay close attention to changes in sedimentation storage capacity resulting from accumulation of highly radioactively contaminated inflow sediment. Frequent occurrences of extreme storm rainfall events due to climate change (Intergovernmental Panel on Climate Change, 2013) will make long-term stable storage of contaminated bottom sediment difficult in dam reservoir beds (Mouri et al., 2014). Also for dissolution of radioesium from dam reservoir beds, an appropriate response needs to be examined based on evaluations from various viewpoints such as evaluating economic losses while also considering ecosystem services at present or in the future and performing cost-benefit analyses of countermeasures to prevent dissolution.

4. Conclusions

Positive and negative roles of dam reservoirs in radioesium behavior in a river catchment were examined based on the results of comprehensive, long-term hydrological monitoring at Matsugabou Dam, which is managed on the upstream reaches of the Uda River, one of main rivers in the northern coastal region of Fukushima Prefecture. The main results are as follows.

- The activity concentration of Cs-137 associated with SS decreased much faster than natural decay in both the forest stream and the downstream reaches of the Uda River. Although the runoff ratio of Cs-137 associated with SS depends on rainfall characteristics, it tends to decrease due to decreasing activity concentration.
- Matsugabou Dam has the function of reducing migration of radioesium associated with SS from the dam reservoir catchment to the downstream reaches by more than 85% by storing SS in the reservoir. Moreover, proactive discharge control has the potential to help fulfill this function more effectively, decreasing the risk of external exposure through re-contamination downstream of the dam.
- An estimation of the annual mass balance of dissolved Cs-137 in the dam reservoir showed that the amount in the discharged water clearly tended to exceed the amount in the inflow, with substantial amounts of dissolved radioesium presumably produced by dissolution from stores in the bottom sediment. Through its dissolution, long-term storage of radioesium in dam reservoir beds may slow down the decrease in dissolved radioesium activity concentration in the discharged water.

Acknowledgement

Hydrological data on the dam reservoir were provided by the Soma Land Improvement District and Matsugabou Dam maintenance facility. We thank Drs. Ito, and Nishiki, and Messrs. Takita and Tsuchiya for their help with the field survey, and Dr. Nishina for his advice on statistical analysis of the dissolved Cs-137 time series data. This study was partially supported by a Grant-in-Aid for Scientific Research (KAKENHI 16H01791) from the Japan Society for the Promotion of Science.

References


Seiji Hayashi

Seiji Hayashi is a research group manager at the Fukushima Branch of the National Institute for Environmental Studies. He serves as project leader for research on radioactive substance behavior in multimedia environments. His energetic research activities are contributing to the environmental recovery of Fukushima Prefecture and its surrounding region.

Hideki Tsuji

Hideki Tsuji is a senior researcher at the National Institute for Environmental Studies. He is conducting field research on the transport and accumulation of radioesium in rivers and lakes. He is also carrying out chemical analysis, constructing a numerical model and developing equipment to be used for environmental measurements of bioavailable radioesium.
Dynamics of $^{137}$Cs in Water and Phyto- and Zooplankton in a Reservoir Affected by the Fukushima Daiichi Nuclear Power Plant Accident

Hideki TSUJI$^1$, Megumi NAKAGAWA$^2$, Kazuki IJIMA$^3$, Hironori FUNAKI$^4$, Kazuya YOSHIMURA$^4$, Kazuyuki SAKUMA$^3$ and Seiji HAYASHI$^1$

$^1$Fukushima Branch, National Institute for Environmental Studies, 10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
$^2$Center for Environmental Biology and Ecosystem Studies, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba-shi, Ibaraki, 305-8506, Japan
$^3$Japan Atomic Energy Agency, 10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
$^4$Japan Atomic Energy Agency, 45-169 Sukakeba, Kaibama, Haramachi-ku, Minamisoma-city, Fukushima, 975-0036, Japan

*E-mail: tsuji.hideki@nies.go.jp

Abstract

Lake water, phytoplankton and zooplankton were sampled in a total of 12 quarterly surveys from August 2014 to May 2017 at a reservoir in the Fukushima nuclear disaster area, and variations in dissolved forms of $^{137}$Cs and planktonic $^{137}$Cs were observed. Seasonal variations in dissolved $^{137}$Cs concentration becoming high in summer and low in winter were observed in the upstream, midstream and downstream areas of the reservoir, but no seasonal or site-specific differences in planktonic $^{137}$Cs concentrations or dominant species were found. The concentration factors of $^{137}$Cs for phytoplankton and zooplankton were 340 and 1,700, which were comparable to previously reported values. The amount of planktonic $^{137}$Cs in the water was less than 1.4% of the total $^{137}$Cs in the reservoir water; therefore the effect of plankton on the dynamics of $^{137}$Cs in the reservoir was minimal.

Key words: $^{137}$Cs, concentration factor, dissolved form, phytoplankton, Yokokawa Reservoir, zooplankton

1. Introduction

Following the accident at the Fukushima Daiichi Nuclear Power Plant (FDNPP) in 2011, a large amount of radiocesium was deposited in the surrounding area. In the main river catchment of the area within 50 km north of the FDNPP, radiocesium was deposited at a higher density in the upper reaches (Ministry of Education, Culture, Sports, Science and Technology, 2011), and there are concerns that the future transport of high concentrations of radiocesium into rivers may result in radioactive contamination of downstream areas. Indeed, in this area, some freshwater fish are still subject to shipping restrictions even nine years after the nuclear accident, because their radioactivity levels from radiocesium (mainly $^{134}$Cs and $^{137}$Cs) are still above the national limit of 100 Bq kg$^{-1}$. (Fukushima Prefecture, 2020a).

On most of the major rivers in this region, dams were built in the upstream areas for storing irrigation water. Dams also have the function of storing most of the inflowing sediment and thus intercepting the discharge of particulate radiocesium to downstream. However, radiocesium in the bottom sediment of a reservoir can gradually leach out, especially when promoted under anaerobic conditions (Evans et al., 1983; Kaminski et al., 1994), suggesting that it may act as a source of non-negligible amounts of dissolved radiocesium in the long term (Funaki et al., 2020). Furthermore, because reservoirs usually have a wide distribution of areas with deep euphotic zones, plankton as one of the main food sources for fish breeds easily and the transfer of radiocesium to plankton is promoted in this environment. Considering these circumstances, dams may play a major role in the radioactive pollution of aquatic ecosystems as a source of bioavailable radiocesium. Therefore, it is important to focus on the dynamics of radiocesium in reservoirs to predict future ecological pollution in this contaminated area.

The fate of dissolved radiocesium, which is a representative form of bioavailable radiocesium, in freshwater has been reported to show the following...
characteristics: its concentration is generally proportional to the averaged $^{137}$Cs inventory in the catchment (Tsuji et al., 2014a; Ochiai et al., 2015; Yoshimura et al., 2015), and shows seasonal variation within the environment with a peak from summer to autumn (Alberts et al., 1979; IAEA, 2006; Tsuji et al., 2016; Wang et al., 2017; Wakiyama et al., 2017; Nakanishi & Sakuma, 2019; Matsuzaki et al., 2020). In addition, dissolved $^{137}$Cs concentrations in natural water decrease faster than the physical half-life (Smith et al., 2005; Onda et al., 2020), but the decrease in concentration is reported to be slower than that of particulate $^{137}$Cs in the area near the FDNPP (Nakanishi & Sakuma, 2019).

The concentration of radiocesium in plankton is mainly regulated by that in water, and the concentration factor of radiocesium (ratio of the radiocesium concentration in organisms to that in water) decreases with increasing salinity (Ishii et al., 2020). The concentration factor of plankton living in seawater is reported to be on the order of $10^0$–$10^1$ (Tateda, 1998; Kaeriyama et al., 2008), whereas the concentration factor for plankton in freshwater environments is $10^2$–$10^4$ (Knapis-Skiba et al., 2003; International Atomic Energy Agency, 2004). Furthermore, because plankton bodies have a high proportion of chemically bioavailable components (Mori et al., 2017), their detritus could be a factor in the reproduction of bioavailable forms of radiocesium.

As described above, the spatio-temporal variation in dissolved radiocesium in the aquatic environment of radioactive contaminated areas and its factors have been elucidated, but the variation in planktonic radiocesium in freshwater lakes is not well understood. For example, it is not known how the concentration and total amount of radiocesium in plankton change seasonally, while the concentration of dissolved radiocesium fluctuates seasonally over a year. Because laboratory experimentation has proven that the $^{137}$Cs concentration factor of plankton increases with water temperature (Wolfe & Coburn, 1970), the hypothesis can be raised that the $^{137}$Cs concentration in plankton in reservoirs is high in summer and low in winter. In addition, the spatial characteristics of planktonic radiocesium in reservoirs are unknown because the environmental conditions of light and nutrients vary spatially in reservoirs and there are large spatial diversities in planktonic species composition and abundance (Seda & Devetter, 2000; Havel & Pattinson, 2004).

In this study, reservoir water, phytoplankton and zooplankton samples were collected from a reservoir located in the nuclear disaster area. Through observation of radiocesium in these samples, the dynamics of dissolved, particulate and planktonic forms of radiocesium were investigated over a total of 12 surveys during three years, mainly focusing on the characteristics of temporal and locational variability of planktonic forms of radiocesium. Among the various isotopes of radiocesium, $^{137}$Cs was targeted in this article, because it accounts for the largest residual amount of radioactivity in the environment several years after the nuclear accident in 2011.

2. Materials and Methods

2.1 Study Site

The reservoir behind Yokokawa Dam, located 23 km northwest of the FDNPP in the mountainous region of the Ota River, was selected as the site for this study (Fig. 1). This reservoir has geological characteristics representative of this area, as 99% of its catchment is covered by forest (Ministry of Land, Infrastructure, Transport and Tourism, 2020) and most of the radiocesium deposited at the bottom of the reservoir from radiocesium fallout in March 2011 remains because the bottom sediment has not been dredged extensively since 2011.

One of the topographic features of this dam is the short average residence time of water, 65 days (estimated from the dam discharge and storage water volume, Takechi et al., in press), compared to natural lakes where the dynamics of radiocesium have been reported so far, because this dam was constructed in a steep ravine. The dam’s catchment area is 44.2 km$^2$, and the average $^{137}$Cs
inventory in the catchment area of Yokokawa Reservoir as of July 2, 2011 is 1.8 MBq m$^{-2}$ (Ministry of Education, Culture, Sports, Science and Technology, 2011). The dissolved $^{137}$Cs concentrations in the reservoir inflow river in 2014–2015 ranged from 140 to 530 Bq m$^{-3}$ (Tsuji et al., 2016). The annual precipitation for 2014–2017 observed at the Yokokawa weather station, which is located in nearly the central part of the catchment area, was 1,697–1,880 mm (Fukushima Prefecture, 2020b).

The suspended solids in the reservoir water are thought to be composed of organic and inorganic particles derived from forest soils in the catchment area, and also biological particles (seston) such as plankton and their detritus, which are generated in the reservoir. Since these particles are expected to exhibit characteristic behaviors for each season and location within the reservoir, the field survey was designed to be repeated three times in four seasons at three locations within the reservoir.

2.2 Collection of Dissolved/Particulate $^{137}$Cs and Plankton in the Reservoir

A total of 12 quarterly surveys were conducted at the reservoir from August 2014 to May 2017 (Table 1). The survey dates were set to avoid the immediate aftermath of heavy rainfall events, aiming for conditions where the reservoir water was not excessively turbid. Observation stations were established in the upstream part of the reservoir (Stn. 1; 37.58492°N, 140.88993°E), at the center of the reservoir (Stn. 2; 37.59186°N, 140.89536°E), and near the embankment (Stn. 3; 37.59963°N, 140.90281°E; Fig. 1). At each station the dissolved, particulate form of $^{137}$Cs, and $^{137}$Cs in phyto- and zooplankton were observed. Based on continuous data on water levels near the embankment measured by the reservoir management office, the continuous water depth at Stns. 1–3 estimated from the measured depths at Stns. 1–3 was as shown in Fig. 2. When the reservoir bottom appeared at the surface on some survey dates in Stn. 1, we moved the survey station to a nearby location where the water depth was more than 1 m.

In the reservoir, a rubber boat was launched, and

Table 1 Survey dates and water depth, euphotic layer, temperature, pH and electrical conductivity of the surface water at each station (Stns.1–3).

<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Station No.</th>
<th>Water depth(m)</th>
<th>Euphotic layer(m)</th>
<th>Temperature (°C)</th>
<th>PH</th>
<th>EC (mS m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>7-Aug</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>29</td>
<td>9.1</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>16</td>
<td>5</td>
<td>29</td>
<td>7.9</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>54</td>
<td>6</td>
<td>29</td>
<td>8.8</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>13-Nov</td>
<td>1</td>
<td>9</td>
<td>7</td>
<td>13</td>
<td>7.4</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>17</td>
<td>11</td>
<td>13</td>
<td>7.5</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>41</td>
<td>14</td>
<td>13</td>
<td>7.3</td>
<td>5.6</td>
</tr>
<tr>
<td>2015</td>
<td>3-Mar</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>7.2</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>16</td>
<td>15</td>
<td>4</td>
<td>7.3</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>39</td>
<td>15</td>
<td>4</td>
<td>7.3</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>19-May</td>
<td>1</td>
<td>6</td>
<td>6</td>
<td>18</td>
<td>8.9</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>16</td>
<td>11</td>
<td>19</td>
<td>9.1</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>43</td>
<td>14</td>
<td>19</td>
<td>9.1</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>4-Aug</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>28</td>
<td>9.0</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>13</td>
<td>10</td>
<td>29</td>
<td>8.7</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>38</td>
<td>11</td>
<td>30</td>
<td>8.4</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>17-Nov</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>13</td>
<td>7.3</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>16</td>
<td>15</td>
<td>14</td>
<td>7.6</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>46</td>
<td>16</td>
<td>14</td>
<td>7.3</td>
<td>3.3</td>
</tr>
<tr>
<td>2016</td>
<td>10-Mar</td>
<td>1</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>8.0</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>17</td>
<td>15</td>
<td>6</td>
<td>7.5</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>50</td>
<td>10</td>
<td>6</td>
<td>7.5</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>17-May</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>16</td>
<td>7.4</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>12</td>
<td>10</td>
<td>17</td>
<td>7.7</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>42</td>
<td>16</td>
<td>17</td>
<td>7.2</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>2-Aug</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>22</td>
<td>7.8</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>8</td>
<td>6</td>
<td>27</td>
<td>8.5</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>43</td>
<td>8</td>
<td>27</td>
<td>8.9</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>10-Nov</td>
<td>1</td>
<td>9</td>
<td>5</td>
<td>13</td>
<td>7.6</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>22</td>
<td>12</td>
<td>13</td>
<td>7.4</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>44</td>
<td>14</td>
<td>13</td>
<td>8.4</td>
<td>3.3</td>
</tr>
<tr>
<td>2017</td>
<td>12-Jan</td>
<td>1</td>
<td>9</td>
<td>5</td>
<td>6</td>
<td>7.4</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>21</td>
<td>10</td>
<td>6</td>
<td>6.9</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>48</td>
<td>10</td>
<td>7</td>
<td>7.1</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>25-May</td>
<td>1</td>
<td>6</td>
<td>6</td>
<td>21</td>
<td>8.6</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>16</td>
<td>9</td>
<td>21</td>
<td>9.2</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>46</td>
<td>12</td>
<td>20</td>
<td>9.0</td>
<td>3.8</td>
</tr>
</tbody>
</table>

EC : electrical conductivity
40 L of surface water was collected using a polyethylene bucket. The reservoir water was pumped through a cartridge filter device (Tsuji et al., 2014b; Yasutaka et al., 2015) on board immediately after collection, and solid-liquid separation (collection of suspended $^{137}$Cs) using a 1 μm pore size filter and assessment of dissolved $^{137}$Cs concentration were conducted simultaneously. The cartridge filters used to collect and concentrate the particulate and dissolved $^{137}$Cs were brought back to the laboratory, and the radioactivity from $^{137}$Cs was measured with a high-purity germanium detector. The amount of $^{137}$Cs detected in the suspended filter [Bq] was converted to $^{137}$Cs concentration per unit weight [$\text{Bq kg}^{-1}$] by dividing the detected amount of $^{137}$Cs by the weight of the suspended solids, which was calculated from the difference in dry weight before and after the 48-hour drying process. The vertical distribution of chlorophyll-a concentrations in the reservoir water was also measured using a multi water quality profiler (AAQ-RINKO, JFE Advantech Co., Ltd., Hyogo, Japan) to observe the vertical distribution of the phytoplankton population.

At the same station, nylon plankton nets with mesh sizes of 41 μm and 200 μm with an inner diameter of 30 cm at the top (NXXX25 and NXX7, Rigo Co., Ltd., Tokyo, Japan) were submerged in the reservoir and repeatedly hauled vertically to recover mainly phytoplankton in the former and zooplankton in the latter device. Phytoplankton was recovered within the euphotic zone (Table 1), which was determined at 2.5 times the visible depth of a transparent plate (Visibility Secchi’s disk, Rigo Co., Ltd., Tokyo, Japan). When the euphotic layer reached the bottom of the reservoir, the phytoplankton recovery area was defined as from the surface to a depth of 1 m above the bottom of the reservoir to prevent contamination by suspended solids due to disturbance of bottom sediments. Zooplankton was recovered from the reservoir surface to a depth of 1 m above the reservoir bottom. However, scanty volumes of phytoplankton and zooplankton were collected at Stn. 1 (upstream) in May 2016 and August 2016 due to the shallow water depths, so the samples served only for identification of species composition, with $^{137}$Cs concentrations not being measured. During this collection process, the plankton samples were adulterated by some abiotic suspended solids, and these impurities were later removed manually as much as possible. When using this method, it is expected for zooplankton to be included in the phytoplankton sample collected by the 41-μm net. However, because the presence of phytoplankton is much larger than that of zooplankton and additionally it is difficult to subtract the effect of zooplankton adulteration due to the difference in collecting range, $^{137}$Cs detected in the samples filtered at 41 μm was considered entirely due to phytoplankton.

Plankton samples collected in polypropylene bottles were frozen for at least 24 h to kill the plankton and after thawing them, the supernatant was removed. 1 mL of the supernatant-removed sample was prepared for observation of plankton species, to which 5 mL of neutral buffered formalin solution was added to fix the cells, and then the number of each plankton species was counted using an inverted microscope (TS100, Nikon, Tokyo, Japan) at ×400 magnification for phytoplankton and ×40–100 for zooplankton. The database of the National Museum of Nature and Science (2011) was used as a reference for the identification of phytoplankton, following the method of Takamura & Nakagawa (2012). For the identification and counting of zooplankton, we followed the method of Takamura et al. (2017).

For the remaining plankton-enriched samples, particulate impurities that had sunk to the bottom of the bottle were removed manually with tweezers, and the amount of $^{137}$Cs radioactivity in the samples was measured in a 100 mL polypropylene U8 container in a frozen condition. However, fine mineral particles with high $^{137}$Cs concentrations ($\approx 5.0 \times 10^4 \text{ Bq kg}^{-1}$, Takechi et al., in press) remained in the U8 container, which may have led to overestimation of $^{137}$Cs in the plankton samples. Therefore, as described below, the Al concentration in the samples was measured to evaluate the purity of the plankton in the samples. Thereafter, the samples were freeze-dried for more than three days (FDU-2200, Tokyo Rikakikai Co. Ltd., Tokyo, Japan) to determine the $^{137}$Cs concentration per dry weight of plankton, and this value

![Fig. 2 Survey dates (arrow symbols) and estimated water depth at Stns.1–3 of Yokokawa Reservoir. The depths estimated in this graph assume no lake water flow.](image-url)
was finally converted to $^{137}$Cs concentration per wet weight of plankton assuming a plankton water content of 90% (Hoekstra et al., 2002; Hammerschmidt & Fitzgerald, 2006).

2.3 Analysis of $^{137}$Cs Radioactivity and the Al Component

$^{137}$Cs radioactivity [Bq kg$^{-1}$] in the cartridge filters used to trap dissolved and particulate $^{137}$Cs, and in the plankton-enriched samples were determined using GEM30-70, GEM60-83, GMX45P4-76 coaxial high-purity germanium detectors (Canberra Japan, Tokyo, Japan) and Spectrum Explorer software (Canberra Japan, Tokyo, Japan). The efficiency of the detector was calibrated using a standard volume radioactivity source MX033U8PP (Japan Radioisotope Association, Tokyo, Japan). Background correction was conducted every two weeks for 200,000 seconds. The measurement time was determined for each sample with a counting error of less than 5%, and the measured $^{137}$Cs activities were corrected for decay on the day of sample collection based on the physical half-life of $^{137}$Cs (30.1 years).

To evaluate the amount of mineral particles remaining in the plankton-enriched samples, taking advantage of the fact that very little Al can transfer to plankton bodies (Pempkowiak et al., 2006; Ho et al., 2007), in all, 28 of the freeze-dried plankton-enriched samples collected during May 2016 to May 2017 were decomposed with hydrogen fluoride, and the Al concentration in each sample was measured using ICP-MS (Agilent 8800, Agilent Technologies, Inc., Santa Clara, CA, USA). Every two samples of bottom sediment collected at Stns.1–3 in the same period were also dried at 105°C and decomposed with hydrogen fluoride in the same way, and the Al concentration was measured.

2.4 $^{137}$Cs Concentration Factor of Plankton and the Occupancy of Planktonic $^{137}$Cs in Reservoir Water

The $^{137}$Cs concentration factors for phytoplankton and zooplankton were calculated using the following equation:

$$CF = \frac{\rho \cdot C_{\text{pl}}}{C_{\text{dis}}}$$

(1)

where $CF$ is the wet weight-based $^{137}$Cs concentration factor for phyto- and zooplankton, $\rho$ is the density of reservoir water (1.0×10$^3$ kg m$^{-3}$), $C_{\text{pl}}$ is the $^{137}$Cs concentration per wet weight of plankton [Bq kg$^{-1}$], and $C_{\text{dis}}$ is the dissolved $^{137}$Cs concentration [Bq m$^{-3}$]. In the evaluation of $^{137}$Cs concentration factors, the purity (weight percentage of plankton) in the plankton-enriched samples was calculated from the detected Al concentration according to the following equation:

$$P_{pl} = 1 - \frac{A_{\text{sample}}}{A_{\text{sed}}}$$

(2)

where $P_{pl}$ is the purity of plankton in the sample, $A_{\text{sample}}$ is the Al concentration in the plankton-enriched sample, and $A_{\text{sed}}$ is the Al concentration in the bottom sediment to which the geometric mean value of the two samples was applied. In this equation, the Al concentration in pure plankton was assumed to be 0 mg kg$^{-1}$. The occupancy of $^{137}$Cs in plankton versus reservoir water was calculated using the following equation:

$$r_{pl} = \frac{C_{\text{pl}} \cdot m_{pl}}{A \cdot n \cdot A \cdot l \cdot (C_{\text{dis}} + C_{\text{par}})}$$

(3)

where $r_{pl}$ is the ratio of planktonic $^{137}$Cs to $^{137}$Cs in the total reservoir water, $m_{pl}$ is the wet weight of the recovered plankton [kg], $A$ is the correction factor for the proportion of plankton recovered from the total plankton in all layers, $n$ is the number of times the plankton net was hauled vertically, $l$ is the cross-sectional area at the top of the plankton net (0.071 m$^2$), $C_{\text{dis}}$ and $C_{\text{par}}$ is the particulate $^{137}$Cs concentration [Bq m$^{-3}$]. The correction factor $\alpha$ was set at $\alpha = 1$ for zooplankton, as it was recovered in almost all layers. While the value of $\alpha$ for phytoplankton was determined based on the vertical distribution of chlorophyll-a concentration, by the following equation:

$$\alpha = \frac{\int_0^L C_{\text{Chl.a}} dz}{\int_0^L C_{\text{Chl.a}} dz}$$

(4)

where $l$ is the depth from the reservoir surface to the end of the euphotic layer [m], $L$ is water depth [m], and $C_{\text{Chl.a}}$ is the chlorophyll-a concentration.

In Eq. 3, it is assumed that the concentrations of dissolved and particulate $^{137}$Cs in the reservoir water are vertically homogeneous and the same as those in the surface layer. As to the validity of this assumption, the dissolved $^{137}$Cs concentration between surface and bottom water in Yokokawa Reservoir showed almost no differences except at the center of the reservoir in summer (Tsuji et al., 2017), and the turbidity was almost uniform except just above the reservoir bottom (unpublished data). Therefore, the total $^{137}$Cs concentration in the surface reservoir water would be a little lower than the averaged $^{137}$Cs concentration in the reservoir water overall, but the underestimation would not be very large.

3. Results and Discussions

3.1 Dynamics of Dissolved and Particulate $^{137}$Cs in Reservoir Water

The concentration of dissolved $^{137}$Cs in surface water at Stns.1–3 in the reservoir was in the range of 110–330 Bq m$^{-3}$, with concentrations high in summer and low in winter (Fig. 3(a)), similar to the seasonal fluctuation observed in the inflowing river (Tsuji et al., 2016), the downstream part of the reservoir (Nakanishi & Sakuma, 2019), and also a natural lake (Matsuzaki et al.,...
No decreases in dissolved $^{137}$Cs concentrations with time or differences among the stations were observed. A uniquely high dissolved $^{137}$Cs concentration was observed at Stn. 3 in January 2017 compared to the other stations, but the dissolved $^{137}$Cs concentrations at Stn. 3 at similar dates in 2015 and 2016 were not so high, suggesting that unexpected $^{137}$Cs contamination may have occurred during this survey. The particulate $^{137}$Cs concentrations were lower than those of dissolved forms in all the data and ranged from 13 to 185 Bq m$^{-3}$, tending to decrease in the downstream flow direction (Fig. 3(a)). This trend was due to concentration of suspended solids decreasing toward downstream (Fig. 3(b)), which strongly indicates precipitation of suspended solids to the bottom of the reservoir during the downstream flow process. In this catchment, a tremendous rainfall event with a total rainfall of 572 mm was observed from September 6 to 11, 2015, but no remarkable change in either form of $^{137}$Cs concentration was observed before or after this period. During the two months from this rainfall event to the survey in November 2015, most of the suspended solids in the influent water from the runoff event would have precipitated to the reservoir bottom.

The $^{137}$Cs concentrations per unit weight of suspended solids collected using a 1 μm pore size filter ranged from $3.2\times10^2$ to $4.3\times10^4$ Bq kg$^{-1}$ with a geometric mean of $1.6\times10^4$ Bq kg$^{-1}$ (Fig. 3(c)), and no significant decreasing trend with time was observed at the three stations. As for the trend in flow direction, there was a period during which the $^{137}$Cs concentration in the suspended solids increased in the flow direction, especially in the November survey in all three years. The distribution coefficient of $^{137}$Cs ($K_d$), calculated by dividing the $^{137}$Cs concentration per unit weight of suspended solids by the

![Fig. 3](image-url) (a) Dissolved and particulate $^{137}$Cs concentrations, (b) suspended solid (SS) concentrations, and (c) $^{137}$Cs concentrations per unit weight of suspended solids and distribution coefficient of $^{137}$Cs ($K_d$) in the surface water at Stn.1 (upstream), Stn.2 (midstream), and Stn.3 (downstream) of Yokokawa Reservoir.
Dissolved $^{137}$Cs concentration, ranged from $1.0 \times 10^4$ to $8.0 \times 10^4$ Bq kg$^{-1}$ with a geometric mean of $8.7 \times 10^4$ Bq kg$^{-1}$ (Fig. 3(c)), which differed little from the reported values in the upstream or downstream parts of the river (Tsuji et al., 2016; Nakanishi & Sakuma, 2019). The trend of the $^{137}$Cs distribution coefficient in the flow direction was similar to that of the $^{137}$Cs concentration in the suspended solids.

During a period when $^{137}$Cs concentrations in the suspended solids increased in the flow direction, a clear decrease in suspended solid concentrations in the flow direction was also observed (Fig. 3(b)). In this period, it is inferred that mineral particles derived from forest soil runoff were abundant in the reservoir water due to some large rainfall events. Therefore, the increase in $^{137}$Cs concentration in the suspended solids in the flow direction could be explained by the sedimentation mechanism of coarse particles being deposited relatively fast in the upstream area during the flow process (Walling & Moorehead, 1989), and finer particles with higher $^{137}$Cs concentration per unit weight (He & Walling, 1996) being transported further downstream. On the other hand, in periods when the inflow of suspended particles from upstream is relatively sparse, especially during winter, the seston particles produced inside the reservoir, specifically plankton, would dominate as suspended solids in the reservoir water, and $^{137}$Cs concentration in such particles may obscure the trend of $^{137}$Cs concentration in suspended solids in the flow direction. Accordingly, it has been suggested that $^{137}$Cs dynamics in plankton affect the formation of the spatial distribution of particulate $^{137}$Cs in lakes in seasons with little rain.

### 3.2 Dynamics of Planktonic $^{137}$Cs and its Concentration Factor

As a species component of phytoplankton in the reservoir, dinoflagellates (*Peridinium cinctum*) were most dominant, with their occupancy decreasing as the reservoir water flowed from upstream (Fig. 4(a)) to midstream (Fig. 4(b)), to downstream (Fig. 4(c)). Among other species, diatoms (*Fragilaria crotonensis*, *Asterionella formosa*) were representative phytoplankton.

![Fig. 4 Components of plankton at (a) Stn. 1 (upstream), (b) Stn. 2 (midstream), and (c) Stn. 3 (downstream) in Yokokawa Reservoir.](image-url)
Among zooplankton, copepods (Calanoida copepodid, Cyclopoida copepodid) and water fleas (Daphnia galeata, Bosmina spp.) were particularly abundant but no distinctive seasonal or horizontal trends were observed. The seasonal trends, however, were unclear for both phytoplankton and zooplankton.

The peak chlorophyll-a concentration in the reservoir water was observed at depths of 2 to 3 m at Stns. 1–3, with higher chlorophyll-a concentrations in summer and in the upper reaches (Fig. 5). Some degree of correlation appeared between the dry weight of the collected phytoplankton and the average concentration of chlorophyll-a in the euphotic layer, (Stn. 1 : R² = 0.68, Stn. 2 : R² = 0.55, Stn. 3 : R² = 0.43), suggesting that the chlorophyll-a concentration was an effective indicator of phytoplankton population density. The vertical distribution of chlorophyll-a concentrations confirmed that most phytoplankton in the reservoir water lived in the range of the euphotic layer.

The 137Cs concentration per wet weight of plankton (converted to 90% moisture content) was 0.86–560 Bq kg⁻¹ (geometric mean: 30 Bq kg⁻¹) (Fig. 6), and the 137Cs concentration factor of phytoplankton calculated from Eq. 1 was 5.3×10⁻¹ to 3.3×10⁴ (geometric mean: 1.3×10³). The 137Cs concentrations of zooplankton ranged from 3.2 to 430 Bq kg⁻¹ (geometric mean: 45 Bq kg⁻¹), and its 137Cs concentration factor was 1.1×10² to 1.6×10⁴ (geometric mean: 2.2×10³). These values, however, have a possibility of overestimation due to adulteration by mineral particles with high 137Cs concentrations. The Al
concentration, which indicates impurities, in 28 plankton samples collected after May 2016 was 43–11,000 mg kg\(^{-1}\), and the Al concentration in the bottom sediment samples collected during the same period ranged from 15,000 to 46,000 mg kg\(^{-1}\) (Table 2). Accordingly, the plankton content in the 28 samples estimated by Eq. 2 was 58%–100% and nine samples of phytoplankton and three samples of zooplankton contained plankton with a purity of >95%. In many of the samples, the influence of inclusion of mineral particles on the \(^{137}\)Cs concentration was considered not to be negligible. Therefore, the \(^{137}\)Cs concentration factor in this reservoir was evaluated only for samples with planktonic content of >95%. By this refinement, the geometric mean values of the \(^{137}\)Cs concentration factor for phytoplankton and zooplankton were 340 and 1,700, respectively, which were of the same order of magnitude as previously reported values (Table 3). Even for these samples, no dependence of the concentration factor on season or on station was observed.

The percentage of planktonic \(^{137}\)Cs to the whole \(^{137}\)Cs in the water estimated by equations 3 and 4 ranged from 0.0044\% (Nov 2016) to 1.4\% (Aug 2015) for phytoplankton and 0.0010\% to 0.17\% for zooplankton for all samples. While limited to samples with planktonic content of >95%, the percentage ranged from 0.012\% to 0.83\% for phytoplankton and 0.00054\% (Mar 2016) to 0.096\% (May 2017) for zooplankton. This result indicates that the effect of \(^{137}\)Cs in plankton larger than 41 μm on the overall \(^{137}\)Cs dynamics in the reservoir is very limited. In past laboratory experiments (Twiss & Campbell, 1998; Thomas et al., 2018), the upper limit of the \(^{137}\)Cs uptake ratio to zooplankton living in freshwater was reported to be less than 1\%. Therefore, the amount of \(^{137}\)Cs that can be taken up by zooplankton may be limited to about 1\% of the total amount of \(^{137}\)Cs in the water. On the other hand, Thomas et al. (2018) reported that the amount of \(^{137}\)Cs transferred to freshwater diatomic phytoplankton, including with cell diameter of 6.5 μm, could exceed 10\% of the total \(^{137}\)Cs in the water according to their laboratory

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Collected date</th>
<th>Station No. (Stn.)</th>
<th>Al content (mg kg(^{-1}))</th>
<th>Estimation weight percentage of plankton</th>
<th>CF</th>
<th>Ratio of planktonic (^{137})Cs to total lake water (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>plankton</td>
<td>17 May 2016</td>
<td>1</td>
<td>8,000</td>
<td>58%</td>
<td>18,000</td>
<td>0.06</td>
</tr>
<tr>
<td>phyto</td>
<td>1 Aug 2016</td>
<td>1</td>
<td>2,300</td>
<td>88%</td>
<td>260</td>
<td>-</td>
</tr>
<tr>
<td>zoo</td>
<td>10 Nov 2016</td>
<td>1</td>
<td>710</td>
<td>96%</td>
<td>360</td>
<td>0.38</td>
</tr>
<tr>
<td>phyto</td>
<td>12 Jan 2017</td>
<td>1</td>
<td>300</td>
<td>98%</td>
<td>250</td>
<td>0.31</td>
</tr>
<tr>
<td>zoo</td>
<td>25 May 2017</td>
<td>1</td>
<td>43</td>
<td>100%</td>
<td>53</td>
<td>0.83</td>
</tr>
<tr>
<td>phyto</td>
<td>2</td>
<td>690</td>
<td>98%</td>
<td>330</td>
<td>0.108</td>
<td></td>
</tr>
<tr>
<td>zoo</td>
<td>3</td>
<td>1,200</td>
<td>97%</td>
<td>470</td>
<td>0.105</td>
<td></td>
</tr>
<tr>
<td>phyto</td>
<td>2</td>
<td>2,500</td>
<td>87%</td>
<td>480</td>
<td>0.010</td>
<td></td>
</tr>
<tr>
<td>zoo</td>
<td>3</td>
<td>3,500</td>
<td>90%</td>
<td>7,100</td>
<td>0.036</td>
<td></td>
</tr>
<tr>
<td>phyto</td>
<td>3</td>
<td>1,800</td>
<td>95%</td>
<td>5,700</td>
<td>0.011</td>
<td></td>
</tr>
<tr>
<td>zoo</td>
<td>3</td>
<td>1,100</td>
<td>97%</td>
<td>700</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>phyto</td>
<td>2</td>
<td>1,100</td>
<td>97%</td>
<td>700</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>zoo</td>
<td>3</td>
<td>1,400</td>
<td>96%</td>
<td>2,200</td>
<td>0.0080</td>
<td></td>
</tr>
<tr>
<td>sediment</td>
<td>13 Nov 2014</td>
<td>1</td>
<td>15,000</td>
<td>24,000</td>
<td>10,000</td>
<td>34,000</td>
</tr>
<tr>
<td></td>
<td>26 Sep 2018</td>
<td>2</td>
<td>34,000</td>
<td>39,000</td>
<td>25,000</td>
<td>46,000</td>
</tr>
<tr>
<td></td>
<td>10 Nov 2016</td>
<td>3</td>
<td>46,000</td>
<td>35,000</td>
<td>25,000</td>
<td>46,000</td>
</tr>
</tbody>
</table>

Table 2 Al concentrations per dry weight in plankton and sediment samples. The percentage of plankton in the samples estimated from the Al concentrations, the concentration factors (CF) of \(^{137}\)Cs of plankton, and the ratio of planktonic \(^{137}\)Cs to total lake water for plankton-enriched samples collected from May 2016 to May 2017. Samples with planktonic content greater than 95\% are shown in bold, and these are considered representative data on the dynamics of planktonic \(^{137}\)Cs.

...
Table 3  

<table>
<thead>
<tr>
<th>Reference</th>
<th>Station/Country</th>
<th>Collected year</th>
<th>Mesh size of plankton net</th>
<th>Range of collection</th>
<th>Plankton</th>
<th>Dominant species</th>
<th>CF*</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>Yokokawa dam Japan</td>
<td>2014–2017</td>
<td>41 μm</td>
<td>euphotic zone</td>
<td>phyto</td>
<td>Peridinium cinctum, Fragilaria crotonensis, Asterionella formosa Calanoida copepodid, Daphnia galeata, Bosmina spp., Cyclopoida copepodid</td>
<td>340</td>
</tr>
<tr>
<td>Matsuda et al. (2015)</td>
<td>Lake Hayama Japan</td>
<td>2012–2013</td>
<td>335 μm</td>
<td>1 m depth</td>
<td>phyto and zoo</td>
<td>-</td>
<td>2400</td>
</tr>
<tr>
<td>Suzuki et al. (2018)</td>
<td>Lake Onuma Japan</td>
<td>2011–2016</td>
<td>100 μm</td>
<td>1 m depth</td>
<td>phyto</td>
<td>Aulaceira sp.</td>
<td>720</td>
</tr>
<tr>
<td>Knapinska-Skiba et al. (2003)</td>
<td>Świna River Poland</td>
<td>1997</td>
<td>60 μm</td>
<td>surface</td>
<td>phyto and zoo</td>
<td>Bosmina longirostris, Holopedium gibberum</td>
<td>470</td>
</tr>
<tr>
<td>Ravera and Giannoni (1995)</td>
<td>Lake Monate Italy</td>
<td>1986</td>
<td>88 μm</td>
<td>whole depth</td>
<td>phyto and zoo</td>
<td>-</td>
<td>220</td>
</tr>
<tr>
<td>Saxén et al. (2009)</td>
<td>Lake Iso Valkjärvi Finland</td>
<td>1992</td>
<td>-</td>
<td>-</td>
<td>zoo</td>
<td>-</td>
<td>170</td>
</tr>
<tr>
<td>Lake Väike Mustajärvi Finland</td>
<td>Lake Väike Mustajärvi Finland</td>
<td>1987–1990</td>
<td>-</td>
<td>-</td>
<td>zoo</td>
<td>-</td>
<td>43</td>
</tr>
<tr>
<td>Lake Halsjärvi Finland</td>
<td>Lake Halsjärvi Finland</td>
<td>1987–1988</td>
<td>-</td>
<td>-</td>
<td>zoo</td>
<td>-</td>
<td>110</td>
</tr>
<tr>
<td>Lake Rahtijärvi Finland</td>
<td>Lake Rahtijärvi Finland</td>
<td>1987–1990</td>
<td>-</td>
<td>-</td>
<td>zoo</td>
<td>-</td>
<td>130</td>
</tr>
<tr>
<td>Lake Savijärvi Finland</td>
<td>Lake Savijärvi Finland</td>
<td>1987–1990</td>
<td>-</td>
<td>-</td>
<td>zoo</td>
<td>-</td>
<td>37</td>
</tr>
<tr>
<td>Lake Vähä Valkjärvi Finland</td>
<td>Lake Vähä Valkjärvi Finland</td>
<td>1988–1989</td>
<td>-</td>
<td>-</td>
<td>zoo</td>
<td>-</td>
<td>38</td>
</tr>
<tr>
<td>Lake Mekkojärvi Finland</td>
<td>Lake Mekkojärvi Finland</td>
<td>1988</td>
<td>-</td>
<td>-</td>
<td>zoo</td>
<td>-</td>
<td>86</td>
</tr>
</tbody>
</table>

*concentration factor of 137Cs (geometric mean value)

experiment. The difference between the report and this study suggested the possibility that the fraction of phytoplankton not recovered by the 41-μm mesh size of the plankton net held non-negligible amounts of 137Cs. Accordingly, it would be difficult to discuss the whole dynamics of planktonic 137Cs in the reservoir by focusing only on plankton larger than 41 μm in cell length.

Even if the amount of planktonic 137Cs is limited compared to the total 137Cs in lake water, the dynamics of planktonic 137Cs are expected to have a significant impact on the uptake of 137Cs by aquatic biota as a pathway of 137Cs bioaccumulation through predation. Therefore, it is necessary to position and consider planktonic 137Cs dynamics in relation to 137Cs transfer to freshwater fish in the future.

To summarize the remaining issues in this study, no seasonal or site-dependent characteristics of planktonic 137Cs in the reservoir could be observed because it was difficult to exclude the effect of adulteration from mineral particles in the plankton samples. It was also suggested that uncollected plankton less than 41 μm in length may make a non-negligible contribution to 137Cs dynamics in lakes. Both of these issues are pertinent to the understanding of the dynamics of 137Cs in freshwater ecosystems, so advances in recovery methods of high purity plankton in the future are expected to clarify these detailed dynamics.

4. Conclusions

The present study of 137Cs dynamics in a reservoir revealed the following.

1. Dissolved 137Cs concentrations in the reservoir’s surface water at stations in the upstream part, central part and near the embankment fluctuated seasonally: they were high in summer and low in winter. No differences in dissolved 137Cs concentrations between the stations were observed.

2. The particulate 137Cs concentration in the reservoir’s surface water was lower than that of dissolved 137Cs.
The $^{137}$Cs concentration per unit weight of suspended solids and the distribution coefficient of $^{137}$Cs tended to be higher toward the downstream direction mainly in autumn, probably because coarse mineral particles with low $^{137}$Cs concentration predominated as suspended solids in this season.

3. No seasonal regularity in composition of plankton species was observed. No seasonal variations of $^{137}$Cs in phyto- and zooplankton could be observed, because the effect of mineral particle contamination was not negligible in many of the samples based on Al concentrations in the plankton-enriched samples.

4. The concentration factors of $^{137}$Cs in phytoplankton and zooplankton were 340 L kg$^{-1}$ and 1,700 L kg$^{-1}$, respectively, which were on the same order as in previous reports.

5. The occupancy of planktonic $^{137}$Cs in plankton larger than 41 μm to total $^{137}$Cs in the reservoir water was much less than 1.4%.

Acknowledgements

Hydrological data on the reservoir were provided by the Yokokawa Dam Management Office. We thank Dr. Ito and Messrs. Iri, Harada and Narita for their help with the field survey, and Prof. Kenji Nanba of Fukushima University for his advice on measuring Al in plankton samples. We would also like to thank the two reviewers for their many helpful suggestions. This study was supported by a Grant-in-Aid for Scientific Research (KAKENHI 15K16129) from the Japan Society for the Promotion of Science.

References


Retrieved from http://dx.doi.org/10.1080/07438140409354097


**Hideki Tsuji**

Hideki Tsuji is a senior researcher at the National Institute for Environmental Studies. He is conducting field research on the transport and accumulation of radiocaesium in rivers and lakes. He is also carrying out chemical analysis, constructing a numerical model and developing equipment to be used for environmental measurements of bioavailable radiocaesium.

**Megumi Nakagawa**

Megumi Nakagawa is a specialist working at the Center for Environmental Biology and Ecosystem Studies, National Institute for Environmental Studies. She has identified and counted phytoplankton and zooplankton in Lake Kasumigaura, the second largest lake in Japan, for 25 years. She is also one of the staff at the Japan Focal Point of UNEP's GEMS/Water program.

**Kazuki Iijima**

Kazuki Iijima heads the Fukushima Environmental Evaluation Research Division at the Collaborative Laboratories for Advanced Decommissioning Science, Japan Atomic Energy Agency (JAEC). He is interested in how radionuclides behave in the environment, especially the interactions of trace amounts of radionuclides with minerals and organic matter of natural origins. Previously, he investigated the behavior of radionuclides under conditions deep underground (stable and static for long periods). After the Fukushima Dai-ichi nuclear power plant accident, he started studying their behavior at the earth’s surface. (He says it is so unstable and too dynamic!)

**Hironori Funaki**

Hironori Funaki is an assistant principal scientist at the Fukushima Environmental Monitoring Division, Japan Atomic Energy Agency (JAEC). He performs research in hydrogeology, geochemistry and environmental radioactivity. His current research interests include the transport of radioactive materials in lakes and reservoirs.

**Megumi Nakagawa**

Megumi Nakagawa is a specialist working at the Center for Environmental Biology and Ecosystem Studies, National Institute for Environmental Studies. She has identified and counted phytoplankton and zooplankton in Lake Kasumigaura, the second largest lake in Japan, for 25 years. She is also one of the staff at the Japan Focal Point of UNEP’s GEMS/Water program.

**Kazuyuki Sakuma**

Kazuyuki Sakuma, Ph.D., is a researcher at the Sector of Fukushima Research and Development, Japan Atomic Energy Agency (JAEA). He is interested in the environmental modeling of radionuclide behavior, watershed modeling, radiation transport simulation in the field, and investigation of radionuclide behavior in forests, rivers, and reservoirs.

**Seiji Hayashi**

Seiji Hayashi is a research group manager at the Fukushima Branch of the National Institute for Environmental Studies. He serves as project leader for research on radioactive substance behavior in multimedia environments. His energetic research activities are contributing to the environmental recovery of Fukushima Prefecture and its surrounding region.

(Received 16 October 2020, Accepted 21 December 2020)
1. Introduction

Assessing radiocesium outflow from forests contaminated by radioactive substances from the Fukushima Daiichi nuclear power plant (FDNPP) accident is a key issue in promoting the return of evacuated residents. An outflow assessment in a decontaminated forest adjacent to a living area would be particularly important scientific knowledge to have for estimating the possibility of recontamination of the decontaminated living area, exposing returned residents to radiation doses.

The transport processes of radiocesium from the forest floor are mainly divided into a soil erosion process in a particulate-bound state attached to fine soil particles and a surface runoff process in a dissolved state in surface running water during rainfall events (Evrard et al., 2015). The majority of the radiocesium is transported in the particulate-bound state. Yamashiki et al. (2014) established a series of nested monitoring stations within the Abukuma River basin, which was affected by radioactive fallout from the FDNPP accident. They estimated that 84% to 92% of the total radiocesium was transported in the particulate form during the period from August 10, 2011 to May 11, 2012. Iwagami et al. (2017) monitored 137Cs discharge via suspended sediment, coarse organic matter, such as leaves and branches, and dissolved 137Cs fraction from a forest headwater catchment in the Yamakiya district, located approximately 35 km northwest of the FDNPP from August 2012 to September 2013. They reported that the annual proportion of the contribution to 137Cs discharge from suspended sediment accounted for 96% to 99% of the total 137Cs flux.

The amount of particulate and dissolved 137Cs wash-off from the forest floor via surface runoff processes was examined using experimental plots installed on the floor of a mountainous forest in the Abukuma Mountains (Nishikiori, et al., 2015; Yoshimura et al., 2015; Niizato et al., 2016). Niizato et al. (2016) installed experimental plots for 137Cs discharge monitoring on a side slope of a valley-head area with a 27°–31° slope angle forested with Japanese konara oak and cedar in the Abukuma Mountains during the summer monsoons of 2013 and 2014. The 137Cs wash-off associated with the outflow of particulate matter was calculated at 85%–94% of the total 137Cs discharge from the forest floor, based on the data in Niizato et al. (2016). Nishikiori et al. (2015) monitored the 137Cs wash-off from a forest floor with slopes of 37°–39° forested with Japanese cypress, red pine and cedar, and a deciduous broadleaved forest with different floor coverings for 145 days from May to October, 2013. They revealed the most of the 137Cs wash-off was associated with soil particles and the amount of soil loss was relatively large in forests with little understory and/or

Tadafumi Niizato* and Takayoshi Watanabe

Fukushima Environmental Evaluation Research Division,
Collaborative Laboratories for Advanced Decommissioning Science, Japan Atomic Energy Agency
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
*E-mail: niizato.tadafumi@jaea.go.jp

Abstract

A three-year monitoring of 137Cs outflow associated with soil erosion from decontaminated and non-decontaminated sites using an experimental plot was conducted in a mountainous forest of Fukushima Prefecture during the rainy season. The annual 137Cs outflow from the decontaminated site was 9–13 times larger than that of the non-decontaminated site. However, the outflow from the decontaminated site decreased from 2.55% to 0.65% corresponding with recovery of the forest floor cover. When the forest floor cover reached 60% or more, the 137Cs outflow from the decontaminated site began to show relatively minor fluctuations at a similar level to the non-decontaminated site. The decrease in the 137Cs outflow corresponding to the restoration of the forest floor cover was due to the recovery of the protective effect of the forest floor against raindrop splashes and a decrease in the ratio of soil components with relatively high 137Cs activity in the particulate matter.

Key words: decontamination, forest, forest floor cover, radiocesium, residents returning
organic layers (forest floor cover; 5%–15%), suggesting that forest cover strongly affected $^{137}$Cs wash-off.

The protective effects of the forest floor cover, that is, the presence of a litter layer, against soil erosion have been reported based on field soil erosion monitoring in artificially disturbed and undisturbed forest floors of evergreen needle-leaved and deciduous broad-leaved forests (e.g., Murai & Iwasaki, 1975; Miura et al., 2003; Hu et al., 2012). Miura (2000) proposed a new term, “floor cover percentage (FCP),” to quantify the forest floor cover from the viewpoint of the protective effects against raindrop erosion. FCP indicates the percentage of forest floor that is covered with either litter or understory within 50 cm height above the forest floor (Miura, 2000). This FCP index enables us to evaluate the total protective function of the forest floor. Miura et al. (2003) measured sediment transport rates using sediment traps in Japanese cypress, cedar and red pine forests located on steep slopes under a humid climate, before and after removing the forest floor cover. The rates increased immediately after removing the floor cover, and decreased corresponding to increased FCP without delay. This result shows the sediment transport rate is sensitive to changes in FCP (Miura et al., 2003). Moreover, the above results indicate diminishment of the forest floor cover results in increased amounts of radiocesium outflow via soil erosion on forest slopes.

From the perspective of reducing radiation doses in the living environment of residents near a forest, removal of organic layers such as fallen leaves, etc. up to about 20 m from the edge of the forest is effective and efficient (Ministry of Agriculture, Forestry and Fisheries, 2011; Kaneko & Tsuboyama, 2012; Ministry of the Environment, 2016). On the other hand, lining up sandbags at the edge of the forest or other measures to prevent soil movement and runoff must be taken after the sandbags at the edge of the forest is effective and efficient (Ministry of the Environment, 2016). On the other hand, lining up sandbags at the edge of the forest or other measures to prevent soil movement and runoff must be taken after the removal of fallen leaves and other organic sediment matter on steep forest slopes (Ministry of the Environment, 2016).

Yamamoto et al (2014) conducted experiments removing organic layers (L, F, and H layers) and monitoring the amount of $^{137}$Cs wash-off from a forest floor with a 31° slope angle in a deciduous broadleaved forest in the Yamakiya district about 40 km northwest of the FDNPP. The monitoring was performed in a plot with organic layers removed and a non-treated plot for five months from July to December 2013. After the removal treatment, 9.65% and 0.64%–0.69% of the $^{137}$Cs in the forest floor had been washed off from the plot with the L-F-H layers removed and the plot with the L-F layers removed, respectively. The wash-off was 0.08% in the plot with no removal treatment (Yamamoto et al., 2014). This revealed a protective function of organic layers against radiocesium outflow from a forest floor, although their discussion of the effect of the forest floor coverage recovery process in natural environments was inadequate.

Although decontamination work in forests near living areas reduces radiation doses in the residents’ living environment, radiocesium outflow via soil erosion from the forest floor is relatively higher compared to a non-decontaminated forest floor. It is expected, however, that the radiocesium outflow associated with soil erosion will gradually decrease with time corresponding to recovery of the forest floor cover due to the deposition of litter and growth of understory on the floor after decontamination.

This study presents the results of three years of monitoring radiocesium outflow via soil erosion and the recovery process of forest floor cover in a forest floor decontaminated according to the Decontamination Guidelines of the Ministry of the Environment, Japan. The natural resilience of the forest floor shown in this study is expected to be applied to measures for preventing radiocesium outflow in combination with engineering measures and chemical treatment.

2. Materials and Methods

2.1 Study Area

Radiocesium outflow monitoring was conducted in a deciduous broadleaved tree forest in the Yamakiya district within the Abukuma Mountains, 35 km northwest of the FDNPP (Fig. 1). The level of radioactive contamination in the district was measured at 497 kBq m$^{-2}$ (as of April 1, 2013) in $^{137}$Cs deposition via the Sixth Airborne Monitoring results (Ministry of Education, Culture, Sports, Science & Technology in Japan, 2020). At this monitoring site, Niizato et al. (2016) carried out monitoring of the radiocesium outflow associated with surface wash-off from experimental plots installed in a non-decontaminated forest floor. The annual $^{137}$Cs outflow was estimated at 0.07%–0.15% of the total $^{137}$Cs deposition to the site from 2013 to 2014 (Niizato et al., 2016).

The mean annual precipitation in this district over the past 30 years (1981–2010) has been 1223.8 mm yr$^{-1}$ at the Yamakiya Meteorological Station, located 2.7 km northwest of the site (Ministry of Land, Infrastructure, Transport and Tourism, 2020). This district is mainly covered by deciduous broad-leaved trees of konara oak (Quercus serrata), mizunara oak (Quercus crispula), and Japanese chestnut (Castanea crenata), except at the southern edge of the forest, where Japanese red pine (Pinus densiflora) trees dominate. The average tree height and tree density in the canopy layer are 10.9 m and 740 ha$^{-1}$, respectively. Most of the forest floor is covered with litter composed mainly of fallen branches and leaves of deciduous broadleaved trees. The thickness of the litter layer is usually 1–3 cm. The undergrowth cover, including mountain azalea (Rhododendron kaempferi) and bamboo grass (Sasa nipponica), ranges from 35% to 60%. Brown forest soil is most common in the forest slopes of the district. The soil down to a 5 cm depth is...
Cs outflow in decontaminated and non-decontaminated forest

Removal of understory and organic layers (L, F, and H layers) in decontamination work on the forest floor at the monitoring site was performed in July–September 2014 and August–September 2015 within 20 m from a living area by the local government. A mineral soil layer was exposed on the forest floor after the decontamination work.

2.2 Monitoring and Sampling

Two experimental plots for monitoring were installed on a decontaminated forest slope (decontaminated plot) and a non-decontaminated forest slope (control plot) facing west with a 27°–30° slope angle (Fig. 1). The decontaminated plot was located 40 m south of the control plot and the plot area was 8 m² (2.0 m × 4.0 m). The control plot had a plot area of 53.4 m² (6.0 m × 8.9 m) in 2016 and 26.7 m² (3.0 m × 8.9 m) in 2017–2018. Both experimental plots were located on rectilinear, straight slopes, and had common features of physical geography except for the forest floor cover. The forest floor in the control plot had an 86%–94% cover ratio from its litter layer and understory during the monitoring period, while the forest floor cover ratio in the decontaminated plot started from 30% in March 2016 and increased to 83% in November 2018 through deposition of litter and understory growth.

Each experimental plot had a rectangular shape, the long side of which was oriented along the dip direction of the slope, and was surrounded with stainless-steel boards for the control plot and with hard vinyl chloride corrugated sheets for the decontaminated plot to prevent transportation of particulate matter and surface runoff water into the plot from the outside (Fig. 1). Particulate matter, composed of soil particles and fine litter fragments, accumulated in a sediment trap installed at the bottom end of each plot with same width as the plot. The particulate matter that drained from the plot with its associated surface runoff water flowed into a 50 L tank for the decontaminated plot and a 200 L tank for the control plot connected to their respective sediment traps via a pipe.

The particulate matter samples collected from the sediment traps were passed through a 2-mm sieve, and weighed after drying at 105°C for 24 h. The samples stored in the tank were mixed well within the tank, then collected as turbid water using a scoop. The turbid water samples were passed through a 2-mm sieve, and weighed after evaporation to dryness at 105°C for more than 24 h using a dry oven. Those samples were homogenized by hand stirring with a dispensing spoon, and then packed and sealed in a polystyrene container (U-8) for radioassay per sampling date.

Samples of the particulate matter were collected within 2- to 8-week intervals in correlation with precursory rainfall events. Associated field surveys and monitoring efforts were performed mainly during Fukushima’s summer monsoon from April to November, in the years 2016–2018. This monthly span was chosen as most appropriate for research due to rainfall acting as the principal cause of transportation of particulate matter.

---

**Fig. 1** Location of the monitoring site (left) and view of the entire decontaminated plot in May 2017 (right). The topographic data were created based on the results of an airborne laser survey conducted by the Geospatial Information Authority of Japan.
within the forested area.

The forest floor cover percentage of the decontaminated plot was calculated from the ratio of intersection points with litter and/or understory on the forest floor with 25 cm square grids in the plot. The intersection points with litter and understory were counted using a digital photograph of the floor taken from above 50 cm height from the floor (Watanabe et al., 2019). The percentages of forest floor cover in the control plot were estimated by direct measurement of the area without the litter layer or understory in the field investigation.

Soil samples were collected using a scraper plate (Tsukahara-SS Corporation, Japan) with a metal frame of 450 cm² (15 cm × 30 cm), the sampling area for vertical distribution of 137Cs near both plots. The samples were homogenized by hand stirring with a dispensing spoon after drying at 105°C for 24 h, and then packed and sealed in a polystyrene container (U-8) for radioassay per sampling date.

### 2.3 Radiocesium Measurements

137Cs activity was determined using an n-type high-purity Ge-detector (GSW275L germanium detector, CANBERRA Industries Inc., Meriden, CT, USA). A multichannel analyzer (MCA7600, Seiko EG & G ORTEC, Tokyo, Japan) with spectrum analysis software (Gamma Explorer + (Plus), CANBERRA Industries Inc) was used for pulse-height analysis employing counts at the 661.64 keV peak. An efficiency calibration was performed with a multiple gamma-ray emitting standard source (including nine nuclides) packed in 100 mL plastic U-8 containers (Japan Radioisotope Association, Tokyo, Japan). The radioactivities reported herein were corrected for radioactive decay with respect to April 1, 2013. The 137Cs activities of the particulate matter, litter and soil are shown in dry weight.

### 2.4 Calculation of 137Cs Outflow

Transportation of particulate matter from the experimental plots was accompanied by the outflow of particulate-bound 137Cs. The volume-weighted mean 137Cs activities of the particulate matter, litter and soil samples were computed by summing the amounts of 137Cs in individual samples during the monitoring period and then dividing this value by the total amount of the sample weight. The 137Cs outflow via soil erosion (Bq m⁻²) was calculated by multiplying the weight of the particulate matter (kg) by its 137Cs activity (Bq kg⁻¹) and then dividing this value by the plot area (m²). The annual 137Cs outflows were calculated by summing up daily flux for the number of days in the monsoon season (April to November). The daily fluxes were calculated by dividing 137Cs outflow during the monitoring period by the number of monitoring days. The outflow percentage of the particulate-bound 137Cs was calculated using 137Cs inventories obtained from decontaminated and non-decontaminated forest slopes near the experimental plots.

### 3. Results and Discussions

#### 3.1 Annual 137Cs Outflow

The forest floor cover in the control plot showed slight seasonal variation (86% in early June and 94% in late November) due to leaf fall from October to November during the monitoring period from 2016 to 2018. The forest floor cover in the decontaminated plot showed significant change with time (Table 1). A sparse distribution of bamboo grass and litter (mostly fallen twigs) was found in March of the year following decontamination of the monitoring site and the cover ratio had increased to 30%. The floor cover percentage had been restored to about 50% by understory growth and litter deposition by early December of that year. After the cover percentage reached 70% in September 2017, two

<table>
<thead>
<tr>
<th>Period</th>
<th>Gross precipitation (mm)</th>
<th>Forest floor cover (%)</th>
<th>Particulate matter (g m⁻²)</th>
<th>137Cs activity (kBq kg⁻¹)</th>
<th>137Cs outflow (kBq m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar. 16-Apr. 4, 2016</td>
<td>15</td>
<td>30.0</td>
<td>9.1</td>
<td>27.7</td>
<td>0.25</td>
</tr>
<tr>
<td>Apr. 4-May 29, 2016</td>
<td>173</td>
<td>47.5</td>
<td>39.3</td>
<td>23.6</td>
<td>0.93</td>
</tr>
<tr>
<td>May 29-July 11, 2016</td>
<td>152</td>
<td>50.0</td>
<td>134.5</td>
<td>26.4</td>
<td>3.56</td>
</tr>
<tr>
<td>July 12-Sept. 1, 2016</td>
<td>436</td>
<td>52.5</td>
<td>416.0</td>
<td>24.4</td>
<td>10.15</td>
</tr>
<tr>
<td>Sept. 2-Nov. 22, 2016</td>
<td>306</td>
<td>no data</td>
<td>52.0</td>
<td>20.9</td>
<td>1.09</td>
</tr>
<tr>
<td>Nov. 22-Dec. 8, 2016</td>
<td>12</td>
<td>47.5</td>
<td>4.5</td>
<td>28.5</td>
<td>0.13</td>
</tr>
<tr>
<td>Apr. 16-May 14, 2017</td>
<td>66</td>
<td>42.5</td>
<td>22.3</td>
<td>25.4</td>
<td>0.57</td>
</tr>
<tr>
<td>May 14-June 14, 2017</td>
<td>60</td>
<td>50.0</td>
<td>58.8</td>
<td>22.2</td>
<td>1.31</td>
</tr>
<tr>
<td>June 14-July 13, 2017</td>
<td>81</td>
<td>no data</td>
<td>37.2</td>
<td>38.8</td>
<td>1.44</td>
</tr>
<tr>
<td>July 13-Aug. 10, 2017</td>
<td>264</td>
<td>52.5</td>
<td>88.3</td>
<td>25.4</td>
<td>2.25</td>
</tr>
<tr>
<td>Aug. 10-Sept. 15, 2017</td>
<td>132</td>
<td>70.0</td>
<td>51.1</td>
<td>23.1</td>
<td>1.18</td>
</tr>
<tr>
<td>Sept. 15-Oct. 13, 2017</td>
<td>83</td>
<td>no data</td>
<td>12.2</td>
<td>18.8</td>
<td>0.23</td>
</tr>
<tr>
<td>Oct. 13-Nov. 30, 2017</td>
<td>291</td>
<td>80.0</td>
<td>17.2</td>
<td>26.9</td>
<td>0.46</td>
</tr>
<tr>
<td>Apr. 28-May 21, 2018</td>
<td>91</td>
<td>70.0</td>
<td>34.6</td>
<td>20.0</td>
<td>0.69</td>
</tr>
<tr>
<td>May 21-July 29, 2018</td>
<td>150</td>
<td>62.5</td>
<td>19.6</td>
<td>16.6</td>
<td>0.32</td>
</tr>
<tr>
<td>July 29-Aug. 27, 2018</td>
<td>142</td>
<td>no data</td>
<td>50.5</td>
<td>23.4</td>
<td>1.19</td>
</tr>
<tr>
<td>Aug. 27-Sept. 24, 2018</td>
<td>126</td>
<td>77.5</td>
<td>22.1</td>
<td>26.1</td>
<td>0.58</td>
</tr>
<tr>
<td>Sept. 24-Oct. 28, 2018</td>
<td>105</td>
<td>82.5</td>
<td>12.8</td>
<td>17.2</td>
<td>0.22</td>
</tr>
<tr>
<td>Oct. 28-Dec. 5, 2018</td>
<td>4</td>
<td>82.5</td>
<td>3.0</td>
<td>18.4</td>
<td>0.06</td>
</tr>
</tbody>
</table>

a: Data from MLIT (2020). b: Counting error ranges from 112 to 599 Bq kg⁻¹. c: Decay corrected to April 1, 2013.
Cs outflow in decontaminated and non-decontaminated forest

years after decontamination, the percentage stayed over 70%, except for May–July, 2018 (Watanabe et al., 2019; Table 1).

The weight of the particulate matter from the decontaminated plot was 10–20 times larger than that of the control plot (Tables 1 and 2). On the other hand, the 137Cs activities of the particulate matter from the decontaminated plot each year were comparatively lower than those from the control plot due to decontamination of the monitoring site (Tables 1 and 2). The 137Cs activity of the soil layer at a depth of 0–1 cm near the decontaminated plot was one sixth that of a similar measurement near the control plot (Fig. 2). The vertical distribution of 137Cs near the decontaminated plot about

**Table 2** 137Cs activity of particulate matter in the control plot during different sampling periods.

<table>
<thead>
<tr>
<th>Period</th>
<th>Gross precipitation a (mm)</th>
<th>Particulate matter (g m⁻²)</th>
<th>137Cs activity b (kBq kg⁻¹)</th>
<th>137Cs outflow c (Bq m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr. 12–May 19, 2016</td>
<td>118</td>
<td>3.8</td>
<td>34.5</td>
<td>132</td>
</tr>
<tr>
<td>May 19–May 30, 2016</td>
<td>4</td>
<td>2.5</td>
<td>8.5</td>
<td>44</td>
</tr>
<tr>
<td>May 30–June 15, 2016</td>
<td>54</td>
<td>5.0</td>
<td>26.2</td>
<td>132</td>
</tr>
<tr>
<td>June 15–June 29, 2016</td>
<td>75</td>
<td>0.7</td>
<td>29.2</td>
<td>22</td>
</tr>
<tr>
<td>June 29–July 13, 2016</td>
<td>25</td>
<td>0.2</td>
<td>26.6</td>
<td>6</td>
</tr>
<tr>
<td>July 13–July 29, 2016</td>
<td>10</td>
<td>0.4</td>
<td>28.2</td>
<td>10</td>
</tr>
<tr>
<td>July 29–Sept. 1, 2016</td>
<td>426</td>
<td>13.0</td>
<td>37.4</td>
<td>488</td>
</tr>
<tr>
<td>Sept. 1–Sept. 16, 2016</td>
<td>56</td>
<td>2.3</td>
<td>45.0</td>
<td>104</td>
</tr>
<tr>
<td>Sept. 16–Sept. 30, 2016</td>
<td>154</td>
<td>1.2</td>
<td>29.4</td>
<td>34</td>
</tr>
<tr>
<td>Sept. 30–Oct. 14, 2016</td>
<td>35</td>
<td>1.7</td>
<td>29.4</td>
<td>49</td>
</tr>
<tr>
<td>Oct. 14–Oct. 28, 2016</td>
<td>2</td>
<td>0.4</td>
<td>31.9</td>
<td>14</td>
</tr>
<tr>
<td>Oct. 28–Nov. 11, 2016</td>
<td>49</td>
<td>0.1</td>
<td>33.2</td>
<td>4</td>
</tr>
<tr>
<td>Nov. 11–Nov. 29, 2016</td>
<td>15</td>
<td>0.2</td>
<td>29.3</td>
<td>6</td>
</tr>
<tr>
<td>Nov. 29–Dec. 9, 2016</td>
<td>7</td>
<td>0.5</td>
<td>44.8</td>
<td>24</td>
</tr>
<tr>
<td>Mar. 24–Apr. 14, 2017</td>
<td>49</td>
<td>1.2</td>
<td>39.5</td>
<td>48</td>
</tr>
<tr>
<td>Apr. 14–Apr. 28, 2017</td>
<td>26</td>
<td>2.2</td>
<td>36.0</td>
<td>78</td>
</tr>
<tr>
<td>Apr. 28–May 12, 2017</td>
<td>4</td>
<td>0.7</td>
<td>28.3</td>
<td>21</td>
</tr>
<tr>
<td>May 12–May 22, 2017</td>
<td>43</td>
<td>2.0</td>
<td>32.2</td>
<td>64</td>
</tr>
<tr>
<td>May 22–May 26, 2017</td>
<td>12</td>
<td>1.4</td>
<td>13.6</td>
<td>19</td>
</tr>
<tr>
<td>May 26–June 9, 2017</td>
<td>38</td>
<td>2.1</td>
<td>21.5</td>
<td>44</td>
</tr>
<tr>
<td>June 9–June 30, 2017</td>
<td>19</td>
<td>1.0</td>
<td>21.5</td>
<td>22</td>
</tr>
<tr>
<td>June 30–July 13, 2017</td>
<td>50</td>
<td>1.2</td>
<td>18.2</td>
<td>22</td>
</tr>
<tr>
<td>July 13–July 28, 2017</td>
<td>168</td>
<td>7.5</td>
<td>20.8</td>
<td>157</td>
</tr>
<tr>
<td>July 28–Sept. 1, 2017</td>
<td>190</td>
<td>6.0</td>
<td>39.4</td>
<td>236</td>
</tr>
<tr>
<td>Sept. 1–Sept. 15, 2017</td>
<td>38</td>
<td>1.3</td>
<td>40.8</td>
<td>51</td>
</tr>
<tr>
<td>Sept. 15–Sept. 29, 2017</td>
<td>58</td>
<td>1.8</td>
<td>32.2</td>
<td>57</td>
</tr>
<tr>
<td>Sept. 29–Oct. 13, 2017</td>
<td>24</td>
<td>1.3</td>
<td>30.3</td>
<td>39</td>
</tr>
<tr>
<td>Oct. 26–Nov. 17, 2017</td>
<td>68</td>
<td>1.6</td>
<td>22.2</td>
<td>36</td>
</tr>
<tr>
<td>Nov. 17–Nov. 30, 2017</td>
<td>24</td>
<td>0.7</td>
<td>23.2</td>
<td>16</td>
</tr>
<tr>
<td>Nov. 30–Dec. 15, 2017</td>
<td>12</td>
<td>0.4</td>
<td>21.1</td>
<td>9</td>
</tr>
<tr>
<td>Apr. 13–Apr. 26, 2018</td>
<td>44</td>
<td>1.0</td>
<td>22.0</td>
<td>21</td>
</tr>
<tr>
<td>Apr. 26–May 11, 2018</td>
<td>73</td>
<td>1.5</td>
<td>20.1</td>
<td>31</td>
</tr>
<tr>
<td>May 11–June 1, 2018</td>
<td>39</td>
<td>1.3</td>
<td>21.5</td>
<td>29</td>
</tr>
<tr>
<td>June 1–June 28, 2018</td>
<td>30</td>
<td>1.0</td>
<td>18.8</td>
<td>19</td>
</tr>
<tr>
<td>June 28–July 30, 2018</td>
<td>99</td>
<td>2.9</td>
<td>25.5</td>
<td>74</td>
</tr>
<tr>
<td>July 30–Aug. 28, 2018</td>
<td>142</td>
<td>3.6</td>
<td>31.7</td>
<td>115</td>
</tr>
<tr>
<td>Aug. 28–Sept. 25, 2018</td>
<td>126</td>
<td>1.3</td>
<td>16.9</td>
<td>22</td>
</tr>
<tr>
<td>Sept. 25–Oct. 29, 2018</td>
<td>105</td>
<td>1.8</td>
<td>19.5</td>
<td>35</td>
</tr>
<tr>
<td>Oct. 29–Dec. 6, 2018</td>
<td>4</td>
<td>0.2</td>
<td>9.6</td>
<td>2</td>
</tr>
</tbody>
</table>

a: Data from MLIT (2020).  b: Counting errors are 210-2124 Bq kg⁻¹, 150-553 Bq kg⁻¹, and 122-306 Bq kg⁻¹ in 2016, 2017 and 2018, respectively. Decay corrected to April 1, 2013.  c: Decay corrected to April 1, 2013.

Fig. 2 Vertical distribution of 137Cs to the depth of 10 cm near the decontaminated and control plots. The numbers on the right side of the bar chart indicate the 137Cs activities of litter and soil layers. The counting error was less than 10%.
three months after decontamination indicates that the surface soil layer was also slightly removed from up to 1 cm depth at maximum in the course of removing the litter layer and understory during the decontamination work.

The annual $^{137}$Cs outflow from the decontaminated plot was 9–13 times larger than that from the control plot, reflecting of the weight of the particulate matter and its $^{137}$Cs activity in both plots (Table 3). Moreover, the outflow from the decontaminated plot decreased corresponding with recovery of the forest floor cover during the monitoring period from 2016 to 2018. The outflow in 2018 from the decontaminated plot was one fourth that in 2016, an outflow percentage of less than 1%. This is a similar level of $^{137}$Cs outflow percentage as with the control plot. When we calculated the $^{137}$Cs outflows of the decontaminated plot based on the $^{137}$Cs inventory in the decontaminated forest floor, they were estimated to be 13.2%, 7.2%, and 3.4% in 2016, 2017, and 2018, respectively (Table 3).

The particulate matter containing $^{137}$Cs was composed of litter and soil components on the forest floor. The weight percentages of the litter and soil were estimated from an end-member mixing analysis using the $^{137}$Cs activities of the particulate matter, litter and soil layers in the forest floor (Table 4). The soil component of the particulate matter in the decontaminated plot ranged from 60% to 90%, though it was less than 20% in the control plot. The weight percentage of the soil component in the decontaminated plot had decreased to 58% by 2018.

A significant amount of splashed soil was attached to the 30-cm-high hard vinyl chloride corrugated sheets bordering the decontaminated plot (Fig. 3, left). There were many 5–25-mm-height pedestals and soil pillars in the decontaminated forest floor (Fig. 3, right). Destruction of these pedestals or soil pillars was observed but no rills developed on the floor. These forest floor conditions indicate that the main factor in the transportation of the particulate matter on the decontaminated forest floor was raindrop splashing of particulate matter on the forest floor.

The above results indicate the decrease in $^{137}$Cs outflow corresponding to restoration of the forest floor cover is the result of recovery of the protective effect of the forest floor against raindrop splashes and a decrease in the amount of soil components with relatively high $^{137}$Cs activity in the particulate matter.

### Table 3 Annual $^{137}$Cs outflow accompanied by the transportation of particulate matter.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Period</th>
<th>Gross precipitation (mm)</th>
<th>Forest floor cover (%)</th>
<th>Particulate matter (g m$^{-2}$)</th>
<th>$^{137}$Cs activity (kBq kg$^{-1}$)</th>
<th>Annual $^{137}$Cs outflow (kBq m$^{-2}$) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decontaminated plot</td>
<td>Mar. 16-Dec. 8, 2016</td>
<td>1094</td>
<td>30.0–52.5</td>
<td>655</td>
<td>24.5</td>
<td>14.7 (2.55)</td>
</tr>
<tr>
<td></td>
<td>Apr. 16-Nov. 30, 2017</td>
<td>977</td>
<td>42.5–80.0</td>
<td>287</td>
<td>25.9</td>
<td>7.9 (1.38)</td>
</tr>
<tr>
<td></td>
<td>Apr. 28-Dec. 5, 2018</td>
<td>618</td>
<td>62.5–82.5</td>
<td>142</td>
<td>21.4</td>
<td>3.7 (0.65)</td>
</tr>
<tr>
<td>Control plot</td>
<td>Apr. 12-Dec. 9, 2016</td>
<td>1030</td>
<td>86.0–94.0</td>
<td>32</td>
<td>33.0</td>
<td>1.1 (0.19)</td>
</tr>
<tr>
<td></td>
<td>Mar. 24-Dec. 15, 2017</td>
<td>1022</td>
<td>86.0–94.0</td>
<td>37</td>
<td>27.8</td>
<td>0.9 (0.16)</td>
</tr>
<tr>
<td></td>
<td>Apr. 13-Dec. 6, 2018</td>
<td>662</td>
<td>86.0–94.0</td>
<td>15</td>
<td>23.7</td>
<td>0.4 (0.06)</td>
</tr>
</tbody>
</table>

*a: Data from MLIT (2020).  b: Volume-weighted mean as of April 1 2013. The counting error ranges from 79 to 128 Bq kg$^{-1}$. c: Percentage of annual $^{137}$Cs outflow was calculated using the inventory of the decontaminated and non-decontaminated forest slopes shown in Fig. 2. See text for details of that calculation.

### Table 4 Estimation of the weight percentage of litter and soil in the particulate matter.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Year</th>
<th>$^{137}$Cs activity (kBq kg$^{-1}$)</th>
<th>Weight percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Particulate matter</td>
<td>Litter</td>
</tr>
<tr>
<td>Decontaminated plot</td>
<td>2016</td>
<td>24.5</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td>25.9</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>21.4</td>
<td>42</td>
</tr>
<tr>
<td>Control plot</td>
<td>2016</td>
<td>33.0</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td>27.8</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>2018</td>
<td>23.7</td>
<td>91</td>
</tr>
</tbody>
</table>

*a: $^{137}$Cs activity shown in Table 3 and Fig. 2.
137Cs outflow in decontaminated and non-decontaminated forest

The daily flux of 137Cs outflow from the decontaminated plot decreased from 2016 to 2018, while no obvious change occurred in the control plot except for May 11, 2017. In detail, there were major fluctuations in the daily flux of the outflow (about 0.5–9.0 × 10^{-4} Bq m^{-2} day^{-1} mm^{-2}) from the decontaminated plot in the period from March 2016 to August 2017. After September 2017, they turned into relatively minor fluctuations (about 0.5–3.7 × 10^{-4} Bq m^{-2} day^{-1} mm^{-2}) corresponding with recovery of the forest floor cover to 60% or more (Fig. 4, lower).

Our three-year monitoring results from the year following decontamination work in 2016 showed 137Cs outflow decreasing to one fourth at the monitoring site in this study. The annual 137Cs outflow percentage decreased to less than 1% of the 137Cs inventory compared to before decontamination. Though the forest floor cover in the decontaminated plot reached 60% or more, the amount of 137Cs outflow and its fluctuation range in the decontaminated plot remained larger than those of the control plot installed in a non-decontaminated location (Tables 1 and 2). There were seasonal variations in forest floor cover percentages in the decontaminated site from 60% in May–June to 80% or more in October–November after August 2017 (Fig. 4, Table 1). This suggests the fallen leaves and twigs did not remain on the forest floor after deposition but were transported from the floor, then probably deposited at the bottom of the forest slope. In the non-decontaminated forest floor, protective effects of the forest floor against 137Cs outflow via soil erosion appeared to be maintained by the pre-existing litter layer when fallen leaves were transported immediately after their deposition on the forest floor due to the effects of wind or raindrop impacts. Thus, for restoration of the protective effects of the forest floor to a pre-decontamination condition, it is important to promote growth of understory, to prevent the transport of fallen leaves and twigs away and to prepare conditions for litter layer formation on the decontaminated forest floor.

4. Conclusion

We conducted monitoring of 137Cs outflow associated with soil erosion at decontaminated and non-decontaminated sites using experimental plots from April 2016 to November 2018 during the rainy season in Fukushima. Our three-year monitoring results showed that the 137Cs outflow from the decontaminated site was 9–13 times larger than that of non-decontaminated site. The outflow from the decontaminated site, however, decreased from 2.55% to 0.65% corresponding to the recovery of the forest floor cover during the monitoring period from 2016 to 2018. The outflow percentage in 2018 was at a similar level to that of the non-decontaminated site. An end-member mixing analysis of 137Cs activities between litter and soil on the forest floor and particulate matter flowing out from the experimental plot showed that the decrease in the 137Cs outflow corresponding to the restoration of the forest floor cover was the result of recovery of the protective effect of the forest floor against raindrop splashes and a decrease in the soil component with relatively high 137Cs activity in the particulate matter. When the forest floor cover
reached 60% or more, the $^{137}$Cs outflow from the decontaminated site began showing relatively minor fluctuations at a level of outflow percentage similar to that of the non-decontaminated site. To restore the protective effects of the forest floor against radioceasium outflow to a pre-decontamination condition, it will be important to promote understory growth resulting in litter layer formation.

Acknowledgement

The authors thank the local landowner who provided us his hill for our monitoring site. We are grateful to members of the Fukushima Environmental Evaluation Research Division and Fukushima Environmental Monitoring Division of Japan Atomic Energy Agency for their helpful suggestions and technical support during the course of this work. Our thanks also go to Messrs. Okino Ryo, Ikeda Makoto and Kawamura Makoto of Mitsubishi Materials Techno Co. for their technical support in compiling data on $^{137}$Cs outflow in the non-decontaminated area.

References


Tadafumi NIIZATO

Dr. Tadafumi Niizato heads the Environmental Research Group of the Sector of Fukushima Research and Development, which conducts environmental dynamics research on the effects of radioceasium from the Fukushima Dai-ichi nuclear power plant accident. He enjoys potted plant cultivation with his wife on weekends in famous for a very old weeping cherry tree, Tazakura.

Takayoshi WATANABE

Mr. Takayoshi Watanabe is an engineer at the Environmental Research Group studying the environmental dynamics of radioceasium in forested environments in Fukushima. He enjoys motor scooter touring, feeling the turn of the seasons through his touring.
Summary of Radioactive Cs Dynamics Studies in Coastal Areas and Assessment of River Impacts

Toshiharu MISONOU*, Tadahiko TSURUTA, Takahiro NAKANISHI and Yukihisa SANADA

Remote Monitoring Research Group, Fukushima Environmental Monitoring Division, Japan Atomic Energy Agency
45-169 Sukakeba, Kaibama, Haramachi-ku, Minamisouma-shi, Fukushima, 975-0036, Japan
*E-mail: misono.toshiharu@jaea.go.jp

Abstract

A large amount of radioactive Cs was released into the environment from the Fukushima Daiichi nuclear power plant (FDNPP) following the 2011 Great East Japan Earthquake. Nine years have passed since this accident, and the radioactive Cs concentration in seabed sediments has decreased. The behavior of radioactive Cs in coastal areas, however, is complicated due to the influence of rivers, waves and so on. The Japan Atomic Energy Agency has conducted several studies at the mouth of the Ukedo River. Here, we review previous studies and evaluate the impact of the radioactive Cs supplied by rivers using a sediment trap. In this study, a mooring system consisting of a sediment trap was installed in the Ukedo River estuary near the FDNPP in 2017. The results showed $^{137}$Cs flux in winter accounting for 60% of the annual flux. This suggests that mobilization of radioactive Cs in the coastal area is primarily due to resuspension and not river discharge.

Key words: estuary, Fukushima Daiichi nuclear power plant accident, resuspension, sinking particle, Ukedo River

1. Introduction

The Tokyo Electric Power Company Holdings (TEPCO) Fukushima Daiichi Nuclear Power Station (FDNPP) released a large amount of radioactive Cs into the environment following the 2011 Great East Japan Earthquake and Tsunami. The released radioactive Cs was deposited over wide land and sea areas (Hirose, 2016; Mishra et al., 2019). The amount of $^{137}$Cs released from the FDNPP has been reported to be 18 PBq (Katata et al., 2015). In particular, the $^{137}$Cs inventory of seabed sediments shallower than 100 m is 0.16 PBq (Otosaka & Kato, 2014) and tends to be higher in coastal areas (Kusakabe et al., 2013). The $^{137}$Cs inventory of surface sediments shallower than 100 m decreased by 27% annually from 2011 to 2015 (Otosaka, 2017). While the radioactive Cs concentration in coastal seabed sediments has been decreasing yearly, seabed sediments with relatively high radioactive Cs content have been observed locally (NRC, 2018). Radioactive Cs in seabed sediments is strongly adsorbed on fine sediment particles and has a low elution rate to seawater (Otosaka & Kobayashi, 2013). Therefore, it is important to collect deep cores and analyze the amount of radioactive Cs with depth.

As mentioned above, the coastal area is expected to be a dynamic area with respect to radioactive Cs even several years after the accident because of the impact of riverine $^{137}$Cs discharge. For evaluating the future distribution of radioactive Cs throughout the entire sea area, it is important to predict radioactive Cs distribution in the estuary. Therefore, in this paper, we first review several studies conducted by the Japan Atomic Energy Agency (JAEA) in the Ukedo River estuary. In addition, to determine the relationship between seafloor sediments and radioactive Cs supplied from rivers, we focused on evaluating the amount of radioactive Cs from rivers and sinking particles collected using sediment traps (Fig.1).

2. Distribution of Radioactive Cs in the Ukedo River Estuary

JAEA has conducted several studies focusing on the behavior of radioactive Cs in the Ukedo River area since 2012. From calculation of the amount deposited using data from the 4th Airborne Monitoring Survey (MEXT, 2011), the amount of radioactive Cs deposited in the Abukuma River basin (578 TBq) and the Ukedo River basin (536 TBq) is almost the same. However, the
catchment area of the Ukedo River is 1/10 that of the Abukuma River, meaning that the concentration of radioactive Cs supplied to the ocean by the Ukedo River is much higher than that supplied by the Abukuma River (Sakuma et al., 2019a). Therefore, the Ukedo River likely has a large impact on the surrounding coastal area.

The distribution of seabed sediments (silt, fine to medium sand, coarse sand to granules, bedrock, and artifacts) in the Ukedo River estuary has been investigated using two methods, depth measurements and acoustic soundings (Tsuruta et al., 2017). The surface area ratios of bedrock and seabed sediments are 65% to 35% (the total area investigated was about 30 km²), respectively (Fig. 2). Sediment accumulation is restricted to the area south of the Ukedo fishing port in two elongated zones. Fine to medium sand (with a surface ratio of 24%) is the main constituent of the seabed sediment. Fine sediment containing a large amount of clay minerals (such as silt) is thought to have high radioactive Cs concentrations (Bostick et al., 2002), but the proportion of fine sediments (≦0.064 mm) was found to be only 0.4%. From results of core sampling of seabed sediments using vibrocoring techniques (to a maximum depth of 100 cm), an inventory of radioactive Cs in the Ukedo River estuary sediment was made (Tsuruta et al., 2017). Figure 3 shows the relationship between $^{137}$Cs
Summary of radioactive Cs dynamics studies in coastal areas and assessment of river impacts

The results obtained from January to March 2014 at the mouth of the Ukedo River (Tsuruta et al., 2017) are compared with the results of Otosaka and Kato (2014) (sampling period from 2011 to 2012) and Black and Buesseler (2015) (sampling period from 2012 to 2013). The $^{137}$Cs inventory in the shallow area (water depth: $< 30$ m) is remarkably larger than that offshore. This suggests that the $^{137}$Cs distribution near the estuary, where the basin has a high level of radioactive contamination, is significantly affected by discharged $^{137}$Cs from the Ukedo River.

A secular change in the $^{137}$Cs concentration in seabed sediments has been attempted by focusing on unmanned surface vehicle technology (Rathour et al., 2015) to enable continuous and wide-area monitoring. The distribution of radioactive Cs concentrations in the seabed sediments was measured using an unmanned observation ship, Windy3S, at the mouth of the Ukedo River seven times from October 2015 to October 2017 (Sanada et al., 2018; Fig. 4). In the measurement area set in the estuary, the $^{137}$Cs concentration in the surface layer tended to differ for each observation period. Also, the $^{137}$Cs inventory tended to decrease over time. This was in good agreement with the physical decay of $^{137}$Cs. There are also reports that radioactive Cs has been detected relatively deep in sediments (Tsuruta et al., 2017). These
results suggest that radioactive Cs remains in the measurement area. Therefore, it is suggested that there is a high possibility of local sediment movement near the estuary.

The discharge of $^{137}$Cs from the Ukedo River was estimated using a tank model and L-Q equation (Sakuma et al., 2019a). The release of $^{137}$Cs in the six months following the FDNPP accident to the Ukedo River accounted for approximately half of the total in the subsequent period (approximately six years). After the accident, 10 TBq (from the Ukedo and Takase rivers) of $^{137}$Cs was supplied to the Ukedo River estuary (Table 1). The $^{137}$Cs inventory of seabed sediments in the Fukushima coastal area ($\leq 100$ m) in 2011 was 160 TBq (Otosaka & Kato, 2014), so the influence of the Ukedo River cannot be ignored.

### Table 1 $^{137}$Cs discharge ratio from different catchments (Sakuma et al., 2019a).

<table>
<thead>
<tr>
<th>River</th>
<th>$^{137}$Cs discharge (TBq) and discharge ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abukuma</td>
<td>18 TBq (3.1%)</td>
</tr>
<tr>
<td>Odaka</td>
<td>0.12 TBq (0.34%)</td>
</tr>
<tr>
<td>Ukedo</td>
<td>3.2 TBq (0.89%)</td>
</tr>
<tr>
<td>Takase (Ukedo River tributary)</td>
<td>1.6 TBq (0.88%)</td>
</tr>
<tr>
<td>Maeda</td>
<td>1.0 TBq (1.1%)</td>
</tr>
<tr>
<td>Kuma</td>
<td>0.91 TBq (1.0%)</td>
</tr>
<tr>
<td>Tomioka</td>
<td>0.25 TBq (0.64%)</td>
</tr>
<tr>
<td>Total of 13 rivers in Fukushima coastal region$^a$</td>
<td>11 TBq (0.79%)</td>
</tr>
</tbody>
</table>

$^a$ Estimated using catchment $^{137}$Cs inventory at each catchment in the Fukushima coastal region and the average $^{137}$Cs discharge ratio from six river basins such as the Odaka, Ukedo, Takase, Maeda, Kuma, and Tomioka Rivers.

### 3. Evaluation of Radioactive Cs Flux in the Ukedo River Estuary

#### 3.1 Materials and Methods

We installed a sediment trap to investigate the migratory behavior of sinking particles, which affect the distribution of radioactive Cs in seabed sediments. Study points were set up at the mouth of the Ukedo River, which is located approximately six kilometers from the FDNPP (Fig. 5(a)). Our targets were points where studies of the topographical shape and core sampling of the seabed sediments had been performed for a previous report (Tsuruta et al., 2017). Because southward flow is predominant along the Fukushima Prefecture coast (Yagi et al., 2013), we selected the area around Line 2 (Fig. 5(a)) on the south side of the Ukedo River. Line 2 includes flat and depressed terrain. Depressions tend to contain high levels of radioactive Cs (Thornton et al.,...
2013), but they also suggest that sediment migration might be restricted. Since depressions are a characteristic place, we chose the area around No. 13 on the flat part and moored the earth and sand trap (Fig. 5 (b)).

We installed the mooring system shown in Fig. 5(c) at the study points (N 37.46866°, E141.0614°, water depth: 16 m). The mooring system was equipped with a sediment trap (SMC-7S500, NiGK Corporation, Japan). During high water periods such as typhoons, sinking particles were collected each day (measurement interval of one day). Table 2 summarizes the sampling period for the sediment trap. The 500-ml collection bottles in the sediment trap were pre-filled with 3.5% NaCl solution to prevent backflow of the sinking particles.

The sinking particles were separated from the seawater using a centrifuge (CR22N, Hitachi, Japan). Centrifugation was performed for 20 min at 3,000 rpm, and the supernatant was discarded. To remove the salt from the sample, deionized water was added to the remaining sample, which was then stirred and centrifuged. This process was repeated three times. The centrifuged sinking particles were dried at 105°C for 24 h, homogenized and then placed in a U-8 container. The radioactive concentration of 137Cs in the sinking particles was determined via gamma-ray spectrometry using a high purity germanium detector (GMX40P4-76, ORTEC, USA). The measurement times were from 3,600 s to 302,400 s. The activity concentrations of 137Cs in the samples were decay-corrected to the sampling date. The 137Cs flux was obtained by multiplying the mass flux of the sinking particles by the 137Cs concentration.

### 3.2 Results

The eight sediment trap observations from February 2017 to November 2017 collected 55 sinking particle samples. The mass fluxes and 137Cs concentrations of the sinking particles are shown in Fig. 6. Mass flux showed a

![Fig. 6](image-url) Mass flux and 137Cs concentration data gathered in this study. Sediment trap observations were conducted eight times in 2017. The black points show the 137Cs concentration (dry). The bars show the mass flux.
large fluctuation range of 0.68–850 g m$^{-2}$ day$^{-1}$ and tended to be high from winter to spring (February to June). High mass fluxes were seen in September, which were thought to be due to typhoons (Sanvu) and low pressure. The $^{137}$Cs concentrations varied from 91 to 7,900 Bq kg$^{-1}$ and tended to increase from summer to autumn (August to November).

3.2.1 Differences in $^{137}$Cs Flux between Coastal and Offshore Regions

$^{137}$Cs flux was calculated by multiplying the mass flux by the $^{137}$Cs concentration. Figure 7 shows the sum of the $^{137}$Cs fluxes for each observation period. The $^{137}$Cs fluxes varied from 18 to 550 Bq m$^{-2}$ day$^{-1}$ and had large fluctuations during each observation period. The $^{137}$Cs flux of the sinking particles was compared to the minimum–maximum values reported in offshore regions (depth: 873 m) 100 km away from the FDNPP. The offshore results indicated that the $^{137}$Cs flux ranged from 9.4 × 10$^{-4}$ to 9.8 × 10$^{-2}$ Bq m$^{-2}$ day$^{-1}$ (Otosaka et al., 2014). There was a difference of several orders of magnitude between the coastal and offshore $^{137}$Cs fluxes. Even though these results cannot be unequivocally compared because of the different collection periods and mooring positions of the sediment trap, it is thought that the $^{137}$Cs flux near the coast is higher than that offshore.

3.2.2 Estimation of the Origin of the Sinking $^{137}$Cs Flux

We examined variations in mass flux and $^{137}$Cs concentrations to estimate the origin of $^{137}$Cs fluxes. The relationship between mass flux and $^{137}$Cs concentration was found by linear regression analysis. The correlation coefficient and P-value were found to be 0.01 and 0.43, respectively (Fig. 8). The quantitative correlation between the mass flux and the concentration of $^{137}$Cs is considered to be low. On the other hand, Spearman’s rank order correlation coefficient (Hogg & Craig, 1978) was −0.71. Therefore, it is thought that mass flux and radioactive Cs concentration tend to have a negative relationship. As described in Section 3.2, the $^{137}$Cs concentration of sinking particles tended to increase from summer to autumn. In particular, the maximum $^{137}$Cs concentration was observed in November. According to a report presenting measured particulate $^{137}$Cs concentrations in the Ukedo River on October 27, 2017, the $^{137}$Cs concentration was 24.7 Bq g$^{-1}$-dry. This was under high flow conditions (Nakanishi & Sakuma, 2019). Therefore, it is suggested that the river flow increases from summer to autumn (August to November), and the amount of radioactive Cs inflow from the land area also increases.

In contrast to river discharge, the mass flux in the sediment trap experiment tended to be high from winter to spring (February to June) when the $^{137}$Cs concentration was low. In winter, sediment discharge from the Ukedo River tended to decrease (Sakuma et al., 2019b). It has been reported that seabed sediments containing radioactive cesium are resuspended in winter and transported offshore (Otosaka et al., 2014). Moreover, resuspension due to waves has been reported in a coastal area (Yagi et al., 2015). Therefore, it is thought that seabed sediments with low $^{137}$Cs concentrations were collected in the sediment trap due to resuspension caused by waves in winter. The $^{137}$Cs flux obtained from the observations was divided into winter to spring (February to June) and summer to autumn (August to November). As a result, the $^{137}$Cs flux in winter was found to be about 1.5 times that in summer. The contribution of winter $^{137}$Cs flux to the annual $^{137}$Cs flux was 60%, suggesting that resuspension had a significant impact in coastal areas.

3.2.3 Estimation of Annual Cs Deposition

The annual total deposition of $^{137}$Cs estimated from the observation results of $^{137}$Cs flux was 11.4 kBq m$^{-2}$. The $^{137}$Cs inventory of the seabed sediments sampled in 2014 was 72 kBq m$^{-2}$ (Tsuruta et al., 2017). The contribution of $^{137}$Cs flux of sinking particles to the seabed sediments was about 16% (including river inflow and seabed sediment resuspension). It has been reported that rates of desorption and resuspension of seabed sediments range from 0–29 % (Otosaka, 2017), and the results of this study are also within that range.

It will be necessary to consider diffusion into
seawater and the possibility of leaching of radioactive Cs by seawater in future studies. It will also be necessary to consider the balance of radioactive Cs supplied via rivers, and determining the contribution of sediment deposition and resuspension by acquiring sinking particles and data on seabed sediments and sea conditions will be important.

4. Summary

We obtained the following conclusions from a review of previous studies in the Ukedo River area and the results of measuring radioactive Cs concentrations of sinking particles caught in a sediment trap.
- The radioactive Cs concentration in seabed sediments shows a decreasing trend. However, the location of the peak value of the radioactive Cs concentration tends to change. In addition, the results of the $^{137}$Cs inventory during each observation period were consistent with the physical decay of $^{137}$Cs, suggesting that the radioactive Cs flowing in from the river is moving locally near the estuary (Sanada et al., 2018).
- The $^{137}$Cs flux in winter to spring (February to June) is 60% of the annual flux, suggesting that resuspension plays a significant role in coastal areas.
- The total annual deposition of $^{137}$Cs in 2017 is estimated to have been 11.4 kBq m$^{-2}$. The $^{137}$Cs inventory of seafloor sediments sampled in 2014 was 72 kBq m$^{-2}$ (Tsuruta et al., 2017), and the contribution of subsiding particles to the seafloor sediments was about 16%.

Acknowledgments

The authors wish to express sincere thanks to Sanyo Techno Marine Co., Ltd. for providing measurement data. The Soma Futaba Fisheries Cooperative is thanked for providing a fishing boat. Sincere thanks are extended to anonymous reviewers for their valuable and constructive comments, which helped improve the clarity of the manuscript.

References


Toshiharu MISONOU

Toshiharu Misonou is a researcher at the Fukushima Environmental Monitoring Division, Japan Atomic Energy Agency (JAEA). His research field is environmental radioactivity in coastal areas. After earning his PhD in Civil Engineering, he has been engaged in the study of environmental radioactivity in coastal areas since 2014.

Tadahiko TSURUTA

After majoring in geology at his university, Tadahiko Tsuruta worked in uranium resource exploration, focusing on R&D related to geological disposal of high-level radioactive waste. He participated in R&D for environmental resilience in Fukushima after the Fukushima nuclear power plant accident. In his R&D in Fukushima, He was in charge of research on the mobilization behavior of radioactive cesium in coastal areas, especially for promoting seabed sediments and suspended particle sampling to estimate the future distribution of radioactive cesium in seabed sediments.

Takahiro NAKANISHI

Takahiro Nakanishi is an assistant principal scientist at the Fukushima Environmental Monitoring Division, JAEA. He has been engaged in the study of environmental radioactivity, mainly in oceans and forests. His current research interests include the assessment of radiocesium transport behavior on the catchment scale. He is also interested in the global carbon cycle.

Yukihisa SANADA

After obtaining his PhD in Radiation Measurement, Dr. Sanada’s research has been primarily related to radiation management, the use of gamma spectrometry systems to measure radionuclide activity concentrations and workplace dose rates at nuclear facilities. Since the Fukushima Daiichi NPP accident in 2011, he has been performing remote radiation surveys such as aerial radiation monitoring using manned or unmanned helicopters. He is now developing a new type of radiation detector to study decontamination effects, and researching migration of radioactive substances. He is a group leader at the Sector of Fukushima Research and Development, Japan Atomic Energy Agency (JAEA).
Case History: Decontamination Challenge of Iitate Village

Yuuzou MAMPUKU

Institute for Agro-Environmental Sciences, National Agriculture and Food Research Organization
3-1-1 Kannondai, Tsukuba-shi, Ibaraki, 305-8666, Japan
*E-mail: manpuku@affrc.go.jp

Abstract

The nuclear power plant accident that occurred at the Fukushima Daiichi Nuclear Power Station operated by Tokyo Electric Power Co. in the aftermath of the Great East Japan Earthquake of 2011 resulted in radioactive contamination of a substantial portion of the surrounding area, mostly in Fukushima Prefecture. Immediately after the accident, direct contamination of crops occurred in areas where radioactive cesium falling from the atmosphere was deposited on plant leaves or branches. As the effects of direct contamination subsided over time, indirect contamination of crops, caused by absorption of radioactive cesium from the soil, became a problem. The local authorities overseeing accident control in Fukushima Prefecture decided to suspend all farming in the area, prohibiting planting of paddy fields within a 30 km radius of the Fukushima Daiichi Nuclear Power Station with soil radiocesium concentrations of more than 5,000 Bq Kg\(^{-1}\). Although the damage caused by the earthquake was relatively minor in Iitate Village in the Date district of Fukushima Prefecture, the influence of radioactive fallout forced all of the villagers to evacuate their homes. While decontamination of the entire region and environmental restoration by the government is in progress, the village is still confronted with various problems, including promoting public awareness of nuclear materials and disposing of radioactively contaminated waste. The author was dispatched to Iitate Village as a specialist for the Industry Promotion Section from April 2012 to the present (FY2020) to collaborate with staff of the municipal government. He partook in various activities, including negotiating with relevant government ministries, attending resident information sessions, and addressing issues of decontamination, waste disposal and agricultural business. In this paper, the process from decontamination to resuming agricultural business and progress toward environmental restoration with disposal of decontamination wastes is discussed in detail.

Key words: decontamination, environmental restoration, radioactive contamination, removed soil, resuming agricultural business

1. Details on the Nuclear Power Plant Accident and Iitate Village

On March 11, 2011, the accident at the Fukushima Daiichi Nuclear Power Station operated by Tokyo Electric Power Co. (TEPCO; hereafter referred to as the TEPCO Fukushima Daiichi nuclear accident) caused a substantial part of the Tohoku Region to be contaminated with radioactive cesium, among which Fukushima Prefecture sustained the most severe contamination. Units 1 to 3 were operating, and 4 to 6 were not, due to scheduled safety inspections when the earthquake hit the area; although all of the active reactors scrambled automatically, they lost all external power. The emergency diesel generators (EDGs) went online immediately, but all of the EDGs, except for one at Unit 6, ceased functioning due to flooding from the tsunami. The reactor cores at Units 1 to 3 were exposed because coolant circulation provided by the emergency core cooling system (ECCS) failed for a certain duration, leading to core meltdowns (Annual Report on Energy for FY2011). Moreover, chemical reactions between steam and zirconium on the fuel cladding tubes and other equipment produced massive amounts of hydrogen. At Units 1 and 3, hydrogen explosions probably caused by hydrogen leaking from the reactor containers occurred in the upper structure of the reactor buildings. Another explosion presumably caused by hydrogen occurred at Unit 4, whose core fuel had been transferred before the accident to the spent fuel pool for a safety inspection. As a result of these explosions, a considerable amount of radioactive cesium was released into the surrounding environment (Ministry of Economy, Trade and Industry, 2012).

The Japanese Government, thereafter ordered residents within a 20 km radius to evacuate and residents within a 20 to 30 km radius of the Fukushima Daiichi nuclear power plant to take shelter. Leakage of
radioactive cesium continued, and depending on wind direction and velocity, rainfall and other weather conditions, deposition of radioactive cesium of varying severities could be observed throughout Japan.

As a result of the TEPCO Fukushima Daiichi nuclear accident, direct contamination occurred, in which radioactive cesium falling from the atmosphere was deposited directly onto crop leaves or branches, increasing plants’ radioactive cesium concentration levels. On March 19, radioactive contamination beyond the provisional regulation value (below 500 Bq Kg$^{-1}$ of radiocesium concentration) was detected in milk in Fukushima Prefecture and spinach in Ibaraki Prefecture. On March 20, vegetables and raw milk produced in six prefectures in the Kanto and Tohoku regions also showed radioactive contamination beyond the regulation value.

While the influence of direct contamination subsided over time, indirect contamination caused by absorption of radioactive cesium from the soil became a problem, and the Local Headquarters for Accident Control in Fukushima Prefecture suspended all farming. On April 8, the government announced the prohibition of planting paddy fields in the area within a 30 km radius of the Fukushima Daiichi Nuclear Power Station where readings of more than 5,000 Bq Kg$^{-1}$ radiocesium concentration were found in the soil. A considerable range of crops and products in the area, including brown rice, herbage and green tea, were affected, exceeding the provisional regulation value. A new regulatory value for radiocesium concentration was set (100 Bq Kg$^{-1}$) in April 2012, and since 2012, all brown rice produced in Fukushima Prefecture has undergone inspection before shipment (Ministry of Agriculture, Forestry and Fisheries, 2011; Prefecture, 2012a). In 2020, some municipalities shifted to extraction inspection.

Iitate Village is a beautiful place located in the northern Abukuma Mountain range, richly blessed with nature. Forest cover accounts for approximately 75% of its total area of 230.12 km$^2$, and the terrain is relatively gentle. The Manogawa River in the north, Niidagawa River and Itoigawa River in the center, and Hosokawa River in the south run through the village, providing water to farm fields of approximately 2,200 ha around the settlements. The average temperature is approximately 10°C, and the annual precipitation is approximately 1,300 mm, exhibiting a typical cool highland climate (Iitate Village, 2020).

Iitate Village did not sustain tsunami damage, but the earthquake measured just under six on the Japanese scale, causing roofing tiles to fall and roads to collapse (Fig. 1). On the night of March 12, the Haramachi-Kawamata town road (Prefectural Road 12) was jammed with vehicles trying to evacuate as far as possible away from the nuclear power plant, and a considerable number of refugees came to the village to take shelter. Many villagers, including members of the village office, firefighting team, local women’s association and social welfare council, worked nonstop at the emergency shelter to accept refugees evacuating from the Hamadori region (coastal Fukushima). The weather on March 15 was rainy, which turned to snow during the night. The radiation level indicated by the radioscope located in front of the Ichibankan Building suddenly rose drastically the same day, with the highest level reaching 44.7 μS vhm$^{-1}$ at 6:20 pm. Fear spread among the people, the village authority took various initiatives, including discussing emergency evacuation with Kanuma City in Tochigi Prefecture, implementing screening tests and thyroid exposure tests for children, and holding information sessions to enhance people’s knowledge about radiation. However, the village authorities were forced to handle demands or inquiries resulting from the daily news being discussed among the refugees, including news about high radiation readings in the village, an announcement from the International Atomic Energy Agency (IAEA) regarding extremely high concentration levels of radioactive cesium detected in the village’s soil on March 20, and a report on March 21 by the national government regarding highly concentrated radioactive cesium detected in tap water in the village.

In the course of accident response, Japan’s government issued guidelines for a directed evacuation and the areas targeted for it on April 11. Iitate Village was included in an area-update issued on April 22 and the entire village was evacuated. By June 22, the village office functions had been relocated to shelters in Inomachi, Fukushima City to continue attending to the aftermath of the accident (Iitate Village, 2011).

2. Contamination Level Evaluation

Various studies have been conducted in Iitate Village involving environmental restoration to resume agricultural business and revive agriculture in the area. These have included assessments of soil contamination levels in the polluted lands, environmental air dose rate evaluations and development of decontamination techniques for removing radioactive cesium.
The Institute for Agro-Environmental Sciences (NIAES) of the National Agriculture and Food Research Organization (NARO) has conducted radioactive cesium monitoring studies continuously since 1959, and the information they had gathered was the only long-term monitoring data regarding radioactive contamination in farmland soil and crops produced in the soil. These particular data were used as the control data in an investigation of soil and contaminated crops in the area (National Agriculture and Food Research Organization, 2010). The level of radiocesium concentration in the soil was measured in each farming field as well, and the results were published on each prefecture’s respective website. Later, radiocesium concentration readings in farmland soil at a depth of 15 cm were organized and published in a distribution map based on an air dose rate map compiled through aircraft radiation monitoring by the Ministry of Education, Culture, Sports, Science and Technology, a digital farmland soil map, and actual radiocesium concentration level measurement values. As of November 2011, areas with high radiocesium concentrations in the soil were distributed northwest of the Fukushima Daiiichi nuclear power plant, and in the south and north of the Nakadori region (inland) of Fukushima Prefecture (Fig. 2). Several areas with high radiocesium concentrations (hotspots) were confirmed locally outside of Fukushima Prefecture, and other hotspots were confirmed within Fukushima Prefecture in cities such as Fukushima or Date. From investigative results in 2011, farmlands that exceeded the regulatory standard for cultivation, set at below 5,000 Bq Kg$^{-1}$ of radiocesium concentration in the soil, were estimated to total approximately 8,900 ha in Fukushima Prefecture (Kohyama et al., 2013). Information was published indicating that radiocesium concentrations in the farmland would steadily decrease due to the subsequent physical decay of radioactive cesium or a phenomenon called weathering, in which radiocesium percolates or drains off.

Municipal governments subjected to full evacuation suffered a severe decrease in government office functions at that time because of the overwhelming amount of issues requiring immediate attention, including securing places of refuge for the people, addressing insufficient information about radioactive cesium, and assisting officials of Japan’s government and relevant ministries. Resident information sessions regarding radioactive contamination, with which no one had ever had any

Fig. 2 Soil Concentration Map of the zones directed to evacuate (total amount of cesium 134, 137 deposited on the ground surface) (as of March 11, 2013) (Nuclear Regulation Authority, 2013).
previous experience, were also challenging. There were instances in which the meanings of the words “radiation,” “radioactive cesium,” and “radioactivity” were confused. In addition, explaining various technical terms in plain language for the people was highly challenging, such as alpha ray, beta ray, gamma-ray, X-ray, neutron ray and the “becquerel” unit that indicates the radiation emission capacity of radioactive cesium, as well as “Sievert,” a measure of radiation’s impact on human health. Many residents directly linked the influence of the nuclear power plant accident with that of the atomic bomb, and sessions were nearly in a state of total chaos. The author also attended these resident information sessions held in Iitate Village and other places, fielding a wide variety of questions regarding the relationship between the regulatory standard for radioactive concentration levels for paddy rice cultivation and the radiation exposure of farmers, or the credibility or certainty of information scattered on SNS or broadcast in the news. He realized the difficulty of explaining technical terms plainly or presenting the current situation with the utmost care and consideration to avoid offending the feelings of the residents. As mentioned earlier, these sessions for the residents involved had to be held repeatedly so that the residents could live without anxiety.

3. Forms of Radio cesium Existing in the Soil

Radio cesium enters the soil and dissolves in water to become a monovalent cation (Cs\(^+\)); thus, it is captured by negative charges in the soil. The negative charges derived from soil organic matter or clay minerals have different levels of affinity for Cs\(^+\), and the composition or content of organic matter/clay minerals differs among soils. In this chapter, the forms of cesium in the soil, the mechanism of Cs\(^+\) adsorption by negatively charged soil, and characteristics of soil constituents, which are essential for characterizing Cs\(^+\) adsorption sites, as well as their distribution in the soil in Japan are discussed in detail. In addition to the above, the soil distribution in Fukushima Prefecture is thoroughly reviewed according to the properties and types of each soil—the radio cesium concentration levels in the farmland soil of Fukushima Prefecture have been reported to the public accordingly. In this report, the impact of radioactive cesium on crops was estimated according to the soil characteristics of Fukushima Prefecture, the distribution of radio cesium concentrations in the soil, and predictions of the behavior of radioactive cesium in the soil of Fukushima Prefecture (Yamaguchi et al., 2012). It has been vital to provide such information to the farmers and their families, but the information available at that time was mostly academic documents requiring scientific expertise. It was regrettable that the relevant authorities could not provide the local residents with such vital information in simple and easily understandable terms.

4. Development of Decontamination Techniques

It was the first time in Japanese history for the country’s farmland to be contaminated with highly concentrated radioactive cesium. According to an investigation of the Chernobyl accident in 1986, the IAEA reported that the soil contamination from radioactive cesium fallout was concentrated at the surface of the soil (Sugiura, 2011). The same condition was suspected in the case of Fukushima so it was expected that by removing the surface soil the contaminated farmland could be restored to a status suitable for cultivation. The National Agricultural Research Center established an operating system to reduce the amount of in-soil radioactive cesium mainly by using agricultural machinery available on the market (e.g., power harrows and front loaders) with consent from the farmers of Iitate Village. It was assumed that farmers would work in the accessible areas with simple protection, such as masks. The Institute for Rural Engineering developed a self-propelled top-soil stripping method for construction machinery (Fig. 3). The decontamination techniques mentioned above were based on land category classification (e.g., paddy fields or plowed fields) and contamination level considerations and application policies. Details of various farmland soil decontamination techniques were reviewed and organized into an operation manual for radioactive cesium removal techniques (decontamination techniques) for farmland (National Agriculture and Food Research Organization, 2011).
These systemized techniques are highly valued because farmers themselves can implement decontamination with equipment available nearby. At the same time, heavy machinery, such as backhoes or bulldozers, was used in actual decontamination practice. Introducing heavy machinery enhanced the efficiency of decontamination work, yet the heavy weight and large vibrations were confirmed to damage the vegetation foundation layer or rupture under drainage. In addition, the Japan Atomic Energy Agency and other relevant authorities conducted decontamination model verification. Subsequently, decontamination of houses, cleansing of school buildings, stripping of schoolyard top-soil, cleansing of road pavement and other measures were investigated (Ministry of the Environment, 2012).

During this period, Iitate Village was designated as one of the special areas under the direct control of the government (according to the “Special Measures” of Act No. 110 of 2012), and resident information sessions provided by the Ministry of the Environment regarding decontamination of houses, farmlands and wood edges were held almost every day. Decontamination practices in Iitate Village were implemented over an area of approximately 5,600 ha that included approximately 2,100 houses, 2,400 ha of farmland, 2,100 ha of forest, and 330 ha of roads, producing approximately 2,000,000 m³ of stripped soil, which has been stored at 96 temporary storage sites (TSSs) in the village (Fig. 4). Transportation of removed soil to an interim storage facility (ISF) began in 2016, and approximately 730,000 m³ had been transferred outside the village by September 2020 (Ministry of the Environment, 2012; Ministry of the Environment, 2016a).

The top-soil stripping method was implemented for the entire farmland area of Iitate Village according to the residents’ intentions. The method conducted by the Ministry of Environment effectively decontaminated the radiocesium deposited on the top-soil of the farmland. Uncontaminated decomposed granite available in the village was used for soil dressing, however, and as a result, farmers accused the Ministry of the Environment of turning their farms into sand boxes. In addition, the cut slopes and ridges in the farmlands were left mostly unattended except for deep pruning of weeds, leaving radioactive cesium in the soil. Decontamination of houses, farmlands, and wood edges has now been completed in all areas except for those in the “difficult-to-return zones,” and projects for resuming agricultural business and farmland maintenance and management have gradually begun to be initiated. Approximately 14 million m³ of removed soil including the decontamination waste (hereinafter referred to as removed soils) was generated across the whole of Fukushima Prefecture. The transportation of the removed soils to the ISF has commenced across the prefecture (Ministry of the Environment, 2016a).

The removed soils will be stored for a specific duration at the ISF, and then their final disposal will be conducted outside the prefecture, as decided by the Cabinet Council. The Ministry of the Environment and Iitate Village are currently verifying the possibility of recycling the removed soils—after implementing anti-scattering measures or placing protective covers—for public construction projects under the ‘Verification Project for Recycling of Removed Soil,” as a part of the “Reconstruction and Revitalization Project for the Specific Area of Restoration,” subject to the consent of the village’s residents (Ministry of the Environment, 2013).

5. Purpose and Significance of Removed Soil Recycling

According to the Basic Guidelines for the Reconstruction and Revitalization of Fukushima (issued on July 13, 2012, by Cabinet decision) and other relevant guidelines, the removed soils are to be transported to the ISF, and the national government is to take responsibility for their final disposal, as described in the guidelines, which say that the government “will implement necessary measures to complete the final disposal of the radioactively contaminated waste outside of Fukushima Prefecture, within 30 years after the commencement of waste storage at the ISF.”

According to calculations by the Ministry of the Environment, the total amount of removed soils is estimated at 14,000,000 m³ (Ministry of the Environment, 2012; Ministry of the Environment, 2013). Some say that it is impossible to dispose of such an immense amount because of the difficulty in securing final disposal sites with adequate handling capacities. Moreover, the estimated amount does not include waste from the places subjected to the Reconstruction and Revitalization Project for the Specific Area of Restoration. Implementing environmental restoration is being discussed for those
places, including the “difficult-to-return zones,” where quantitative estimation is impossible. The estimated amount does not include wastes with over 100,000 Bq/Kg. As mentioned above, it is possible that the burden at the ISF may increase. Therefore, it is necessary to formulate a method to use the removed soils partially for public construction projects because the soil itself is a valuable natural resource. However, it should not be used as it is because it contains radioactive cesium.

The Ministry of the Environment has been holding “Meetings for the Development of Reduction and Recycling Technology of Removed Soil Stored at ISF” since July 2015. Referring to the investigation results of the Working Group for the Safety Assessment of Radiation Effects in Recycling of Removed Soil and Relevant Waste and Working Group for the Development of Reduction and Recycling Methods of Removed Soil and Relevant Waste Stored at ISF, the ministry has organized guidelines titled Basic Concept Regarding the Safe Use of Removed Soil Recycled as the Resource (Ministry of the Environment, 2016b), which were issued in June 2018.

“Recycled resource” has been defined at the Strategic Meetings as removed soils that have undergone proper pre-processing and several contamination-level-reduction stages of physical processing, as well as a quality management control process to satisfy the required criteria to be used as material at target sites. Likewise, the term “recycle-use” is defined as using recycled resources for strictly limited purposes, such as public construction projects, in which the management body or responsible party is public. These would take forms such as embankment materials in structural foundations, in which the material properties would not likely be subject to alteration by humans, so that the recycled resources would be used under proper management control, including setting radiation concentration thresholds to reduce and minimize secondary exposures, sealing them with protective covers, taking anti-scattering measures, and organizing/storing record documents. “Recycle-use” differs from less strict counterparts like the Clearance Program, which excludes materials from the regulatory framework of radiation protection and grants the free distribution of recycled materials without restriction. “Recycle-use” as defined here follows the regulation standard set in the Special Act on Countermeasures Against Radiation Contamination by Radioactive Cesium Released in the nuclear power plant Incident Due to the Great East Japan Earthquake on March 11, 2011 (Act No. 110 of 2011), which is supposed to be practiced under proper management. As for the byproducts of chemical/heat processing of the removed soils or relevant subsequential waste, such as heat processing ash, they are not currently included as the subject of the Basic Concept because not all of the pre- and post-processing properties or the quality/possible use of those byproducts have thus far been confirmed.

To evaluate recycled resources technically, it is necessary not only to promote technical development of reduction/recycling technology to maximize the reduction of removed soils but also to establish a system for recycling soil obtained from reduction processing with low radioactive concentrations, after securing a proper level of safety and receiving the consent of the local residents. The Ministry of the Environment has implemented a verification project for recycled resources (used as foundation materials for road embankments; it is currently continuing as an environmental monitoring project) in Minamisoma City since 2017, and another verification project (of foundation material in land for development) commenced in Iitate Village in 2018 with the understanding and cooperation of the residents of Nagadoro administrative district (Fig. 5) (Ministry of the Environment, 2012).
6. Concept and Awareness of the Recycle Use of Removed Soils

The removed soils processed in the decontamination of Iitate Village are planned to be provided for limited use under proper management control. After undergoing appropriate pre- and post-processing or physical processing such as classification, the quality of the recycled material will be modified to suit the conditions of the target site and used strictly as structural foundation material such as embankment material in public construction projects, in which the management body or responsible party is public, and in which the material properties would not likely be subject to alteration by humans (Ministry of the Environment, 2018a).

In final disposal outside the prefecture or other recycle-use of the removed soils, it will be critically important to foster a nationwide consensus and trust regarding the concept and implementation of technological developments, recycle-use of removed soils and safety measures against radiation. Conducting a verification project requires detailed information disclosure to the municipal government and local residents. The findings and experiences obtained in these verification projects should be reflected in future recycling projects.

The Ministry of the Environment conducted a nationwide internet survey in November 2018, targeting men and women in their 20s to 60s (3,600 responses; 400 each in nine regions of Hokkaido, Tohoku (except for Fukushima), Fukushima Prefecture, Kanto, Chubu, Kinki, Chugoku, Shikoku, and Kyushu/Okinawa). The response rate of each region corresponded to its respective population composition ratio. The result was that more than half of the respondents answered “Never heard of it before” regarding the recycle-use of removed soils, revealing that nationwide awareness of this is extremely low (Ministry of the Environment, 2015).

7. Evaluating Amounts of Secondary Exposure

To minimize amounts of secondary exposure to residents, facility users and construction workers in the recycle-use of removed soils, the material is to be used for limited purposes, and all necessary measures are to be taken accordingly, including setting standard radioactive concentration levels for recycled materials and securing proper thicknesses of covering soil. Concentration levels of radiocesium (134+137Cs) in recycled material were calculated under the condition of secondary exposures not exceeding 1 mSv/y throughout the period during which secondary exposure amounts were evaluated. In practice, additional measures such as radiation shielding are implemented to reduce exposure amounts further, so as not to exceed 1/100 of the threshold (Reconstruction Agency, 2017).

8. Initiatives in Nagadoro, Iitate Village

The Nuclear Emergency Response Headquarters of the Japanese Government reviewed the area that had undergone planned evacuation in Iitate Village in June 2012 and designated within it a “zone in preparation of the lifting of the evacuation order,” “restricted residence area,” and “difficult-to-return zone,” according to the yearly integrated radiation amount. In this particular review, Nagadoro, a settlement in Iitate Village, was designated as a “difficult-to-return zone” due to readings of over 50 mSv/y. The Revised Act on Special Measures for the Reconstruction and Revitalization of Fukushima was enacted in May 2017 to establish a base for reconstruction and revitalization of the “difficult-to-return zone.” The establishment of a special reconstruction and revitalization base is now in progress in Nagadoro as well.

In addition to establishment of the base, a series of discussions among the national government, municipal government and local residents have been conducted repeatedly regarding the recycle-use of materials in the Environmental Restoration Project.

November 11, 2017: The Environmental Restoration Project was approved in an extraordinary general meeting of Nagadoro administrative district in Iitate Village.
November 13, 2017: Nagadoro administrative district informed the Mayor of Iitate Village in writing regarding the affirmative vote at the general meeting.
November 14, 2017: The Environmental Restoration Project was approved by the Iitate Village Council and a conference with all village members.
November 20, 2017: The Iitate Village Council submitted the request for implementation of the Environmental Restoration Project to the Ministry of the Environment.

The request demanded that the nation and relevant ministries provide Nagadoro with proper support, including recycling of soil removed from the village, environmental reformation through land development/concentration of Nagadoro, and other necessary support to ensure long-term land use, such as cultivation of gardens/resource crops in the settlement after environmental restoration through implementing findings regarding the recycle-use of removed soils currently being investigated by the national government.


The Ministry of the Environment and Iitate Village
agreed that both parties would work closely on the Environmental Restoration Project, including recycling of the removed soils in Nagadoro, to contribute to the revitalization of not only Nagadoro but also of Iitate Village and Fukushima Prefecture. The Ministry of the Environment, Iitate Village and the Naganuma settlement in the adjacent Iwase District were to collaborate and initiate verification projects, reflecting experts’ recommendations and paying utmost consideration to safety and security in the environment.

January 28, 2018: An information session presenting the restoration project was held during an extraordinary general meeting of Nagadoro administrative district in Iitate Village.

March 25, 2018: Another information session presenting the restoration project was held during an extraordinary general meeting of Nagadoro administrative district in Iitate Village.

April 20, 2018: The Restoration and Revitalization Program for Areas Requiring Special Attention was approved for implementation in Iitate Village.

June 3, 2018: An information session for residents on the restoration project was held targeting the residents of Nagadoro.

In considering residents’ feelings, verification projects regarding the recycle-use of removed soils must be evaluated from every possible aspect, employing the expertise of the “Environment Restoration Project Organizing Committee for Restoration and Revitalization of Nagadoro in Iitate Village” so that the project can commence with proper care and consideration for safety and security through efforts to review and confirm factors causing anxiety among residents. The accomplishments a verification project previously conducted in Minamisoma City will be introduced in these projects. A series of crop cultivation tests will be conducted as well, targeting gardening/resource crops in response to a request from Nagadoro (Ministry of the Environment, 2012; 2017).

9. Outline of Verification Project

This project aims to verify various aspects of removing soil stored in the TSSs in the village to be recycled as embankment materials for farmland development. The aim is to establish a technical framework for promoting the recycle-use of materials from the viewpoint of their management, including examination of practical management methods for protection from radiation during the recycling process and assurance of quality as embankment materials for farmland development, and securing safety from radiation during the experimental recycle-use of soil (Ministry of the Environment, 2012; 2017).

The first step is to transfer and store approximately 30,000 bags of removed soils being held in the village’s TSS to a stockyard designated in Nagadoro administrative district and establish a recycling plant in the vicinity of the designated recycling facility (Fig. 6) (Ministry of the Environment, 2012; 2017).

The recycling procedure consists of two processing phases: a pre-processing phase to break the container bags and remove unnecessary components for farmland development (e.g., garbage, irrelevant organic materials and metals), and a quality control phase to manage the soil quality according to the target use of the recycle-soil.

To maximize the amount of recycled material and reduce unnecessary organic materials or metals, the soil will be sifted using a vibrating screen in the pre-processing phase to remove alien substances larger than a specific size. The recycle-soils will be evaluated in the quality control phase to determine if it satisfies the required quality standard (e.g., density, ignition loss, moisture weight percentage and particle size distribution) for use as embankment material in farmland development. Those that fail to satisfy the standard will be evaluated to determine if the quality could be improved by mixing and stirring with the soil to be used as the shielding.

The recycle-soils will then be measured by a radioactive concentration measurement/sorting device and categorized according to their concentration levels; those that do not meet the designated threshold will not be used as recycled material. The soil processed in Nagadoro will be categorized as either over 5,000 Bq Kg or below 5,000 Bq Kg. Specifically, the soil is put into the hopper of the radioactive concentration measurement/sorting device and lands on a conveyor (transfer speed: 35 cm/sec) equipped with a belt scale and a cesium iodide (CsI) scintillator detector (with a 1.2-second detection interval) to measure its weight and radiation dose. Then the radioactive concentration measurements are sent to the sorting device, in which the sorting chute divides the soil into groups with over 5,000 Bq Kg and under 5,000 Bq Kg. The soil to be recycled as embankment...
material for farmland development will then be verified accordingly.

The recycled material will undergo a rolling compaction process to secure more than 50 cm of shielding soil pressure (shielding thickness) in the construction of the embankment, in which the relevant data, including hydraulic conductivity, cone index, compaction degree, settlement of the embankment, surface dose rate, air dose rate, soil radioactive concentration level and other data after the compaction of each layer are recorded. The productivity of the actual construction project is also estimated accordingly by investigating key elements, such as cycle time at each construction stage.

The ground at the site of the recycled material verification project has been cured with an impervious sheet or other materials wherever necessary to prevent contamination of the local panel, and its rainwater drainage system is being properly attended by placing required facilities such as gutters so that the level of radioactive concentration can be measured appropriately.

Tents (100 m x 30 m) have been set up at the recycled material verification project site, and all work has been conducted inside the tents to prevent infiltration of rainwater or outflow of the removed soils. Upon resolving technical issues, the full-scale Environmental Restoration Project, which will encompass the farmland stretching from east to west between the Hisokawa River and the prefectural road, will use the quality-controlled recycling materials obtained by the above method (Figs. 7 and 8) (Ministry of the Environment, 2012; 2017).

10. Outline of the Cultivation Verification Project

A cultivation verification project assuming the recycle-use of materials for the planting base material has been implemented. In this verification project, the area of farmland development is approximately 0.1 ha, on which various garden crops and other crops premised on the use of biomass have been tested in greenhouses. The safety of using recycled materials is being evaluated in these cultivation tests using shielding materials and recycled
11. Reducing Amounts of Radiocesium Transferred to Crops

Research institutes in the prefectures of Fukushima, Ibaraki, Tochigi and Gunma collaborated with NARO in a paddy rice cultivation experiment in 2011 to investigate the influence of potassium fertilizer on the transfer of radiocesium in the soil to cultivated brown rice (Ministry of Agriculture, Forestry and Fisheries, 2015). The results showed that the transfer coefficient of radiocesium to brown rice could be reduced, except for in soil with a low transfer coefficient, by applying an amount of potassium fertilizer three times greater than the usual application. This fertilizer was rich in clay minerals and had a high radiocesium fixation capacity. The concentration levels of exchangeable potassium were relatively high in soil applied to cow dung compost for a long period in addition to a chemical fertilizer, showing a low concentration level and transfer coefficient of radiocesium to brown rice. Soils containing zeolite or vermiculite as clay minerals were evaluated, and a recommendation was made to reduce radiocesium concentration by adjusting the usual amount of applied fertilizer in each area with a low potassium content in the paddy field to the level at which the amount of exchangeable potassium was around 25 mg-K\textsubscript{2}O (100 g\textsuperscript{-1}) (Fig. 10). According to the above results, a countermeasure to radioactive absorption was implemented to increase the amount of potassium in approximately 84,000 ha of paddy fields in Fukushima and other prefectures during implementation of the Agricultural Business Restoration Project in 2013 (Ministry of Agriculture, Forestry and Fisheries, 2011).

In soybean cultivation, it was also revealed that the potassium concentration in the soil contributed to suppression of radiocesium absorption in the same way as observed in paddy rice cultivation, and the same target level of exchangeable potassium was set at approximately 25 mg K\textsubscript{2}O (100 g\textsuperscript{-1}) in practice. It was reported, however, that application of potassium chloride in soybean cultivation would prohibit root nodule adhesion; therefore, the influence of the potassium concentration in soybean cultivation was evaluated and the reduction of root nodule adhesion was confirmed to be minimal at the target level of around 25 mg K\textsubscript{2}O (100 g\textsuperscript{-1}), posing no ill effect on the growth or harvest of the crop. For buckwheat cultivation, this countermeasure was recommended with a target level of approximately 30 mg K\textsubscript{2}O (100 g\textsuperscript{-1}) (Ministry of Agriculture, Forestry and Fisheries, 2011; Kato et al., 2015).

Pasture renovation can reduce the radiation air dose rate at the pasture surface and the radiocesium concentration level in newly seeded pasture. A total renovation method combining plowing with burial of radiocesium deep in the soil has been found highly effective as a countermeasure in pasture cultivation. When thorough soil turnover is accomplished, the surface turnover by disc harrows should be enough to reduce radioactive absorption in the crop.

Potassium fertilizer has also been applied in Iitate Village after soil decontamination. However, work involving commuting between where the evacuated farmers have relocated and the village imposes a significant burden on the farmers. Since some radiocesium remains after decontamination, continuous practice of radioactive countermeasures, such as surface...
Case history: decontamination challenge of Iitate Village

155

polished and boiled rice has been found to be one-eighth that of brown rice, revealing the dynamics of radiocesium during cooking and processing. Along with food processing technology, a systematic procedure to easily measure radiocesium concentrations in food has already been established in each municipality, contributing to consumers’ safety. The radiocesium concentrations in mountain vegetables and mushrooms, however, remains high, and residents often demand appropriate actions to resolve the situation. Relevant initiatives have been taken since 2012 in Iitate Village so that farmers can measure radioactive concentration levels in crops they cultivate themselves to ensure safety (Ministry of Agriculture, Forestry and Fisheries, 2015; Ministry of Health, Labour and Welfare, 2011).

13. Environmental Restoration of Fukushima

The decontamination of the entire region of Fukushima Prefecture, except for the “difficult-to-return zones,” was completed by the end of 2018. A considerable amount of contaminated soil was produced in the process, reaching a total of approximately 16,500,000 m$^3$ in Fukushima Prefecture alone. These contaminated wastes have been stored at either TSSs set up at approximately 1,300 sites during the peak period or on residential quarters/open ground in areas where it is difficult to set up storage deposits (e.g., densely populated areas such as Fukushima City or Koriyama City). All of the wastes will

12. Dynamic Analysis of Radiocesium in Cooking and Processing of Crops

It has been nearly ten years since the accident, and the natural decay of radioactive cesium released to the environment should be progressing, yet consumers’ anxiety about the influence of radiocesium ($^{137}$Cs) remains dominant; thus the validity of the measurement standard for radioactive concentrations in food has been evaluated. The Food Sanitation Law defines the standard value of radiocesium concentrations in typical food as below 100 Bq Kg$^{-1}$, and it is necessary to examine the dynamism of radiocesium in the cooking and processing of the target foods for accurate risk assessment and management (National Agriculture and Food Research Organization, 2017b). In brown rice cooking, it has been confirmed that radiocesium is removed with the rice bran and washing water during the polishing and boiling of brown rice (Fig. 11) (Ministry of Agriculture, Forestry and Fisheries, 2015). In milled rice, the radiocesium concentration in polished and boiled rice has been found to be one-eighth that of brown rice, revealing the dynamics of radiocesium during cooking and processing. Along with food processing technology, a systematic procedure to easily measure radiocesium concentrations in food has already been established in each municipality, contributing to consumers’ safety. The radiocesium concentrations in mountain vegetables and mushrooms, however, remains high, and residents often demand appropriate actions to resolve the situation. Relevant initiatives have been taken since 2012 in Iitate Village so that farmers can measure radioactive concentration levels in crops they cultivate themselves to ensure safety (Ministry of Agriculture, Forestry and Fisheries, 2015; Ministry of Health, Labour and Welfare, 2011).

13. Environmental Restoration of Fukushima

The decontamination of the entire region of Fukushima Prefecture, except for the “difficult-to-return zones,” was completed by the end of 2018. A considerable amount of contaminated soil was produced in the process, reaching a total of approximately 16,500,000 m$^3$ in Fukushima Prefecture alone. These contaminated wastes have been stored at either TSSs set up at approximately 1,300 sites during the peak period or on residential quarters/open ground in areas where it is difficult to set up storage deposits (e.g., densely populated areas such as Fukushima City or Koriyama City). All of the wastes will
be transferred to SSFs set up in Okuma Town and Futaba Town. Transportation (Figs. 12 and 13) began in 2015 with an initial transportation test run with 46,000 m$^3$ from each municipality in the prefecture. A total of 4,059,000 m$^3$ of temporarily stored soil/waste was transported to the ISF in 2019, and as of 2019, a total of 8,509,000 m$^3$ (August 2019 under the direct control and June 2019 under the indirect control of the Ministry of the Environment, with information updated daily on its website) has been transported. By the end of FY2021, the transportation should be almost complete. Once this is completed, the lands used as TSSs, which were leased to the national government, will be restored to their previous state before use for storage deposits and returned to the landowners) (Ministry of the Environment, 2012; 2016b).

As for the ISFs, a total of approximately 1,600 ha of land has been allocated for their creation, and the remains of the TSSs, including deposit-sorting facilities for contaminated soil/waste transported from temporary dumping sites and soil storage facilities, and other wastes, such as sorted logs or materials from dismantled buildings, will be compacted by combustion and the resulting incineration ashes with high concentrations of radiocesium will be sent to radioactively contaminated waste storage facilities. The storage time at the ISF is set at within 30 years, after which the contents will be disposed of at waste disposal sites set up outside Fukushima Prefecture (the location of which is to be decided). At the ISF, the waste is being stored in two groups, that below and that above a threshold of 8,000 Bq Kg, to prevent rainwater infiltration with necessary curing to limit infiltration of the groundwater by contaminated soil particles or radiocesium. Regarding the final disposal of radioactively contaminated waste at
the ISF, relevant laws and guidelines, including the “Basic Guidelines for the Reconstruction and Revitalization of Fukushima” issued on July 13, 2012 (Cabinet decision), determine that “necessary measures must be taken to complete the final disposal of soil outside Fukushima Prefecture within 30 years from the start of interim storage.” Further actions will be required in the future (Ministry of the Environment, 2012).

In Iitate Village, where the author was dispatched, it seems that the level of awareness among farmers regarding radioactive cesium has been enhanced greatly compared to during the farmland decontamination measures verification project, which encompassed approximately 40 ha of farmland in Iitate Village (in the settlements of Nagadoro, Komiya, and Kusanomukaioishi) and Kawamata Town (in the settlements of Yamakiyahosoda and Yamakiyahinada), and after the evacuation order was lifted in the “zones in preparation of the lifting of the evacuation order” and “restricted residence areas.” The residents can prepare to protect themselves against lingering undiscovered radioactive cesium and recover from their evacuation to the present. Although environmental restoration by decontamination is in progress, there remain various issues in resuming life in the village after environmental restoration, including some residents’ lack of desire to return to the village after their prolonged evacuation and discontent with the slow reconstruction of village infrastructure. As for resuming agricultural business in the area, a reduction in the number of residents and the increasing age of those who wish to return and resume farming will have a great impact, requiring close attention in the future.

14. Conclusion

A multi-perspective approach to countermeasures against contamination by radioactive cesium is extremely vital to the environmental restoration of Fukushima Prefecture, the area most severely affected by radioactive cesium in our country. A substantial augmentation of control technologies and data contributing to resumption of agricultural business should be mandatory, and cross-sectional initiatives to defend against radioactive cesium must be implemented continuously in close collaboration among the national and municipal governments, research institutes, private corporations and other relevant organizations.

Acknowledgments

Extremely careful yet swift actions are required in response to radioactive cesium contamination. The author was dispatched to Iitate Village in the Date district of Fukushima Prefecture where he served as a specialist in the Industry Promotion Section. The author wishes to express profound gratitude to the following individuals for their guidance and understanding:

- Doctor Makoto Nakatani, Vice President of NARO;
- Doctor Masami Yasunaka, NARO;
- Dr. Takeshi Kimura, National Federation of Agriculture Co-operative Associations;
- Professor Takuro Shinano, Hokkaido University;
- Drs. Takeshi Ota, Hisatsa Matsumani, Yoshisada Nagasaka, Namiko Yoshino, Sachie Horii, Kazunori Kohyama, Noriko Yamaguichi, Hideshi Fujiwara, Yasuko Togamura, Mayumi Hachinohe, Tomijiro Kubota, and Takeo Tsuchihara, NARO;
- Associate Professor, Moono Shin, Fukushima University;
- Drs. Mutusato Sato and Takashi Saito, Fukushima Prefecture;
- Drs. Masaya Suzuki and Hirohisa Yamada, National Institute of Advanced Industrial Science and Technology;
- Prof. Tsutomu Saito, Hokkaido University; and all the staff members of the Iitate Village Restoration and Reconstruction Division. Lastly, the author wishes to express gratitude from the bottom of his heart to all those who have supported us in relevant organizations.

References

Yuuzou MAMPUKU

Yuuzou Mampuku is a researcher at the Institute for Agro-Environmental Sciences, National Agriculture and Food Research Organization. His research interests and specialties are environmental circulation system engineering and agricultural civil engineering. He has been making efforts to restore the environment in Fukushima Prefecture after the Great East Japan Earthquake.

(Received 19 October 2020, Accepted 28 December 2020)
Experimental Study on the Mechanism of Cs Removal from Contaminated Soil and Incineration Ash by Pyroprocessing

Kazuo YAMADA1*, Kazuhiko TOKOYODA1,2 and Masahiro OSAKO3

1Fukushima Branch, National Institute for Environmental Studies
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
2Taiheiyo Cement Corporation
1-1-1 Koishikawa, Bunkyo-ku, Tokyo, 112-8503, Japan
3Center for Material Cycles and Waste Management Research, National Institute for Environmental Studies
16-2 Onogawa, Tsukuba-city, Ibaraki, 305-8506, Japan
*E-mail: yamada.kazuo@nies.go.jp

Abstract

After the Fukushima Daiichi nuclear power plant accident, a large region of northeastern Japan was contaminated by radio-Cs (r-Cs). Contaminated soil and incineration ashes are generated through decontamination processes and daily human activities, respectively. To reduce the volume of such substances, several kinds of pyroprocessing techniques have been developed. R-Cs is thought to be trapped within aluminosilicates. With the addition of Ca to these compounds, alkali metals may be readily removed. Next, Cl is added and the alkali metals are volatilized in the order of Cs > K > Na. On the basis of this estimation, the highest Ca content is expected to produce the best conditions for the removal of Cs. Calcium silicate and aluminate with the highest Ca concentration are found in Portland cement. To understand the mechanism of Cs volatilization, the effect of the Ca/(Si+Al) ratio on the ratio of Cs remaining is introduced on the basis of data from the literature. A high-efficiency Cs removal process in cement is also investigated using a small scale rotary furnace for real contaminated soil and ashes, and by pilot-scale experiments with model soil. Additionally, through detailed experiments using pollucite—a cesium aluminosilicate—Cs removal behaviors were found to correspond to phase change, depending on the Ca/Si and Cl/Cs ratios. At high Ca/Si ratios, even without adding Cl, a significant amount of Cs could be removed. Potassium existing in or added to the initially contaminated samples facilitated Cs removal such that Cs was reduced to an undetectable level even without the addition of Cl.

Key words: aluminosilicate, cesium removal, chloride volatilization, incineration ash, pollucite, Portland cement, pyroprocessing, radio-cesium

1. Introduction

After the Fukushima Daiichi nuclear power plant (FDNPP) accident, a wide region of northeastern Japan was contaminated with radio-Cs (r-Cs) (IAEA, 2015). Because of the nature of this accident, the major contaminant was limited to volatile r-Cs.

To reduce the additional radiation dose to 1 mSv/y, the target level determined by the Japanese government, the surface soils in many regions surrounding the FDNPP have been removed and are currently being transported to an interim storage facility (ISF) (MOE, 2018a). From this soil, combustibles are removed and sent to temporal incinerators to reduce their volume; here, contaminated incineration ash (IA) is generated. In addition, daily human activities generate various kinds of wastes, such as municipal solid waste (MSW) and sewage sludge, which are then contaminated by r-Cs. In Japan, the majority of these wastes are sent to incinerators for volume reduction; here, contaminated IA is also generated in concentrated form. Because of the limited space in ISFs, the volumes of this IA and relatively highly contaminated soils must be reduced. For this purpose, various technologies have been proposed in Japan for the removal of Cs from these contaminated substances (JESCO, 2016–2020). One of the most efficient methods is based on chloride volatilization (Spalding, 1994).

Two major pyroprocessing systems using chloride volatilization have been proposed; one involves the use of a melting furnace to reduce the volume of MSW-IA (Kamata et al., 2015) and the other involves a rotary kiln that is used for Portland cement production (Tokoyoda et al., 2018a). In both systems, a high temperature, approximately 1,300°C to 1,500°C, is required. From both
pyroprocessing systems, concentrated Cs is obtained as CsCl salt. The decontaminated product obtained by the melting system is a slag, while that from the rotary kiln system is a hydration-inactive sintered mineral agglomerate or cement clinker (which is the raw material used for Portland cement). These systems require quite high temperatures, but the decontaminated products may be used as commercial materials such as slag, sintered agglomerates that may be used as aggregates, or Portland cement. The management of decontaminated wastes is of great importance. If it is difficult to find a use for decontaminated materials, then a landfill site must be used. In 2018, the Japanese Ministry of the Environment ordered the construction of two kinds of pyroprocessing systems, and in March 2020, the systems began operation (Yamada et al., 2020) although the rotary kiln system was not adopted.

Considering the mechanism of Cs removal using these pyroprocessing techniques, we note an interesting report. After the FDNPP accident, intensive surveys of various incinerators were conducted, and it was found that r-Cs tended to concentrate in fly ash rather than in bottom ash. The ratio of these concentrations depended on the nature of the original combustible wastes (Yui et al., 2018; Fujisawa et al., 2017). When a significant amount of Cl was included in the combustible wastes, the Cs tended to become fly ash in a water-soluble form, such as CsCl. Without Cl, Cs remained in aluminosilicate form. This suggests that even at relatively low temperatures such as 800°C to 900°C within incinerator furnaces, chloride volatilization of Cs may occur. The melting and boiling temperatures of CsCl are 645°C and 1,295 °C, respectively. Exceeding the boiling temperature of CsCl is not needed to achieve volatilization, and some vapor pressure of CsCl may be estimated enough at such low incineration temperatures.

According to previous reports on pyroprocessing systems for volume reduction of IA and contaminated soils (Kamata et al., 2015; Tokoyoda et al., 2018a; Honma et al., 2014; Manpuku et al., 2017), r-Cs is assumed to exist within clay, pollucite, and glass minerals, and others. The phases containing Cs are assumed to be aluminosilicates. As was determined experimentally (Kamata et al., 2015; Tokoyoda et al., 2018b; Honma et al., 2014; JAEA, 2011; MOE, 2018b) by adding CaO and CaCl₂, the majority of Cs in an aluminosilicate may be volatilized at an appropriately high temperature. The mechanism of Cs volatilization can be assumed as follows:

- Upon addition of Cl, excess alkali metals oxides form alkali chlorides and these phases exhibit significant vapor pressures at high temperatures that may be lower than the boiling temperature of Cs₂O.
- Alkali metals transition from solid to vapor phases at these temperatures. The tendency of volatilization of alkali metals follows the order of Cs > K > Na; Cs, including r-Cs, is therefore preferentially volatilized.
- The vapor may then be cooled in a cooling system and recrystallized as solid alkali chlorides, which are collected in a bag filter system. From the flue gas following this bag filtration, the r-Cs content in the flue gas is reduced to undetectable levels even when using a high-volume sampler.

Considering the above-mentioned concepts, higher ratios of Ca/(Al+Si) and Cl/Cs should be suitable for promoting the removal of r-Cs from IA and soil. From the viewpoint of a high Ca/(Al+Si) ratio, the use of Portland cement provides the most favorable system. In this study, a series of experimental investigations on the effects of the Ca/(Al+Si) and Cl/Cs ratios for Cs removal from pollucite (CsAlSi₅O₁₀) were conducted to elucidate the removal mechanism of Cs via pyroprocessing treatments. These were done after reviewing the characteristic mineral combination of Portland cement.

2. Chemical Reactions in Portland Cement Production

To understand the mechanisms underlying the formation of the minerals considered in this paper, a basic understanding of Portland cement must be introduced. Portland cement is one of the largest industrially produced materials. It is a mixture of burned minerals, known as cement clinker, and calcium sulfate. The basic components of cement clinker are 3CaO·SiO₂ (known as alite), 2CaO·SiO₂ (known as belite), 3CaO·Al₂O₃, and 4CaO·Al₂O₃·Fe₂O₃, which have mass fractions of roughly 65, 20, 7.5, and 7.5 w/w% (mass percent), respectively. These mass fractions are determined on the basis of the total balance of performance of the Portland cement used in concrete.

3CaO·SiO₂ and 3CaO·Al₂O₃ are the most Ca-rich silicate and aluminosilicate minerals in the CaO–SiO₂–Al₂O₃ ternary system. Upon burning of the raw powders of these materials and after the decarbonation of CaCO₃ to form free lime, 2CaO·SiO₂ crystals and the Ca–Al–Fe–O liquid phases are generated within the temperature range of 900°C to 1,300°C. At temperatures of 1,300°C to 1,450°C, 2CaO·SiO₂ reacts with free lime to form 3CaO·SiO₂. The amounts of the Ca–Al–Fe–O liquid phases affect the formation speed of 3CaO·SiO₂, which must be controlled within an appropriate range. This reaction does not proceed well when these quantities are too small. When these quantities are too large, the burned material adheres to the inner surface of the kiln, and the
products are not discharged from the kiln. After burning, the burned materials, known as clinker, which are composed of particles a few centimeters in diameter, are sent to a cooler. Rapid cooling is important for the stabilization of the high-temperature phases of $3\text{CaO} \cdot \text{SiO}_2$ and $2\text{CaO} \cdot \text{SiO}_2$. $2\text{CaO} \cdot \text{SiO}_2$ may be stabilized as $\beta-2\text{CaO} \cdot \text{SiO}_2$ via rapid cooling, but the thermodynamically stable phase is $\gamma-2\text{CaO} \cdot \text{SiO}_2$, which does not express hydration reactivity. The Ca–Al–Fe–O liquid phase constitutes a matrix (known as an interstitial phase) of these calcium silicates, and with a decrease in temperature, this liquid phase crystallizes into two different phases, $3\text{CaO} \cdot \text{Al}_2\text{O}_3$ and $4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$.

The chemical compositions are shown in the CaO–SiO$_2$–Al$_2$O$_3$ ternary phase diagram with the chemical composition of ordinary Portland cement (Fig. 1). In actual cement, alkali metals and sulfur at quantities on the order of 0.1 w/w% exist as contaminants that derive from the raw materials. Na exists mainly in $2\text{CaO} \cdot \text{SiO}_2$ and orthorhombic $3\text{CaO} \cdot \text{Al}_2\text{O}_3$, while K exists mainly in alkali sulfate. In $2\text{CaO} \cdot \text{SiO}_2$, more cations may be contained as compared with $3\text{CaO} \cdot \text{SiO}_2$. $3\text{CaO} \cdot \text{Al}_2\text{O}_3$ is known to have both orthorhombic and cubic crystalline structures. When the alkali/sulfur molar ratio exceeds 1.0, the excess amount of alkali materials is included in orthorhombic $3\text{CaO} \cdot \text{Al}_2\text{O}_3$.

In modern production processes for cement, with the exception of typical raw materials including limestone, silica sand, clays and the iron and heat sources provided by coal, a large variety of wastes are used as raw materials and alternative fuels. Only the chemical compositions of the raw materials for the production of Portland cement must be controlled. There is no need to control either the mineral or chemical forms of these materials. During thermal processing at approximately 1,450°C, all components are decomposed to form clinker minerals. A typical alternative heat source is processed MSW, in which vinyl chlorides are included. When Cl is included in a raw material, potassium is preferentially volatilized as KCl in rotary kilns. In general, the volatilizing tendencies of alkali chlorides follow the order of Cs > K > Na, and the boiling temperatures of these materials follow the order of 1,295 < 1,420 < 1,465°C. However, the Cs content of cement is assumed to be 1 to 10 ppm, which is much less than that of K, which is on the order of 0.1 w/w%. Because of the volatilization tendencies and the molar ratios of the existing elements, the ratio of Cs remaining in Portland cement is not easily estimated and should be examined in real systems.

The behaviors of alkali elements and Cl in Portland cement production are similar to those in the incinerators for MSW, which both involve chloride volatilization from alkali materials. However, differences exist in the processing temperatures and Ca content.

In Japan, a unique type of Portland cement plant has been introduced, known as “eco-cement,” because more than half of the raw materials that are used are wastes such as IA rich in Cl. The Cl content of cement must be controlled because Cl may cause steel corrosion when Portland cement is used in reinforced concrete. In an eco-cement system, Cl is removed via the volatilization of alkali chlorides by adding alkali carbonates. Without the addition of alkali elements, Cl forms a calcium chloroaluminate liquid phase at burning temperatures of over 1,350°C, and in this phase, alkali metals may dissolve. Therefore, the volatilization behaviors of alkali chlorides have been of great interest in the cement industry.

3. Cs Removal in Pyroprocessing

3.1 Literature Review of Several Systems for the Removal of Cs

In nature, r-Cs is thought to be fixed within clay minerals (Manpuku et al., 2017) and is difficult to remove via simple heating processes (Honma et al., 2019). As explained in Chapter 1, the addition of a sufficient amount of Ca to aluminosilicate may aid this removal process. On the basis of three previous studies (Kamata et al., 2015; Tokoyoda et al., 2018a; Honma et al., 2014) discussing the effects of adding CaO and CaCl$_2$ at varying Ca/(Si+Al) ratios and temperatures, the removal of Cs through various pyroprocessing techniques was therefore studied.

Honma et al. (2014) investigated several types of contaminated soil with a maximum r-Cs concentration of 25 kBq/kg. By adding CaO and CaCl$_2$ and heating the mixture to 1,350°C, they were able to reduce the r-Cs content of the pyroprocessed materials to 50 Bq/kg. The performance of this system was also demonstrated using a large-scale rotary kiln with a 10 t/day capacity (Honma et al., 2019; Tokoyoda et al., 2018b). By adjusting the
Ca/Si and Cl/K ratios and temperature, the r-Cs concentrations in soils contaminated with 21 kBq/kg of r-Cs and incineration ashes with contamination levels of 1 to 111 kBq/kg were successfully reduced to less than 100 Bq/kg (the clearance level) in the majority of the tested batches. These operations were carried out in 26 runs from May 2018 to January 2019, for 470 t of contaminated soil and ashes. The amounts of contaminated wastes were reduced by approximately one tenth. In this system, the Cl content was controlled in terms of the K concentration ratio of the contaminated samples because Cs is considered to be more easily volatilized than K. If the Cl content is sufficient to volatilize K, then all of the Cs may volatilize. Moreover, the applicability of the decontaminated samples as aggregates for civil engineering works or concrete was examined in their study.

Kamata et al., 2015 demonstrated the high performance of a different system involving a surface melting furnace. The optimized parameters of that were similar to those of the rotary kiln system described above. The differences between the two systems pertain to the materials obtained after decontamination. The former process mainly results in 2CaO·SiO₂ and gehlenite, while the latter produces slag. By adjusting the process parameters and by considering model soil and ashes containing 0.2 w/w% of stable Cs, a 99.9% removal of Cs was achieved. In this system, the chemical compositions were adjusted to result in a sufficient amount of alkali elements with Cl/K molar ratios ranging from 4.6 to 22 in order to obtain a molten phase at 1,400°C.

Tokoyoda et al. (2018b) examined the performance of a Portland cement system at laboratory scale using real contaminated materials. They used a larger rotary kiln with an inner diameter of 450 mm, length of 8,340 mm, and capacity of 30 kg/h using a model soil containing 0.1 w/w% of stable Cs. To obtain the cement clinker, the Ca/Si molar ratio was controlled to around 3.0. The Cl/K molar ratio was controlled at 1.0, as performed by Honma et al., 2014.

The chemical compositions of the materials examined by the three studies are shown in Fig. 2 for the CaO–SiO₂–Al₂O₃ ternary system at 1,400°C. As shown, a wide range of chemical compositions were examined while considering the melting system. In the rotary kiln system, two chemical compositions were examined. One was a typical hydration reactive Portland cement, while the other involved non- or less-hydration reactive minerals.

In Fig. 3, the ratios of Cs remaining to the respective original concentrations of the treated materials are plotted against the Ca/(Si+Al) molar ratio. Kamata et al. (2015) proposed an optical basicity considering various elements as an additional index because other minor elements may behave as cations or anions. For example, under oxidizing conditions, Fe may behave similarly to Al. P₂O₅ can participate in calcium silicates as part of the silicate. As shown in the above figure, a higher Ca/(Si+Al) ratio results in a lower ratio of Cs remaining. For the Portland cement composition utilized by Tokoyoda et al. (2018a), Cs was reduced to an undetectable level. However, as the detection limit was 0.01%, the actual efficiency may be higher than was indicated in this study. As indicated above, the Ca ratio in terms of cation capacity in aluminosilicates appears to be a key factor that is independent of the pyroprocessing system. Judging from the aforementioned results, we expect Portland cement to provide the best chemical composition for removal of Cs from various sources.

As a decontamination material, cement composed of
model soil at 1,450°C demonstrated normal performance as Portland cement, satisfying Japanese Industrial Standard JIS R 5210: 2019 (Tokoyoda et al., 2018a).

3.2 Detailed Effects of Temperature and Cl/K Ratios in a Portland Cement System

3.2.1 Experiments

From the discussion in the former chapter considering the system with the highest Ca concentration, Portland cement is expected to provide a highly efficient system for removing Cs. The effects of temperature and Cl/K ratio from the viewpoint of the ratio of Cs remaining may next be examined on the basis of data provided by Tokoyoda et al. (2018b) with additional IA data.

The samples used in this study were obtained from residential land soils, pond deposits and incineration fly and bottom ashes generated in Fukushima Prefecture. The chemical compositions and radiation concentrations of r-Cs in the examined samples are shown in Table 1. The examined samples are examples of real contaminated materials that require treatment, but because of limited capacity to treat radioactive materials in our laboratory, only samples with relatively low contamination levels were used. Therefore, the detection ability for determining the removal efficiency of the overall system was also limited. The chemical compositions for the experiments were adjusted to those of Portland cement by using reagent-grade free lime (CaO) and CaCl₂, as well as commercial silica sand. The target mineral compositions were 60, 20, and 20 w/w% for 3CaO∙SiO₂, 2CaO∙SiO₂, 3CaO∙Al₂O₃, and 4CaO∙Al₂O₃∙Fe₂O₃, respectively.

The major factors examined were the types of samples, heating temperature and Ca/Si and Cl/K ratios. The pyroprocessing conditions are shown in Table 2. The samples were ground, mixed and then heated in a rotary furnace. The homogeneous heating zone was φ = 50 × 120 mm. The samples were heated at a rate of 5°C/min and maintained at their respective target temperatures for 60 min.

Radioactivity was measured by using a Ge detector, and other major elements were measured by X-ray fluorescence (XRF) analysis. The detection limit of radioactivity depends on measurement time; hence, the detection limits in this study varied from 3 to 15 Bq/kg depending on the available machine time.

From X-ray diffraction/Rietveld analysis, the mineral compositions determined for the samples 3CaO∙SiO₂, 2CaO∙SiO₂, 3CaO∙Al₂O₃, and 4CaO∙Al₂O₃∙Fe₂O₃ treated at 1450°C were 62, 21, 6, and 10 w/w%, respectively. At this temperature, we confirmed that the target clinker minerals formed.

3.2.2 Results

1) Effects of temperature

Figure 4 shows the effects of the pyroprocessing temperature on the ratio of Cs remaining. In this series, the Cl/K molar ratio was controlled at 1.0, and the amount of Cl was controlled at an excess in terms of the Cs content. The ratio of Cs remaining was calculated from the original irradiation concentration and that existing after pyroprocessing. The detectable ratio of Cs remaining depended on the original value and detection limit. This is the reason for the wide variation in the detection limits shown in Fig. 4.

Under these conditions, the amounts of all alkali metals were also reduced at higher temperatures. The order of the ease of removal was Cs > K > Na, as expected even under conditions of their significantly different concentrations. Cs was reduced to undetectable

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>SO₃</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>P₂O₅</th>
<th>Cl</th>
<th>Ig.Loss</th>
<th>Total</th>
<th>r-Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential land soil</td>
<td>21.26</td>
<td>5.83</td>
<td>2.03</td>
<td>64.20</td>
<td>0.92</td>
<td>0.07</td>
<td>0.82</td>
<td>0.78</td>
<td>0.10</td>
<td>0.59</td>
<td>7.43</td>
<td>104.02</td>
<td>793</td>
</tr>
<tr>
<td>Pond deposits</td>
<td>18.29</td>
<td>3.56</td>
<td>2.31</td>
<td>53.08</td>
<td>0.34</td>
<td>0.00</td>
<td>0.21</td>
<td>0.34</td>
<td>0.10</td>
<td>0.55</td>
<td>35.94</td>
<td>114.69</td>
<td>2250</td>
</tr>
<tr>
<td>Incineration fly ash</td>
<td>20.37</td>
<td>3.36</td>
<td>4.47</td>
<td>58.54</td>
<td>0.62</td>
<td>1.59</td>
<td>0.30</td>
<td>1.19</td>
<td>0.15</td>
<td>0.89</td>
<td>9.12</td>
<td>100.60</td>
<td>6819</td>
</tr>
<tr>
<td>Incineration bottom ash</td>
<td>21.83</td>
<td>4.93</td>
<td>2.00</td>
<td>63.93</td>
<td>0.90</td>
<td>0.12</td>
<td>0.72</td>
<td>1.14</td>
<td>0.23</td>
<td>0.86</td>
<td>2.72</td>
<td>99.38</td>
<td>8198</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>SO₃</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>P₂O₅</th>
<th>Cl</th>
<th>Ig.Loss</th>
<th>Total</th>
<th>r-Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential land soil</td>
<td>21.26</td>
<td>5.83</td>
<td>2.03</td>
<td>64.20</td>
<td>0.92</td>
<td>0.07</td>
<td>0.82</td>
<td>0.78</td>
<td>0.10</td>
<td>0.59</td>
<td>7.43</td>
<td>104.02</td>
<td>793</td>
</tr>
<tr>
<td>Pond deposits</td>
<td>18.29</td>
<td>3.56</td>
<td>2.31</td>
<td>53.08</td>
<td>0.34</td>
<td>0.00</td>
<td>0.21</td>
<td>0.34</td>
<td>0.10</td>
<td>0.55</td>
<td>35.94</td>
<td>114.69</td>
<td>2250</td>
</tr>
<tr>
<td>Incineration fly ash</td>
<td>20.37</td>
<td>3.36</td>
<td>4.47</td>
<td>58.54</td>
<td>0.62</td>
<td>1.59</td>
<td>0.30</td>
<td>1.19</td>
<td>0.15</td>
<td>0.89</td>
<td>9.12</td>
<td>100.60</td>
<td>6819</td>
</tr>
<tr>
<td>Incineration bottom ash</td>
<td>21.83</td>
<td>4.93</td>
<td>2.00</td>
<td>63.93</td>
<td>0.90</td>
<td>0.12</td>
<td>0.72</td>
<td>1.14</td>
<td>0.23</td>
<td>0.86</td>
<td>2.72</td>
<td>99.38</td>
<td>8198</td>
</tr>
</tbody>
</table>
levels at temperatures higher than 1,300ºC. The volatilizations of the alkali metals did not occur in the order of Cs > K > Na, but rather simultaneously. Only the ratios of each element differed. Although the ratios of K and Na remaining depended on the sample type, those of r-Cs were similar for all subjects. Simply all data were below the detection limit and the differences were thought to be unobservable. Residential land soil and bottom ash samples demonstrated similar behaviors. The pond deposits showed much lower ratios of Na and K remaining, and the fly ash exhibited the smallest values. The mechanisms underlying these removal processes are unclear.

2) Effects of the Cl/K ratio

Figure 5 shows the effects of the Cl/K molar ratio on the ratio of Cs remaining. In this series, the temperature was modified to 1,400ºC or 1,450ºC, and the Ca/Si molar ratio was modified to 3.0 or 2.2. A ratio of 3.0 is required for Portland cement, while 2.2 is required for an aggregate. The order of ease of alkali metal volatilization is the same as that shown in Fig. 4. Cs is the most easily volatilized, followed by K and Na, which are much less easily volatilized. All alkali metal concentrations were reduced by increasing the Cl/K ratio.

At 1,450ºC, without the addition of Cl, the ratio of Cs remaining decreased to the detection limit. The mechanism of volatilization is unclear, but Cs may be volatilized as Cs₂O. At 1,400ºC without Cl, 2.8% and 5.6% of Cs remained at Ca/Si ratios of 3.0 and 2.2, respectively. In both cases, Cs was reduced to the detection limit by increasing the Cl/K ratio.

4. Effects of Ca/Si and Cl/Cs Ratios on Behavior of Cs from Pollucite at High Temperatures

4.1 Use of Pollucite

As seen in the discussion above, the optimal conditions for the removal of Cs from various sources were determined. The Cs content was very limited and it was difficult to clarify the behavior of Cs in the solid-phase materials. Therefore, pollucite, which is a Cs aluminosilicate (CsAlSi₂O₆), was used in this study to examine the detailed behaviors of Cs during pyroprocessing.

4.2 Experiments

4.2.1 Materials

Pollucite was synthesized according to process described in a previous study (Kobayashi et al., 1991). The chemical composition of the synthesized pollucite analyzed by XRF analysis is shown in Table 3. The X-ray diffraction (XRD) pattern of the obtained pollucite is shown in Fig. 6. All peaks of the obtained material matched the standard data for cubic pollucite well.

4.2.2 Experimental conditions

As explained in the previous chapters, the addition of CaCl₂ and CaO is important for removing Cs. The combined effects of these additions at a temperature range of 900ºC to 1,100ºC were reported by Jiao et al.

Table 3 Chemical composition of the synthesized pollucite (w/w%).

<table>
<thead>
<tr>
<th>Ig. loss</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>SO₃</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>Cs₂O</th>
<th>P₂O₅</th>
<th>Cl</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.29</td>
<td>37.9</td>
<td>16.3</td>
<td>0.02</td>
<td>&lt;0.01</td>
<td>0.0</td>
<td>&lt;0.01</td>
<td>0.12</td>
<td>0.04</td>
<td>39.7</td>
<td>0.00</td>
<td>0.00</td>
<td>99.81</td>
</tr>
</tbody>
</table>
Experimental study on the mechanism of Cs removal from contaminated soil and incineration ash by pyroprocessing (2018). In this series of experiments, the generation of commercially valuable slag, aggregate, or Portland cement as decontaminated products was examined using an applied temperature reaching 1,450°C.

The chemical composition parameters examined were the Ca/Si and Cl/Cs ratios. The Ca/Si molar ratios were set at 3.3, 2.2 and 1.0, and the Ca/(Si+Al) molar ratios were set at 2.4, 1.6 and 0.72, respectively, with the assumption of the formation of a cement clinker, non-hydration reactive aggregate and slag, respectively. To retain the appropriate amount of liquid phase at the burning temperatures, the Si/(Al+Fe) ratio was also controlled at 2.2, 2.1 and 2.0, respectively, for each of the aforementioned products.

To adjust the chemical compositions for each purpose, reagent-grade CaO and CaCl₂, as well as silica sand, were added to the synthesized pollucite. Minor elements such as Fe, Na and K were brought from the silica sand. Under each condition, the Cl/Cs molar ratio was modified to range from 0.0 to 5.0.

Pyroprocessing was carried out using the same rotary furnace described in Sub-section 3.2.1. The heating temperature was 1,450°C, which was maintained for 60 min. The temperature was increased at a rate of 5°C/min. The volatilized materials were recollected in a HEPA filter from the exhaust gas after cooling. Sampling from the HEPA filter was carried out following all experiments, but was not performed for each batch.

4.2.3 Measurements

The chemical compositions of the pyroprocessed materials were measured by XRF. The mineral phase compositions of these materials and the phase changes that occurred during heating were evaluated qualitatively by XRD. To conduct the high-temperature XRD analysis, the temperature was increased at a rate of 10°C/min from 25°C (room temperature) to 1,400°C, and measurements were performed at every 100°C increment. The scanning range of 2θ was from 5° to 65°, and the scanning speed was 50°/min. For observing the formed textures of the pyroprocessed materials, back-scattered electron imaging (BEI) was used. The chemical composition of each phase including element distributions was analyzed by electron probe micro analyzer (EPMA).

4.3 Results

4.3.1 Cs Volatilization Behaviors

The effects of the Cl/Cs ratio on the ratio of Cs remaining at different Ca/Si ratios after pyroprocessing at 1,450°C are shown in Fig. 7. The Cl/Cs ratio affects the ratio of Cs remaining differently at different Ca/Si ratios. Without the addition of Cl (i.e., at a 0.0 Cl/Cs molar ratio), a higher Ca/Si ratio resulted in a lower ratio of Cs remaining, as was expected.

At a Ca/Si ratio of 1.0, without added Cl, almost of all the Cs remained in the solid phase. By increasing the Cl/Cs ratio from 0 to 1.0, the ratio of Cs remaining was decreased to 3%.

At a Ca/Si ratio of 2.2, the effects of Cl/Cs were limited to the range of less than 0.4. With an increase in the Cl/Cs ratio to 0.6, the ratio of Cs remaining decreased from 16 to 8%. When the Cl/Cs ratio was increased to 1.1, the ratio of Cs remaining became less than 0.06%.

When the Ca/Si ratio was 3.4, even without the addition of Cl, the ratio of Cs remaining was 4.8%, and it decreased to less than 0.06% at a Cl/Cs ratio of 1.0.

Therefore, a higher Ca/Si ratio resulted in a lower ratio of Cs remaining, as was expected.

4.3.2 Phases Generated after Pyroprocessing

To investigate the reactions occurring during pyroprocessing, the phase composition was evaluated via XRD. The material obtained in the filter system of the exhaust gas after all experiments was pure CsCl, as shown in Fig. 8. This finding, however, does not deny the possibility of Cs₂O formation because Cs₂O reacts strongly with water to form CsOH. Because CsOH is highly deliquescent, it is difficult to detect via XRD.
Figure 9 shows the XRD patterns of the pyroprocessed materials at 1,450°C. At a Ca/Si ratio of 3.4 (Fig. 9(a)), the original pollucite content was reduced to zero for all Cl/Cs ratios, and typical clinker minerals such as Ca₃SiO₅ and β-Ca₂SiO₄ were identified. Hereafter, chemical compositions are described in total, such as Ca₃SiO₅, and not as separate components such as 3CaO·SiO₂. The phase composition of the interstitial phase, however, varied with the Cl/Cs ratio. At Cl/Cs ratios of 0 and 1, Ca₁₂Al₁₄O₃₂Cl₂ was identified, while at a ratio of 5, Ca₁₂Al₁₄O₃₂Cl₂ was identified.

Figure 9(b) shows the XRD patterns for a Ca/Si ratio of 2.2. At all Cl/Cs ratio values, the original pollucite content disappeared while the identified mineral compositions differed depending on the Cl/Cs ratio. Without the addition of Cl, the major phases identified were β-Ca₂SiO₄ and Cs₂Ca₂Al₈O₁₅. As the Cl/Cs ratio increased to 1.0, the crystalline form of Ca₃SiO₅ changed from β to γ. This is suitable for use as a pyroprocessed product such as a non-hydration-reactive aggregate. Moreover, the phase containing Cs disappeared as expected from Fig. 7 and Ca₁₂Al₁₄O₃₂Cl₂ was detectable. At a higher Cl/S ratio (5.0), the crystalline form of Ca₃SiO₅ changed from γ to β. Without the amount of this form decreased compared to Fig 9(a). The interstitial phase, Ca₃Al₂O₆, was identified as possessing an amorphous phase, which was suggested by a hollow region at 2θ ≈ 32°.

Figure 9(c) shows the XRD patterns at a Ca/Si ratio of 1.0. Without the addition of Cl, a limited amount of Ca₃SiO₅ (in different crystalline forms from Figs. 9(a) and 9(b)) formed, while the majority of the material was unreacted pollucite as expected from Fig. 7. The crystalline form of pollucite changed from a cubic stable state at room temperature to an orthorhombic stable state at higher temperatures. With the addition of increasing amounts of Cl, only the amorphous phase without any crystalline phases was detected.

Figure 8 XRD pattern of material collected from the exhaust gas filter.
4.3.3 Decomposition of Pollucite with Increasing Temperature

The decomposition of pollucite and phase changes were dependent on both the Ca/Si and Cl/Cs ratios. To understand the decomposition behaviors of pollucite, high-temperature XRD analysis was utilized for several combinations of Ca/Si and Cl/Cs ratios and the obtained results are shown in Fig. 10, showing only the major peak of pollucite.

At a Ca/Si ratio of 3.4 and a Cl/Cs ratio of 1.0, the pollucite peak disappeared at 1,000°C with a slight shift at 900°C. When the Ca/Si ratio was decreased to 2.2 at a similar Cl/Cs ratio, the peak remained until 1,100°C. Therefore, a greater Ca content facilitates the decomposition of pollucite at lower temperatures. When the Cl/Cs ratio was decreased to 0.6, the peak remained until 1,300°C, even at a Ca/Si ratio of 3.4. In the case of a Ca/Si ratio of 2.2, we observed a peak shift at 900°C, but the peak remained until 1,300°C. Cl may therefore also play an important role in the decomposition of pollucite.

4.3.4 Textures of Mineral Phases after Pyroprocessing

Considering the observed Cs removal behaviors and phase changes analyzed by XRD, we carried out direct observations and compositional analysis of the textures of the mineral phases formed after pyroprocessing.

Figure 11 shows a BEI of the pyroprocessed material at a Ca/Si ratio of 3.4 and a Cl/Cs ratio of 0. Three major phases are indicated: many rectangular and small, rounded gray particles; small, round white spots within the gray particles, and a darker matrix. Figure 12 shows the EPMA mapping of the same area. As indicated, the white spots correspond to high concentrations of Cs.
The chemical compositions of these three phases analyzed by EPMA are shown in Table 4. From the analysis data and with utilization of the major elements, the molar ratios are also indicated. Point A of the rectangular phase is considered to be Ca$_3$SiO$_5$, the major clinker phase. Point B of the matrix is essentially considered to be Ca$_3$Al$_2$O$_6$, as estimated from the results of XRD, but 5 mol % of aluminate is replaced with silicate. The white spots (C) indicate cesium calcium aluminosilicate. From the texture of the region surrounded by Ca$_3$SiO$_5$, the white spots may be remnants of the original pollucite particles that decomposed during pyroprocessing. Because of the limited area of these spots, no clear diffraction pattern could be obtained by XRD. From Fig. 7, 4.8 w/w% of Cs remained after pyroprocessing. Judging from the texture shown in Fig. 11, the reason Cs remained can be surmised as Cs bearing phases remained in the crystalline 3CaO.SiO$_2$ phases and Cs was prevented from volatilizing but not as an issue of phase equilibrium. Therefore, if the raw materials are ground finer, the ratio of Cs remaining may decrease more.

Figure 13 shows a BEI analysis of the pyroprocessed material at a Ca/Si ratio of 2.2 and a Cl/Cs ratio of 0. Figure 14 shows an EPMA mapping of the same area. From these figures, three phases can be distinguished: large gray rounded particles, white rectangular grains at the grain boundary of the gray particles, and a small amount of a dark matrix. In Table 5, the chemical compositions of these phases are shown. Points A, B and

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Chemical compositions of the three phases (A, B, and C) shown in Fig.11 (upper: w/w%; lower: mol %).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>SiO$_2$</td>
</tr>
<tr>
<td>A</td>
<td>25.26</td>
</tr>
<tr>
<td>B</td>
<td>4.61</td>
</tr>
<tr>
<td>C</td>
<td>13.96</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Position</th>
<th>SiO$_2$</th>
<th>CaO</th>
<th>Al$_2$O$_3$</th>
<th>Cs$_2$O</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>24.5</td>
<td>75.0</td>
<td>0.5</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td>B</td>
<td>5.5</td>
<td>74.2</td>
<td>20.3</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td>C</td>
<td>17.8</td>
<td>60.6</td>
<td>16.6</td>
<td>5.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Fig. 13 BEI of the pyroprocessed material (Ca/Si ratio = 2.2, Cl/Cs ratio = 0).

Fig. 14 EPMA mapping of elements (same area as indicated in Fig. 11; warm colors such as white or pink indicate higher concentrations).
C, indicating the white grains, have similar chemical compositions and are considered to be cesium calcium aluminate. We identified CsCaAlO$_3$ from XRD fitting, while the results obtained by EPMA differed. This phase may be some solid solution of different Cs/Ca ratios. The compound cesium calcium aluminate is therefore thought to have formed from the pollucite, CsAlSi$_2$O$_6$. The Cs containing phase was transformed from aluminosilicate to calcium aluminate. There are two types of gray particles in different crystalline phases indicated from the results obtained by XRD and represented as the same chemical composition of CaSiO$_3$ by points D and E. Point F in the dark matrix indicates Ca$_2$Al$_2$O$_5$ gehlenite, but the quantity was limited and undetectable by XRD.

Figure 15 shows a BEI of the pyroprocessed material at a Ca/Si ratio of 3.4 and a Cl/Cs ratio of 5. Figure 16 shows an EPMA mapping of the same area. From these figures, three phases can be distinguished: gray

### Table 5 Chemical compositions of the six points indicating the two phases (A, B, C, D, E, and F) shown in Fig. 13 (upper: w/w%; lower: mol%).

<table>
<thead>
<tr>
<th>Position</th>
<th>SiO$_2$</th>
<th>CaO</th>
<th>Al$_2$O$_3$</th>
<th>FeO$_3$</th>
<th>MgO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>Ca$_2$O</th>
<th>P$_2$O$_5$</th>
<th>Cl</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.59</td>
<td>18.53</td>
<td>38.82</td>
<td>0.20</td>
<td>0.08</td>
<td>0.15</td>
<td>0.12</td>
<td>26.45</td>
<td>0.03</td>
<td>0.01</td>
<td>84.97</td>
</tr>
<tr>
<td>B</td>
<td>1.59</td>
<td>17.88</td>
<td>39.37</td>
<td>0.18</td>
<td>0.00</td>
<td>0.25</td>
<td>0.08</td>
<td>26.13</td>
<td>0.00</td>
<td>0.00</td>
<td>85.48</td>
</tr>
<tr>
<td>C</td>
<td>0.83</td>
<td>17.83</td>
<td>39.82</td>
<td>0.19</td>
<td>0.09</td>
<td>0.22</td>
<td>0.14</td>
<td>26.98</td>
<td>0.01</td>
<td>0.00</td>
<td>85.21</td>
</tr>
<tr>
<td>D</td>
<td>33.02</td>
<td>63.94</td>
<td>1.01</td>
<td>0.07</td>
<td>0.18</td>
<td>0.04</td>
<td>0.03</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
<td>98.33</td>
</tr>
<tr>
<td>E</td>
<td>32.55</td>
<td>64.57</td>
<td>1.14</td>
<td>0.04</td>
<td>0.16</td>
<td>0.04</td>
<td>0.02</td>
<td>0.00</td>
<td>0.07</td>
<td>0.00</td>
<td>98.60</td>
</tr>
<tr>
<td>F</td>
<td>5.37</td>
<td>45.11</td>
<td>38.63</td>
<td>0.62</td>
<td>1.75</td>
<td>0.22</td>
<td>0.08</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>91.79</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Position</th>
<th>SiO$_2$</th>
<th>CaO</th>
<th>Al$_2$O$_3$</th>
<th>Cs$_2$O</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.2</td>
<td>40.5</td>
<td>46.7</td>
<td>11.5</td>
<td>100.0</td>
</tr>
<tr>
<td>B</td>
<td>3.2</td>
<td>38.7</td>
<td>46.9</td>
<td>11.2</td>
<td>100.0</td>
</tr>
<tr>
<td>C</td>
<td>1.7</td>
<td>38.9</td>
<td>47.8</td>
<td>11.7</td>
<td>100.0</td>
</tr>
<tr>
<td>D</td>
<td>32.3</td>
<td>67.1</td>
<td>0.6</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td>E</td>
<td>31.8</td>
<td>67.6</td>
<td>0.7</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td>F</td>
<td>7.0</td>
<td>63.2</td>
<td>29.8</td>
<td>0.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Fig. 15 BEI of the pyroprocessed material (Cs/Si ratio = 3.4, Cl/Cs ratio = 5).

Fig. 16 EPMA mapping of elements (same area as shown in Fig. 15; warm colors such as pink or red indicate higher concentrations).
rectangular particles, darker gray dendritic particles and a bright matrix. Table 6 shows the chemical compositions of these phases. Point A, indicating gray rectangular particles, represents Ca₃SiO₅. Point B, indicating darker gray particles, represents Ca₃SiO₅. Point C, indicating the bright matrix, represents calcium chloroalumino-silicate. From the results obtained by XRD analysis, this phase was identified as Ca₁₂Al₁₄O₃₂Cl₂, although the actual chemical composition was found to contain a greater amount of Cl, and some Al₂O₃ was replaced by SiO₂.

Figure 17 shows a BEI of the pyroprocessed material at a Ca/Si ratio of 2.2 and a Cl/Cs ratio of 5. Figure 18 shows an EPMA mapping of the same area. From these figures, four phases can be distinguished: small amounts of a dark phase between the interparticle spaces; gray, round particles; and darker-gray, irregularly shaped particles showing exsolution and a bright matrix. In Table 7, the chemical compositions of these phases are shown. Point A, indicating the dark phase, represents calcium chloroalumino-silicate (Ca₁₂Al₁₄O₃₂Cl₂) as detected by the XRD analysis, but with a greater Cl content. Point B, indicating a gray round particle, represents Ca₃SiO₅. Point C, indicating a darker-gray, irregularly shaped particle, represents calcium chloroalumino-silicate with a low Cl content. According to the texture of these particles, they may be composed of multiple phases such as Ca₃SiO₅ and Ca₁₂Al₁₄O₃₂Cl₂. Point D, indicating the bright matrix, also represents calcium chloroalumino-silicate, but with a lower aluminate content and greater silicate content as compared with point A. This phase is surmised to be an amorphous phase, as detected by XRD.

**Table 6** Chemical compositions of the three phases (A, B, and C) shown in Fig. 15 (upper: w/w%; lower: mol%).

<table>
<thead>
<tr>
<th>Position</th>
<th>SiO₂</th>
<th>CaO</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>Cs₂O</th>
<th>P₂O₅</th>
<th>Cl</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>25.30</td>
<td>73.14</td>
<td>0.51</td>
<td>0.01</td>
<td>0.23</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.06</td>
<td>0.04</td>
<td>99.30</td>
</tr>
<tr>
<td>B</td>
<td>32.08</td>
<td>64.04</td>
<td>0.99</td>
<td>0.01</td>
<td>0.10</td>
<td>0.00</td>
<td>0.02</td>
<td>0.00</td>
<td>0.09</td>
<td>0.23</td>
<td>97.56</td>
</tr>
<tr>
<td>C</td>
<td>8.03</td>
<td>61.35</td>
<td>9.11</td>
<td>0.28</td>
<td>0.00</td>
<td>0.00</td>
<td>0.05</td>
<td>0.00</td>
<td>0.03</td>
<td>26.31</td>
<td>105.17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Position</th>
<th>SiO₂</th>
<th>CaO</th>
<th>Al₂O₃</th>
<th>Cl</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>24.3</td>
<td>75.3</td>
<td>0.3</td>
<td>0.1</td>
<td>100.0</td>
</tr>
<tr>
<td>B</td>
<td>31.6</td>
<td>67.5</td>
<td>0.6</td>
<td>0.4</td>
<td>100.0</td>
</tr>
<tr>
<td>C</td>
<td>6.5</td>
<td>53.1</td>
<td>4.3</td>
<td>36.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**Fig. 17** BEI of the pyroprocessed material (Cs/Si ratio = 2.2, Cl/Cs ratio = 5).

**Fig. 18** EPMA mapping of elements (same area as shown in Fig. 17; warm colors such as white, pink and red indicate higher concentrations).
4.4 Discussion

To achieve removal of Cs from pollucite, this material must first be decomposed. The Ca/Si, Ca/(Si+Al), and Cl/Cs ratios affect the decomposition process; higher values of these quantities result in more advanced decomposition. At low Ca/Si ratios and without Cl, pollucite is stable and no Cs is removed. When the Ca/Si ratio is adequately high, a Cl/Cs ratio of 1.0 is effective for the complete removal of Cs. However, as the Cl/Cs ratio is increased at a low Ca/Si ratio, a Cl-containing glass phase forms and alkali metals including Cs may dissolve into this phase, thereby preventing the complete removal of Cs. These complicated phenomena are related to the formation of different mineral phases depending on the Ca/Si and Cl/Cs ratios. Therefore, the addition of too much Cl may produce undesired results; an appropriate amount of Cl is recommended for use at high Ca/Si ratios.

In Section 3.2, we showed that Cs was removed to undetectable levels from pond deposits without the addition of Cl. A significant amount of Cs resulting from pollucite remained, however. This difference may be accounted for by the existence of potassium. Considering the samples examined in Section 3.2, we included around 1 w/w% of potassium and determined the amount of Cl using the Cl/K ratio. This means that Cl/Cs is in excess, and the excess Cl volatilizes as KCl and no glass phase forms. Potassium acts as an accelerant in Cs removal.

Cs removal under high Ca/Si ratio conditions may be achieved by simple volatilization of CsO, but Cl volatilization is not always required. Considering the experimental results, we consider a higher Ca/Si ratio to be preferential for the efficient removal of Cs.

5. Conclusions

We discussed efficient conditions for Cs removal from radioactive solids contaminated by r-Cs, such as soil and incineration ashes, via pyroprocessing. After decontamination, the resulting materials may be preferentially used for other purposes. Therefore, a target Ca/(Si+Al) ratio was used to produce slag and Portland cement.

The dependence of the Cs removal efficiency on the Ca/(Si+Al) ratio was shown on the basis of data obtained from the literature. The highest Ca/(Si+Al) ratio could be realized in the system producing Portland cement. The optimal conditions of pyroprocessing were then examined. We showed that higher temperatures and a higher Cl/K ratio are preferential for Cs removal from various contaminated wastes. All kinds of alkali metals were removed with different efficiency, and Cs levels were reduced preferentially, with the ease of volatilization following the order of Cs > K > Na at 1450°C, even without the addition of Cl. Potassium in the target subjects is considered to act as an accelerant for the removal of Cs.

The effects of the Ca/Si and Cl/Cs ratios on mineral-phase changes were analyzed through experiments using pollucite. A higher Ca/Si ratio was observed to facilitate the decomposition of pollucite and the efficient removal of Cs.

Acknowledgment

This study was conducted in collaboration with the National Institute for Environmental Studies, Taiheiyo Cement Corp., and the National Agriculture and Food Research Organization.

The discussion with Mr. Kenichi Honma of Taiheiyo Cement Corp. was very helpful to summarize this study.

References:


Kazuo YAMADA

As a materials scientist with a specialty in cement-related materials, Kazuo Yamada, who holds a doctorate of engineering, works at the Wastes and Material Cycles Research Section of the Fukushima Regional Collaborative Research Center, National Institute for Environmental Studies (NIES). He joined NIES in 2012 and has worked on technologies for reducing the volume of contaminated soil and waste, and on safe disposal of concentrated wastes in concrete facilities. He is also active in the Society of Remediation of Radioactive Contamination in the Environment as secretary of a research committee on technological strategies for final disposal of nuclear waste material out of Fukushima.

Kazuhiko TOKOYODA

Kazuhiko Tokoyoda holds a master of engineering. He was formerly a special researcher at NIES’ Fukushima Branch (currently renamed the Fukushima Regional Collaborative Research Center). He is a mechanical/chemical engineer with experience in the construction and operation of various production facilities at Taiheiyo Cement Corp. spanning more than 20 years. He joined NIES in 2017 and has worked there for three years, focusing especially on optimization and mechanism analysis of Cs volatilization by pyroprocessing in Portland cement production systems.

Masahiro OSAKO

Masahiro Osako, who holds a doctorate of engineering, serves as director of the Material Cycles Division, National Institute for Environmental Studies (NIES). His specialty is environmental engineering, focusing on waste management. Since the Fukushima nuclear accident that resulted from the Great East Japan Earthquake in 2011, he has been dedicated not only to conducting various researches to properly manage radioactively contaminated wastes but also to playing an important role in the relevant policy-making by the national government. He also chairs the research committee on technological strategies for the final disposal out of Fukushima in the Society of Remediation of Radioactive Contamination in the Environment.
Insolubilization of Cesium Contained in Fly Ash by Co-heating with Potassium Feldspar

Yasumasa Tojo

Graduate School of Engineering, Hokkaido University
N13 W8, Kita-ku, Sapporo, Hokkaido, 060-8628, Japan
*E-mail: tojo@eng.hokudai.ac.jp

Abstract

At present, reducing the volume of decontamination wastes/soils is an indispensable task in Japan because to secure final disposal sites with vast capacity is considered difficult. One promising option is thermal treatment to separate radioactive cesium (Cs) from wastes/soils. This, however, generates Cs concentrates in which Cs is thought to have high solubility. From a long-term viewpoint on ensuring safety, the solubility of Cs itself in the concentrates should be reduced even though it will be stored in containers. In this study, insolubilization of Cs by co-heating with potassium feldspar (hereafter, K-feldspar) was investigated. This process can insolubilize almost 100% of Cs when only Cs carbonate and K-feldspar are co-heated. However, concentrates in actuality consist mainly of fly ash and contain various elements. Thus the objective of this study was to elucidate the influence of the presence of fly ash. In particular, elements that inhibit Cs capture were focused on. Various co-heating experiments on mixtures of CsCl, K-feldspar, fly ash and alkali metal compounds were conducted. As a result, the following findings were obtained: 1) the efficiency of Cs insolubilization decreased in the presence of fly ash, 2) Ca in fly ash inhibited Cs insolubilization. Notably, when Ca was in chloride form, this inhibition was at a maximum, 3) converting CaCl₂ in fly ash to CaCO₃ by use of Na₂CO₃, improved the efficiency of Cs insolubilization. When the ratio of fly ash to K-feldspar was increased, however, the efficiency showed a gradual decrease.

Key words: cesium, decontamination waste, fly ash, insolubilization, K-feldspar

1. Introduction

After the nuclear accident in 2011, various decontamination activities were carried out in the region affected by radioactive fallout. As a consequence, huge amounts of contaminated wastes and other substances were generated, the majority of which were incineration ash from combustible wastes and soil removed during decontamination of environments. It is estimated that the amount of wastes and soils generated through decontamination activities was about 14 million m³ (Ministry of the Environment, Japan, 2019). There are plans to store these wastes at interim storage sites for 30 years hereafter and then they are to be disposed of at a final disposal site. It is thought, however, that to find and secure a suitable site with vast capacity will be extremely difficult because of opposition from residents. Therefore, the government is planning to reduce the volume/mass of these wastes/soils. First, soils of low radioactivity will be utilized as construction material. The remainder, 380 thousand tons that cannot be thus utilized, will be subjected to thermal treatment to separate out radioactive cesium (Cs). After treatment, soils/wastes from which Cs has been removed are to be used as construction materials at interim storage sites. On the other hand, however, residues with highly concentrated Cs will be generated simultaneously as a byproduct. The residues (mainly composed of fly ash) are planned to be stored in rigid containers with sufficient durability for long-term storage. From various previous studies, it has been reported that Cs in fly ash generated from many municipal solid waste (MSW) incinerators after the accident is soluble because most of it is in chloride form (National Institute of Environmental Studies, 2012). Cs concentrates produced through thermal treatment of decontamination wastes are thought to have the same characteristics, since some volatilization acceleration agents (such as CaCl₂) are added during the heating process for Cs separation (Kamata, 2015; Abe, 2015). Thus, from a long-term viewpoint on securing safety related to leakage of Cs from stabilized fly ash bodies after thermal treatment, it would be better to insolubilize Cs.

Past studies (Saffarzadeh, 2014; Dote, 2014; Tojo, 2016) have clarified that Cs in bottom ash is hardly soluble at all unlike Cs in fly ash. The authors investigated why Cs in bottom ash is insoluble and...
revealed that Cs in bottom ash is captured in an amorphous phase formed around a specific oxide mineral composed of K, Al and Si. That mineral was identified as potassium feldspar (KAlSi₃O₈) (hereafter, K-feldspar) (Tamura, 2016). The surface of K-feldspar particles, when heated at 700°C to 900°C in the presence of Cs, melts and captures Cs in the amorphous melt phase, making the Cs insoluble. In order to reproduce this capturing mechanism, the authors mixed K-feldspar with Cs₂CO₃ and heated the mixture at 900°C. As a result, nearly 100% of the Cs remained in the sample after heating in an insoluble state, and particles with Cs concentrated in the peripheral region (white region around the particle in back-scattered electron images (BEI) or bright part in Cs mapping images in energy dispersive spectrographs) were found as shown in Fig. 1 (Sakamoto, 2017). When the Cs compound was changed to CsCl, however, the efficiency of insolubilization drastically decreased. (Hereafter, the term “insolubilization efficiency” is used to express the ratio of insolubilized Cs, which cannot be extracted by water after co-heating, to the initial amount of Cs.) Thus, the effects of pretreatment of K-feldspar and optimum heating temperature was further examined. Grinding K-feldspar as a pretreatment, resulting in amorphization of K-feldspar by grinding it over long periods, significantly increased insolubilization efficiency even if the Cs was in CsCl form. Additionally, a 700°C heating temperature produced the highest insolubilization efficiency.

As mentioned above, the previous studies had been conducted mainly under pure conditions (only feldspar and Cs compounds present). However, the actual Cs concentrates generated from thermal processing of soils/wastes from decontamination activities, are deemed to contain many other elements. Therefore, it is crucial to confirm whether Cs insolubilization by K-feldspar works when fly ash containing various other elements is present. If any element interferes with Cs insolubilization, the reason should be elucidated. In addition, measures to prevent such interference must be developed. Therefore, in this study, the following objectives were set: 1) to confirm the influence of fly ash on the insolubilization efficiency of Cs, 2) to identify substances contained in fly ash that interfere with Cs insolubilization and 3) to develop a method to prevent such interference. Concretely, the following experiments were performed.

First, co-heating experiments using mixtures of fly ash, CsCl and K-feldspar were conducted to confirm the influence of fly ash on Cs capture. From the co-heating experiments above, increasing the ratio of fly ash to K-feldspar resulted in decreased Cs insolubilization efficiency. To elucidate the reason, a pure system free of fly ash was set up and the effects of alkali elements on Cs insolubilization were examined. The reason alkali elements were focused on was that this Cs capturing (and insolubilization) is thought to be related to the charge balancing ability of cations in K-feldspar’s matrix. In K-feldspar (KAlSi₃O₈), part of the Si⁺ in the silicate (SiO₄ tetrahedral matrix) is substituted with Al³⁺. Potassium is present to compensate for the positive charge deficiency. In albite (NaAlSi₃O₈), Na plays this role and in anorthite (CaAl₂Si₂O₈), Ca plays it. Cs is also a monovalent alkali element. In this study, the capture was considered to occur mainly through replacement of the “K” in K-feldspar by Cs. Thus, what may interfere with this replacement was thought to be alkali elements which can behave similarly. Thus, Na, K, and Ca were selected. An additional reason was that they are contained in large amounts in fly ash.

From co-heating experiments using certain alkali salts, it was found that the proportion of insoluble Cs was particularly low when using CaCl₂. Therefore, subsequent experiments were conducted to confirm whether specifically only CaCl₂ interferes with Cs insolubilization or the presence of Ca itself interferes, by trying Ca(OH)₂ and CaCO₃. The reason these two compounds were selected as the Ca compounds was that fly ash generally contains slaked lime (Ca(OH)₂) blown in for hydrogen chloride removal, and CaCO₃ is produced as a neutralization product. Furthermore, Ca(OH)₂ reacts with CO₂ in the air relatively easily in the presence of water, converting to CaCO₃.

From the above experiments, it was found that only CaCl₂ causes a decrease in Cs insolubilization efficiency. Therefore, it was thought that by replacing the CaCl₂ in fly ash with other Ca compounds interference in Cs insolubilization could be avoided. Therefore, a few pretreatment methods to change the form of Ca were examined.

2. Materials and Methods

2.1 Materials

2.1.1 Fly Ash

MSW fly ash was obtained from an MSW incinerator (stoker type). If it had been possible, it would have been better to use fly ash generated from an actual thermal treatment process for decontamination soils/wastes, but...
no full-scale plants were in operation yet, so its characteristics were not known. Thus, MSW fly ash was used as an alternative. Table 1 gives the elemental composition of the fly ash as determined by X-ray fluorescence (XRF) analysis (Horiba MESA-500). Since the Cs concentration in the MSW fly ash was too low to analyze after co-heating experimentation, the Cs content of the fly ash was artificially increased by adding CsCl (hereafter, this fly ash is termed as “Cs-fly ash”). For Cs, stable Cs was used.

2.1.2 K-feldspar

For K-feldspar, Indian feldspar (Quantum®, ceramic grade potassium feldspar CAS# 68476-25-5) purchased from a ceramics raw material supplier (Nittorengenyo Co., Ltd) was used. According to an XRD (X-ray Diffraction) analysis and phase identification by Match! Co., Ltd) was used. According to an XRD (X-ray Diffraction) analysis and phase identification by Match! EVO-II (Rigaku) was used. The heating temperature was set at 700°C.

2.2 Methods

2.2.1 Confirmation of the Influence of Fly Ash on Cs Insolubilization by K-feldspar

Three grams of pretreated K-feldspar were added to Cs-fly ash. The amount of CsCl in the Cs-fly ash was fixed at 0.6 g and the amount of fly ash was varied from 0 to 2.0g. In other words, the influence of fly ash under ratios of fly ash to K-feldspar of from 0 to 0.67 was examined. A sample without K-feldspar was also prepared. Then, the mixture was put into a ceramic combustion boat and heated in a tubular electric furnace for 2 h. The temperature was set at 700°C.

2.2.2 Identification of Substances in Fly Ash that Interfere with Cs Insolubilization

Five grams of pretreated K-feldspar were added to 1g of CsCl reagent and 1g of powdered reagent of either NaCl, KCl or CaCl₂. Then they were mixed well using a mortar and pestle. The mixed sample was placed in a crucible and heated in a muffle furnace for 2 h. The heating temperature was set at 700°C.

After heating, the sample was removed after the temperature in the furnace became sufficiently low, and transferred to a desiccator to cool further. The cooled sample was treated in the order of water washing and hydrofluoric acid digestion to quantify soluble Cs and insoluble Cs. Among the added Cs, the portion which could not be detected in the solutions obtained by either water washing or acid digestion was regarded as volatilized Cs.

2.2.3 Interference by Ca in Cs Insolubilization from Different Ca Compound Forms

Five grams of pretreated K-feldspar were added to 1 g of CsCl reagent and 1 g of powdered reagent of Ca compound (i.e., Ca(OH)₂ or CaCO₃). Then they were mixed well using a mortar and pestle. The procedures of heating and subsequent chemical analysis were the same as described above in Sub-section 2.2.2. In this experiment, analysis of Ca was also performed on the solution obtained by washing and acid digestion to confirm the form of Ca after heating. Thermogravimetric analysis was also carried out to elucidate the behavior of each Ca compound in the heating temperature range of this experiment. For TG-DTA analysis, a Thermo plus EVO-II (Rigaku) was used.

2.2.4 Pretreatment of Fly Ash to Change the Form of Ca to Prevent Interference

To make Cs-fly ash, the amount of fly ash was set at 0.75 g, 1.12 g and 2.24 g. To each of these three fly ashes, 1g of CsCl reagent was added. Thus three types of Cs-fly ash were prepared. For the co-heating experiment, pretreated K-feldspar was used.

Three pretreatment methods were examined:

- Adding water to the Cs-fly ash to dissolve the CaCl₂,


<table>
<thead>
<tr>
<th>Element</th>
<th>Ca</th>
<th>Cl</th>
<th>Na</th>
<th>K</th>
<th>Zn</th>
<th>Si</th>
<th>S</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content (wt%)</td>
<td>40.1</td>
<td>32.3</td>
<td>10.3</td>
<td>8.1</td>
<td>2.3</td>
<td>2.3</td>
<td>2.0</td>
<td>2.6</td>
</tr>
</tbody>
</table>

• Moistening the Cs-Fly ash and exposing it to a CO₂ gas environment for 48 hours to form CaCO₃.
• Adding Na₂CO₃ to the Cs-fly ash with water, dissociating Ca from CaCl₂ to form CaCO₃. This carbonation reaction can be expressed as [CaCl₂ + Na₂CO₃ = CaCO₃ + 2NaCl].

The water-added sample was subjected directly to heating with 5 g of pretreated K-feldspar. For Cs-fly ash subjected to carbonation with CO₂ gas or carbonation with Na₂CO₃, the sample was dried after treatment and then mixed with 5 g of pretreated K-feldspar. Then these mixtures were heated in a furnace at 700°C for 2 h. After heating, the sample was subjected to water washing and acid digestion to determine the ratio of soluble and insoluble Cs by the same methodology as described above in Sub-section 2.2.2. In addition, the residue after washing was examined by SEM-EDS (JSM-6360LA (JEOL)) to confirm the presence of insoluble Cs.

3. Results and Discussion

3.1 Influence of Fly Ash on Cs Insolubilization by K-feldspar

Figure 2 shows the ratios of insoluble Cs and soluble Cs after co-heating of K-feldspar with Cs-fly ash. The horizontal axis shows the amount of fly ash added to the 3 g of K-feldspar. Although more than 90% of the Cs became insoluble when no fly ash was present, the ratio of insoluble Cs decreased drastically as the amount of fly ash was increased. When the amount of fly ash was almost half that of the feldspar (i.e., amount of fly ash of 2.0 on the horizontal axis), the ratio of insoluble Cs decreased to less than 40%. To secure more than 80% insoluble Cs, the mass of the fly ash must be only 10% that of the feldspar. From this result, it can be said that the presence of fly ash reduces the ratio of insolubilized Cs.

3.2 Substances in Fly Ash that Interfere with Cs Capture and Insolubilization

Figure 3 shows the results of the experiment in which three types of alkali salts were used to confirm their influence on Cs insolubilization by co-heating with feldspar. The vertical axis indicates the ratio of soluble, insoluble and volatilized Cs to the total amount of Cs added. When NaCl, KCl and CaCl₂ were mixed and co-heated, the ratio of insoluble Cs decreased compared to the case in which no alkali salt was added. In particular, the ratio of insoluble Cs decreased significantly when CaCl₂ was added. Therefore, it was thought that the decrease in the ratio of insoluble Cs confirmed in the co-heating experiment conducted in Section 3.1 above was mainly attributable to Ca in the fly ash.

3.3 Identification of Ca Compounds that Inhibit Cs Insolubilization

Figure 4 shows the ratio of Cs in the sample after heating when CaCO₃ or Ca(OH)₂ was added as a Ca compound. For comparison, the results with CaCl₂ and without any Ca compound are also shown. Compared to

![Fig. 2](image-url) Changes in the ratio of insolubilized Cs resulting from addition of fly ash in co-heating with K-feldspar.

![Fig. 3](image-url) Ratios of Cs forms after co-heating with CsCl, K-feldspar and each alkali salt.

![Fig. 4](image-url) Ratios of Cs forms after co-heating with CsCl, K-feldspar and each Ca compound.
the ratio obtained in the case of adding CaCl₂, no significant decrease in the ratio of insoluble Cs was confirmed with the addition of CaCO₃ or Ca(OH)₂. That is, it is thought that the decrease in insoluble Cs was mainly due to CaCl₂ in the fly ash. It is inferred that this is related to the state of the Ca compound at the heating temperature used in this study (i.e., 700°C).

The ratio of Ca forms after the co-heating experiments is shown in Fig. 5. The ratio was calculated based on recovered amounts, i.e., the sum of the soluble fraction and insoluble fraction was regarded as 100%. When CaCl₂ was used as the Ca source, the ratio of insoluble Ca was low, and the majority of the added Ca was soluble. On the other hand, when CaCO₃ or Ca(OH)₂ was used as the Ca source, most was in an insoluble form and there was almost no soluble Ca. That is, when CaCl₂ was added and co-heated with K-feldspar and CsCl, most of both the Cs and Ca existed in a soluble form in the sample after heating. Thus, it is thought that the fact that both Ca and Cs remained in the soluble state even when heated at 700°C was related to inhibition of Cs insolubilization.

The phenomenon of Cs capture and insolubilization by K-feldspar applied in this study is most efficient around 700°C. The reason for this is thought to be as follows: the melting point of CsCl is 645°C. Based on Bowen’s Reaction Series, which describes formation steps of minerals from magma, K-feldspar is formed at around 750° to 800°C (Earle, 2019). This means that at around this temperature range, K-feldspar has both a solid phase and melt phase. In a state in which both CsCl and K-feldspar melt and both K and Cs can become readily mobile, substitution of Cs and K is thought to occur. Since Cs has a higher charge balancing ability than K (Hess, 1991), the K in K-feldspar is replaced by Cs, and Cs is as consequence captured in the melt phase and insolubilized. There is a big difference in their ion radii, however. Cs cannot enter into the crystal matrix of K-feldspar. The author thinks this is why Cs is captured in the glassy amorphous phase created at the surface of the feldspar particle as indicated in Fig. 1.

If this phenomenon is inhibited by Ca, there is a possibility that the Ca in CaCl₂ is also likely to move when heated at 700°C, similar to Cs and K. Figure 6 shows the results of a thermogravimetric analysis of the Ca(OH)₂, CaCO₃, and CaCl₂ used in this study.

In the case of Ca(OH)₂ in Fig. 6(a), a significant decrease in TG and an endothermic peak in the DTA can be confirmed above 400°C. This is because Ca(OH)₂ is thermally decomposed as it approaches 580°C and becomes CaO. The reaction of CaO with KAlSi₃O₈ to...
form compounds such as CaAl₂Si₂O₈ is said to be a general reaction in the cement manufacturing process (Arai, 1990). That is, the mobility of Ca is low because Ca(OH)₂ has already been converted to other compounds in the heating temperature range used in this study. Thus, it is thought not to be involved in the Cs capture reaction.

The thermal decomposition temperature (decarbonation temperature) of CaCO₃ is said to be about 890°C. In Fig. 6(b), the decrease in TG is confirmed from around 700°C, and the DTA shows a large endotherm at around 800°C. It is reported that CaCO₃ reacts with Al₂O₃, SiO₂, etc. to form compounds even below the thermal decomposition temperature in the cement clinker formation process (Arai, 1990). Thus, since CaCO₃ also participates in such reactions, CaCO₃ is thought not to inhibit the Cs capture reaction.

In the case of CaCl₂ as shown in Fig. 6(c), there is a decrease in TG and an endotherm before 200°C, which is considered to be due to dehydration of absorbed moisture. The melting point of CaCl₂ is 772°C. In the figure, a gradual decrease from around 700°C in TG and an endotherm at around 770°C are observed. This indicates that CaCl₂ starts melting and the mobility of Ca becomes high in the heating temperature range adopted in this study. That is, in the case of CaCl₂, it only melts around 700°C, and the mobility of Ca becomes high. However, because conversion to other compounds does not occur, it is thought to be involved in the Cs capture reaction.

3.4 Effect of Pre-treatment of Fly Ash on Interference of CaCl₂

Figure 7 shows the ratio of Cs that became insoluble after co-heating of Cs-fly ash with K-feldspar. The ratio of insoluble Cs was 74% when the amount of fly ash was 0.75 g and no pretreatment of the Cs-fly ash was done. This, however, improved to 100% when a carbonation pretreatment for the Cs-fly ash using Na₂CO₃ was conducted. On the other hand, in the case of ionization and CO₂ gas exposure, the efficacy was slightly reduced. Though the results are not shown, from XRD analysis of the samples after pretreatment, a clear increase in the CaCO₃ peak was observed for carbonation with Na₂CO₃, but not for the sample after CO₂ gas exposure. In addition, when a theoretical calculation using PHREEQC (Parkhurst & Appelo, 2013) was performed, no CaCO₃ precipitate was formed through contact of the CaCl₂ solution with CO₂ gas. These results corroborate the observation that only in the case of Na₂CO₃ could an increase in the ratio of insoluble Cs after co-heating be confirmed. When the amount of fly ash was small relative to K-feldspar (K-feldspar 5 g: fly ash 0.75 g), carbonation with Na₂CO₃ was sufficiently effective.

In any pretreatment, however, the ratio of insoluble Cs decreases as the added amount of fly ash is increased. In the carbonation pretreatment with Na₂CO₃, although the amount of Na₂CO₃ was increased according to any increase in the amount of fly ash, there is a possibility that sufficient carbonation of the Ca did not proceed. Alternatively, since inhibition of Na and K on Cs insolubilization was not zero according to the experiments done in 3.2 (as indicated in Fig. 3), the increased amount of Na may also have had an effect. Especially in carbonation by Na₂CO₃, although Ca is converted to carbonate, NaCl is generated in the same reaction. That is, it is thought that increased Na in the system may have contributed to the inhibition of Cs insolubilization.

SEM-EDS images of the particles after water washing of the sample obtained by co-heating of the Cs-fly ash pretreated by carbonation using Na₂CO₃ and pretreated K-feldspar are shown in Fig. 8.

Particles having a high concentration of Cs have the following characteristics; in BEI (Backscattered electron images), the particles have a gray core at the center, a white area surrounding it, and a shell-like gray surface existing outside it. The center is considered to be K-feldspar (KAlSi₃O₈) because it is rich in Al, Si and K, and also no Cl, Ca, and Na are confirmed in the elemental mapping image. The structure in which Cs concentrates around K-feldspar is the same as the concentrating mechanism of Cs identified so far (Fig. 1) (Tojo, 2014; Tamura, 2016; Sakamoto, 2017). That is, Cs is trapped where the feldspar surface melts and becomes glassy and amorphous. A further characteristic newly observed is that the outer surface is rich in Ca or Na. The positions where Cs and Ca or Na concentrate are reciprocal and they are located so as to avoid each other.

4. Conclusions

In this study, aiming to facilitate long-term safe management of Cs concentrate generated from thermal
treatment of decontamination waste, a method of capturing and insolubilizing Cs using K-feldspar was investigated. The insolubilization efficiency of Cs by K-feldspar decreased as the amount of fly ash present was increased. To boost the ratio of insoluble Cs to 80% or more, it was necessary to reduce the amount of fly ash to 10% of the amount of K-feldspar. The salt in fly ash that inhibited Cs insolubilization by K-feldspar was CaCl2. Inhibition by NaCl and KCl was found to be slight compared to that by CaCl2. Besides, no inhibition was identified when CaCO3 or Ca(OH)2 were present. The reason was thought to be the state of CaCl2. The heating temperature applied in this study was 700°C. At this temperature, both K-feldspar and CsCl melt, so replacement of Cs and K, which are both monovalent cations, was likely to occur. Since CaCl2 is also in a molten state at that temperature, the high mobility of Ca is thought to interfere with the substitution reaction of Cs and K. By converting the CaCl2 in fly ash to CaCO3 by pretreatment with Na2CO3, it was possible to avoid inhibition from Ca. When the amount of fly ash was increased, however, the total amount of alkali elements increased and as a result, the Cs insolubilization efficiency gradually decreased. The most significant issue in the management of decontamination waste is to reduce its mass/volume because to secure a final disposal site is extremely difficult. Thus, it will still be necessary to develop a method that realizes a higher insolubilization efficiency of Cs using minimal amounts of K-feldspar even if the total amount of fly ash is increased.

Acknowledgements

This research was supported by the Environment Research and Technology Development Fund (3K153015 and 3-1803 [JPMEERF20183003]) of the Environmental Restoration and Conservation Agency of Japan.

References


Yasumasa Tojo

Yasumasa Tojo is an associate professor at the Solid Waste Disposal Laboratory, Hokkaido University. His main fields of interest are the long-term behavior of substances in landfills, landfill stabilization, insolubilization of hazardous elements, heavy metal leaching from wastes and recycled materials, long-term management of cesium, and landfill management under extreme conditions.

(Received 26 August 2020, Accepted 22 December 2020)
A Study on the Durability of Covering Sheets Used at Temporary Storage Sites in Fukushima Prefecture

Yusuke TAKAHASHI* and Masahiro KOISO

Abstract

The durability of the covering sheets used for storage of decontamination soil and waste at temporary storage sites (TSSs) in Fukushima Prefecture was investigated. In this study, we investigated durability from three viewpoints, accelerated UV exposure tests, comparisons among several municipal TSSs, and material aging. The results indicated that the water resistance of gas-permeable/waterproof sheets (GWSs) used for more than two years at TSSs was much lower than its standard value in many cases, which means the possibility of rainwater intrusion to storage containers holding decontamination soil. On the other hand, the tensile strength and water resistance of the geomembrane used at TSSs remained above the standard values. The results of accelerated UV exposure tests showed no significant damage observable in the microstructure of the microporous membranes of GWSs, even after accelerated UV exposure equivalent to 10 years of outdoor use. On the other hand, sunlight exposure for more than two years at TSSs caused significant damage among GWSs to the microporous membrane and its water resistance. The aging of GWSs at TSSs might be stimulated not only by UV radiation and moisture but also by other factors not considered in the accelerated UV exposure tests.

Key words: gas-permeable/waterproof sheet, geomembrane, tensile strength, water resistance, temporary storage site

1. Introduction

Soil removed and waste generated during decontamination work in Fukushima Prefecture following the Fukushima Daiichi nuclear power plant accident on March 11, 2011 are being kept in storage containers for decontamination soil at temporary storage sites (TSSs) and on-site storage locations. The two main types of storage containers for decontamination soil and waste are flexible containers and large weather-resistant sandbags (MOE, 2013). The former generally consist of polyethylene or polyester woven fabric and the latter of polypropylene woven fabric which is weatherproofed by use of light stabilizers and antioxidants. Generally, the storage containers are covered with a sheet to avoid deterioration from exposure to sunlight, wind and rain (MOE, 2013). The two main types of covering sheet are gas-permeable/waterproof sheets (GWSs) and geomembrane. GWSs are a type of geocomposite that combines non-woven fabric and waterproof microporous membranes, while geomembrane is a flexible waterproof sheet material made of ethylene propylene diene monomer rubber, polyvinyl chloride, polyethylene and other compounds (JIGS, 2016). In addition, a degassing pipe is required in the case of using a geomembrane, while it is not necessary with a GWS.

The transportation of decontamination soil and waste from TSSs to interim storage facilities began in 2015, and the amount of decontamination soil and waste is estimated to be about 14 million m³ in total while its transportation to the interim storage facilities was about 60% complete as of October 2020, with 551 TSSs continuing to store decontamination soil and waste according to the Ministry of the Environment’s website with information on interim storage facilities (MOE, 2020). As a result, there are still many sites where decontamination soil and waste have been stored for longer than the originally anticipated period of three years, and there are concerns about damage to the above-mentioned materials used at TSSs (MOE, 2015; MOE, 2016). There have been some cases where the sheets covering them were damaged by sunlight exposure at TSSs in Fukushima Prefecture (Fig. 1), which can cause deterioration of storage containers due to ultraviolet exposure, enabling rainwater to intrude.

Center for Material Cycles and Waste Management Research, National Institute for Environmental Studies
16-2 Onogawa, Tsukuba-shi, Ibaraki, 305-8506, Japan
*E-mail: takahashi.yusuke@nies.go.jp

Fukushima Prefectural Centre for Environmental Creation
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan

Global Environmental Research
24/2020: 181-190
printed in Japan

©2020 AIRES
To collect knowledge for the proper management of decontamination soil and waste and TSSs, the authors have reported their survey results on long-term durability of the flexible containers and large weather-resistant sandbags used as storage containers for decontamination soil and waste. They found that some exposed materials had experienced significant strength loss (Takahashi, 2018; Takahashi et al., 2019).

In this study, the authors investigated the long-term durability of the covering sheets (i.e., GWSs and geomembrane) which have actually been used at TSSs for two to six years to protect the storage containers for decontamination soil and waste.

2. Experimental Study

2.1 Collection of Sheet Materials Used at TSSs

In this study, two types of GWS and one type of geomembrane were collected from TSSs managed by municipalities in Fukushima Prefecture (Fig. 2). All these sheet materials were used in sun-exposed conditions. The three municipalities managing the TSSs where the sheet materials were collected in this study are referred to here as “Municipality a/b/c,” with the TSS in Municipality a being called “TSS (a),” the TSSs in Municipality b being called “TSS (b-1),” “TSS (b-2),” “TSS (b-3),” and the TSS in Municipality c being called “TSS (c).” The geomembranes used in this study were made of PVC (polyvinyl chloride) with a thickness of 1.5 mm.

Photographs and low-magnification SEM images of two types of GWS are shown in Fig. 3. The microporous GWS membranes consists of polyethylene and a non-woven fabric consisting of polyethylene or polyethylene terephthalate (Nishimura et al., 2012). Type 1 uses a thin non-woven fabric for the exposed side, and the overall thickness of the sheet is about 5 mm (Fig. 3 (A)), while Type 2 uses same non-woven fabric on both sides, with the overall thickness of the sheet being about 4.5 mm (Fig. 3 (B)). Type 1’ has a different microporous membrane structure from Type 1 (Fig. 3 (C)), but their basic structure is almost the same. Therefore, in this study, Type 1 and Type 1’ are treated as similar materials with the same weatherability and mechanical properties. The materials collected from the TSSs in this study were GWS types 1 and 2 and the test procedures used for them are described below in Sub-sections 2.3.2 and 2.3.3, while the test targets of the accelerated UV exposure test described in Sub-section 2.3.1 were GWS types 1’ and 2.

In addition, unused GWSs and geomembrane were prepared as undamaged materials for comparison with the materials collected from TSS.

2.2 Method

2.2.1 Tensile Test

Tensile tests were performed using a universal tester (AGS-10kNG, Shimadzu) on the GWS and geomembrane materials prepared in Section 2.1, and the tensile strength of the sheet body in the cross-machine direction was calculated from the following formula:

$$p = \frac{P}{B}$$  \hspace{1cm} (1)

where $p$ is maximum tensile strength [N/cm], $P$ is the maximum tensile load [N], and $B$ is the width of the test specimen [cm].
The tensile strength for sheet joints was also determined in the cross-machine direction. The fabrication and testing conditions of the test specimens conform to the voluntary standards of Japan Lining Systems and Technology Association (JIS L 1908 for GWS and JIS K 6251 for geomembrane) (JLSTA, 2014). The number of replications was set at three.

2.2.2 Puncture Resistance Test
The conditions for preparation and testing of the test specimens were in accordance with the method (ASTM D 4833) specified in the voluntary standards of JLSTA. The number of replications was set at three.

2.2.3 Water Resistance Test
The conditions for fabricating and testing the specimens were in accordance with the method (JIS L 1092 B method (high water pressure method)) specified by JLSTA. The number of replications was set at three.

2.2.4 Morphological Observation
The surface and cross-sectional microstructures of the specimens were observed using a scanning electron
Table 1  Covering sheet material types and test methods.

<table>
<thead>
<tr>
<th>Material use</th>
<th>Unused material</th>
<th>Accelerated UV-exposed material</th>
<th>Material used at municipal TSSs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GWS (Type 1')</td>
<td>GWS (Type 2)</td>
<td>GWS (Type 1')</td>
</tr>
<tr>
<td>Elapsed year</td>
<td></td>
<td></td>
<td>c</td>
</tr>
<tr>
<td>Tensile test</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Water resistance</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Puncture resistance index</td>
<td>-</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

2.3.1 Accelerated UV Exposure Test

Unused sheet materials were exposed to UV light using a sunshine carbon arc lamp weathering apparatus (JISC, 2007). The tested specimens were GWS types 1 and 2 and PVC geomembrane, shown as “accelerated UV exposure material” in Table 1. The exposure conditions were in accordance with the JIS L 1096 weathering test, where the black panel temperature was 63 ± 3°C and the water spray time was 18 minutes per cycle of 120 minutes. Under these conditions, 300 hours of accelerated exposure is considered to be equivalent to one year of outdoor use (JLSTA, 2014; PWRC, 2012). Three different exposure times (900, 1500, and 3000 hours) were examined in this study.

Tensile tests and puncture resistance tests were conducted on the materials that were subjected to the above accelerated UV exposure. For some of the materials, water resistance tests were also conducted.

2.3.2 Comparisons among Municipal TSSs

The tested specimens were GWS (Type 1) and geomembrane (PVC) shown as “material used at TSS” in Table 1 and they were collected from the TSSs managed by municipalities a, b and c. The same type of GWS (Type 1) was used in municipalities a and b, and the same type of geomembrane was used in municipalities b and c. Tensile tests and water resistance tests were conducted on the above sheet materials. Here, the number of replications was set at five or 10.

2.3.3 Aging of Material

The tested specimens were GWS types 1 and 2 shown as “material used at TSS” in Table 1 and they were collected from TSS (b-2) and TSS (b-3). Tensile tests and water resistance tests were conducted on the above sheet materials. The tensile strength of the sheet body was evaluated in the machine-direction and cross-machine direction. For some of the materials, light shielding tests were also conducted. There were fewer test specimens of Type 2 compared to Type 1. Aging of the sheet materials was evaluated as a function of elapsed years by calculating elapsed time from the TSS construction date.

It is important to note that the test procedures in Sub-sections 2.3.2 and 2.3.3 evaluated different specimens. This is because the timing of collection and detailed testing conditions were different, even though both materials were collected from the same TSS. The test results for Sub-sections 2.3.2 and 2.3.3 are described in Sections 3.2 and 3.3 below, respectively.

3. Results and Discussion

3.1 Accelerated UV Exposure Test

Figure 4 summarizes the tensile curves of the sheet materials after accelerated UV exposure.

In the GWS sheet body (Type 1'), the tensile strength first decreased significantly due to fracturing of the surface textile at a strain of 20–30 mm, and then the tensile strength based on the non-woven fabric on the unexposed surface reached a maximum at a strain of 90–100 mm. The tensile strength based on the non-woven fabric of the unexposed surface did not change significantly when comparing the unexposed product and the UV exposure time of 900/1,500/3,000 hours, while the tensile strength based on the surface textile showed a clear decrease in tensile strength depending on the UV exposure time. This means that in the whole GWS sheet
(Type 1') the surface textile was susceptible to UV light exposure. In addition, the sheet joints also showed a clear decrease in tensile strength as a function of exposure time to UV light, which may have been because the structure of the sheet joints peeled off when the surface textile was fractured.

In GWS Type 2, unlike Type 1', preferential deterioration of the surface textile was not observed. Comparing the unused sheet with the one exposed to UV light for 900 hours, there was a clear decrease in strength in both the sheet body and the joint, but the decreases in strength at 1,500 hours and 3,000 hours were less than that of sheet joints and surface textile of the Type 1' sheet body. There was no significant difference in tensile strength between the sheet body and the joint.

Unlike in the two types of GWS, there was no clear reduction in tensile strength of the geomembrane under unused and UV exposure conditions of 900, 1,500 or 3,000 hours. However, a decrease in maximum strain was shown at 3,000 hours of UV exposure.

The maximum tensile strength of the sheet materials that underwent accelerated UV-exposure is summarized in Fig. 5. For GWS Type 1', the tensile strength of the surface textile was added to the tensile strength of the sheet body. After 3,000 hours of accelerated UV exposure, the maximum tensile strength of the surface

Fig. 4 Tensile curve of GWS and geomembrane after accelerated UV exposure.
textile of Type 1’ was about 53% (96.7 [N/cm]) that of the unused material, and the maximum tensile strength of the Type 1’ joints was about 20% (32.8 [N/cm]) that of the unused material. On the other hand, the strength of the Type 2 joints after 3,000 hours of UV exposure was about 59% (133.6 [N/cm]) that of the unused material. This value is higher than the standard value (57 [N/cm] after 1,000 hours of accelerated UV exposure) specified in the voluntary standard of JLSTA.

The results of the puncture resistance tests of the sheet materials that underwent accelerated UV-exposure are shown in Fig. 6. Unlike the results of the tensile test (Fig. 5), both GWSs Type 1’ and Type 2 were found to meet the standard value even after 3,000 hours of accelerated UV exposure (the standard value for GWSs was 500 [N], while no standard value for geomembrane had been set) (JLSTA, 2014). This is presumably due to the non-woven fabric on the unexposed surface retaining its puncture resistance.

SEM images of GWSs that underwent accelerated UV-exposure are shown in Fig. 7. The observation targets were limited to the GWSs, with geomembrane not included in this study because no significant strength reduction had been observed. Regarding both Type 1’ and Type 2, the fiber structure of the surface textile was damaged after 3,000 hours of accelerated UV exposure. On the other hand, the microporous membranes of the GWSs maintained their microstructure after 3,000 hours of accelerated UV exposure, suggesting that the water resistance of the GWSs was maintained. We have already confirmed that after 3,000 hours of accelerated UV exposure, GWS types 1’ and 2 met the standard value (1,000 [mmH2O] ≈ 9.81 [kPa]) of the water resistance test (data not shown), supporting the SEM observation result.

Therefore, GWS Type 2 and the geomembrane retained practical durability (tensile strength, puncture resistance and water resistance) even after 3,000 hours of exposure.

Fig. 5 Tensile strength of GWS and geomembrane after accelerated UV exposure.

Fig. 6 Puncture resistance of GWSs and geomembrane after accelerated UV exposure.

Fig. 7 SEM images of GWSs (types 1’ and 2), unused material and after accelerated UV-exposure (3,000hr).
accelerated UV exposure equivalent to 10 years of outdoor use. On the other hand, GWS Type 1’ showed a significant loss of strength at the surface textile and joints. This result confirms the fractures in GWS seen in actual TSS environments (Fig. 1).

### 3.2 Comparisons among Municipal TSSs

Figure 8 shows the results of the tensile test of GWS Type 1 and the geomembrane collected from the TSSs managed by municipalities a, b and c. It was confirmed that the tensile strength of GWS Type 1 collected from TSSs (a), (b-1) and (b-2) exceeded the standard value specified by JLSTA (57 [N/cm]). Considering that unused Type 1’ material showed a tensile strength of 182.8 [N/cm], the deterioration of the tensile strength is considered to be limited regarding GWS Type 1 used at TSSs. In addition, tensile strength of the joints of the geomembrane in the TSSs of municipalities b and c was roughly equivalent to tensile strength of the unused sheet (184.2 [N/cm]) shown in Fig. 5, and it was confirmed that they maintained sufficient durability. Considering that the sheet body of GWS Type 1’ and geomembrane maintained tensile strength after 3,000 hours of accelerated UV exposure (equivalent to 10 years of outdoor use) as shown in Fig. 5, the results with the materials used at TSSs are basically consistent with the tendencies of the accelerated UV exposure tests in terms of tensile strength.

Next, the results of the water resistance tests of GWS Type 1 and geomembrane are shown in Fig. 9. Unlike the tensile tests, water resistance of GWS Type 1 was reduced to below its standard value (9.81 [kPa]) for most samples. Many cracks were observed on the microporous membranes of the GWS by visual observation, which confirmed the loss of waterproofing performance of the microporous membranes (no image). There were no differences in water resistance among the GWSs in TSSs (a), (b-1) and (b-2). However, a few specimens collected from the ponding part of the sheet maintained their water resistance. This is presumably because the ponding part of the sheet had less damage from sunlight exposure (JAG, 2016).

The water resistance of GWS Type 1 was clearly reduced, while the water resistance of the geomembrane was maintained. These results indicate that GWS Type 1 used at TSSs for more than two years lost its water resistance regardless of the location of the installation. The possibility of fracture of the surface textile and the joint under UV exposure was indicated in Section 3.1, but these results show that GWS Type 1 may lose its water resistance through sunlight exposure even if no fractures are observed on the surface textile. Although the microporous membranes did not show any damage under 3,000 hours of accelerated UV exposure (equivalent to 10 years of outdoor use), the water resistance deteriorated after about two years of sunlight exposure, indicating that degradation of the GWS in the actual TSS environment was stimulated by factors not considered in the accelerated UV exposure tests, such as temperature changes between day and night, freezing, creep stress due to strong wind and others.

### 3.3 Material Aging

The results of the tensile tests of GWS types 1 and 2 collected from TSSs (b-2) and (b-3) are shown in Fig. 10. The elapsed time of the tested sheets ranged from 2.6 to 5.5 years. As the results in Section 3.2 (Fig. 8) indicate, it was confirmed that all specimens met the standard value (57 [N/cm]). Considering that unused Type 1’ material showed a tensile strength of 182.8 [N/cm], the deterioration of the tensile strength is considered to be limited regarding GWS Type 1 used at TSSs. In addition, tensile strength of the joints of the geomembrane in the TSSs of municipalities b and c was roughly equivalent to tensile strength of the unused sheet (184.2 [N/cm]) shown in Fig. 5, and it was confirmed that they maintained sufficient durability. Considering that the sheet body of GWS Type 1’ and geomembrane maintained tensile strength after 3,000 hours of accelerated UV exposure (equivalent to 10 years of outdoor use) as shown in Fig. 5, the results with the materials used at TSSs are basically consistent with the tendencies of the accelerated UV exposure tests in terms of tensile strength.

Figure 11 shows the results of the water resistance tests of GWS Type 1 and geomembrane (no image). Unlike the tensile tests, water resistance of GWS Type 1 was reduced to below its standard value (9.81 [kPa]) for most samples. Many cracks were observed on the microporous membranes of the GWS by visual observation, which confirmed the loss of waterproofing performance of the microporous membranes (no image). There were no differences in water resistance among the GWSs in TSSs (a), (b-1) and (b-2). However, a few specimens collected from the ponding part of the sheet maintained their water resistance.
found to be maintained after about three years of use.

SEM images of GWS types 1 and 2 collected from TSSs (b-2) and (b-3) are shown in Fig. 12. Compared with the SEM images of the materials after accelerated UV exposure shown in Fig. 7, the materials used at the TSSs showed damage not only to the surface textile but also to the internal microporous membrane. Many cracks with width exceeding 50 μm were found on the microporous membrane of Type 1, which clearly indicated its structural failure. This observation confirms the test results in Figs. 9 and 11. On the other hand, GWS Type 2 had voids of less than 10–50 μm in diameter compared to the unused sheet, indicating damage to the microporous membrane structure. The damage in Type 2 was limited compared to that in Type 1, which confirms the result of the water resistance test of GWS Type 2 shown in Fig. 11. These results show that the water resistance of GWS Type 1 decreased after about 2.5 years of use, while Type 2 maintained its water resistance under similar conditions.

To investigate differences in weatherability between Type 1 and Type 2, light shielding tests of the GWSs were conducted and the results are shown in Table 2. The results show that the light shielding ratio of the GWSs (entire sheet) was 100%, and the ratio of the surface textile removed from the GWSs was more than 99.9%. There was almost no difference between Type 1 and Type 2. These results suggest that the difference in weatherability between Type 1 and Type 2 does not depend on the shading performance of the non-woven fabric, but is influenced by other factors, such as adiabatic performance and mechanical properties of the non-woven fabric.
Table 2 Light shielding ratio of GWSs (types 1 and 2) used at TSSs.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Elapsed time</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Average [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWS (Type 1)</td>
<td>5.5</td>
<td>99.97</td>
<td>99.93</td>
<td>99.82</td>
<td>99.91</td>
</tr>
<tr>
<td>GWS (Type 2)</td>
<td>2.8</td>
<td>99.94</td>
<td>99.95</td>
<td>99.94</td>
<td>99.95</td>
</tr>
</tbody>
</table>

| Entire sheet | 4.4 | 100 | 99.99 | 99.99 | 100 |
| GWS (Type 2) | 2.8 | 100 | 100 | 100 | 100 |

4. Summary and Conclusion

The durability of covering sheet materials after accelerated UV exposure or sunlight exposure for two to six years at TSSs for decontamination soil and waste in Fukushima Prefecture was investigated. The GWSs showed clear decreases in tensile strength and water resistance, while the geomembrane did not change significantly over time at the TSSs. In particular, the decrease in water resistance was difficult to judge from the appearance of the sheet materials, and the possibility of rainwater intrusion into the storage containers under the sheet needs to be taken into consideration for proper management of TSSs. Our experimental results show that the water resistance of GWS Type 1 was more severely reduced by use at a TSS for 2.5 years than by accelerated UV exposure equivalent to 10 years of outdoor use, suggesting that the deterioration rate at TSSs is accelerated by factors not considered in the accelerated UV exposure tests (e.g., temperature differences between day and night, creep stress from strong winds, etc.). Meanwhile, GWS Type 2 had a limited loss of strength compared to Type 1 and maintained its water resistance even after three years of use at TSSs.

The number of TSSs in Fukushima Prefecture has already peaked, and the phase of TSS restoration to the original state rather than managing them has begun. On the other hand, there are still some TSSs outside of Fukushima Prefecture where plans for transporting the waste have not been developed. Technical issues regarding decontamination soil and waste from decontamination work still require a long time and continuous research to resolve before completing their final disposal.

Acknowledgement

In this study, collection of the samples tested and measurement of data were conducted with support from the municipalities maintaining TSSs (especially Nishigo Village and Iwaki City). Also, some of the experiments in this study were conducted with support from the Fukushima Technology Centre. We would like to express our gratitude to them.

References:


References:
Yusuke Takahashi

Yusuke Takahashi is a postdoctoral fellow at the National Institute for Environmental Studies, Japan. He specializes in analyzing the degradation behavior of plastic materials. He is elucidating the degradation process of civil engineering materials such as water-proof sheets and flexible containers used in temporary storage sites. His research has contributed to the proper management of decontamination waste generated in Fukushima Prefecture. He is currently working on developing methods to predict fragmentation behavior of degraded plastics.

Masahiro Koiso

Masahiro Koiso is a researcher in the Research Department of the Fukushima Prefectural Centre for Environmental Creation. He specializes in measures for handling technical issues at temporary storage sites for wastes generated from decontamination activities in Fukushima Prefecture. The research results he has obtained are contributing to the proper management of decontamination waste generated in Fukushima Prefecture. Currently, he is conducting research on how to address technical issues involved in restoring former temporary storage sites to their original state.

(Received 9 October 2020, Accepted 27 December 2020)
Promoting Local Revitalization to Solve Issues on Degraded Forests in Japan: A Case Study in Oku-Aizu, Fukushima

Makoto OOBA*, Shogo NAKAMURA and Takuya TOGAWA

Fukushima Branch, National Institute for Environmental Studies
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
*E-mail: ooba.makoto@nies.go.jp

Abstract
The degradation of forest ecosystems due to depopulation, aging and economic depression of industries in rural areas, has been extensively discussed, while at the same time, increased demand for renewable energy from woody biomass has resulted in much attention to forestry and rural areas. This study provides an overview of regional circulation in a small woody biomass energy system in a typical Japanese rural area, Mishima Town, Fukushima Prefecture. To resolve the problem of forest degradation, two issues (energy and forests) in the study area are focused on and discussed in light of the national-level background. We have derived two constraints (circulation radius and feasible size) and conducted four research activities (focused respectively on forest resources, production, energy infrastructure and the social system and scenarios) for local revitalization. To address implementation of an energy system, Mishima Town established a council that has working groups strongly related to our research activities. Finally, it can be stressed that the goal of our project is identical to the concept of "regional circular and ecological spheres" (regional CESs).

Key words: cogeneration system, forest management, regional circulation, renewable energy, woody biomass

1. Introduction

The degradation of forest ecosystems has been extensively discussed in Japan. This degradation can be attributed to decreasing population in rural areas and a decline in local industrial activity, as well as to synergistic effects arising from these factors. Meanwhile, power generation from woody biomass has gained attention because of the renewable energy feed-in tariff (FIT) system implemented in 2011 after Japan’s nuclear disaster (METI, 2017). Increased demand for woody biomass can result in higher biomass production and promote forest harvesting. The latter includes forest carbon sinks and sites where carbon dioxide is absorbed, leading to climate change mitigation and implementation of policies to substitute biomass fuel for fossil fuels.

However, the FIT system is based on large biomass power plants, which may require an annual supply in the tens of thousands of tons of woody-biomass (Sakai et al., 2017). This implies that biomass procurement from local forests to produce fuel should require sustainable measures assessed through planned deforestation. Although FIT is a policy aiming to promote the development and installation of renewable energy at the initial stage, the permanence of high purchase prices compared to the price of electricity from conventional electric power companies is not guaranteed. After 2017, new solar power-generation facilities of 2,000 kW production or higher were no longer eligible for FITs (and that number was lowered to 500 kW in 2019). Although future power plants will need to operate on wholesale and retail schemes, it is difficult to implement them in large-scale domestic woody-biomass power plants. Thus, almost all of them will need to expect conditions of reliance on use of the FIT system.

This study addresses general issues related to Japanese forests and describes the efforts that have been conducted to achieve local revitalization and provide solutions for environmental problems. Subsequently, it discusses the adoption of renewable energy in Japan within the context of woody biomass and explores socioeconomic constraints on the use of forest resources as a modern energy source. Then it provides an overview of the regional circulation in a small combined heat and power (CHP) woody biomass energy system, which is the goal of this study. It describes the initiatives proposed in Mishima Town, Fukushima Prefecture, and their current results. Finally, it addresses the convergence of these initiatives with similar ones, such as the Regional Circular and Ecological Spheres (CESs) and Sustainable Development Goals (SDGs).
2. Issues Affecting Forests in Japan

Due to a lack of timber for construction in the 1960s, Japan made a major transition from firewood and natural forests to plantation forests. However, timber importation regulations were relaxed and price competition arose between domestic and imported timber. As a result, timber prices decreased, resulting in difficulties for domestic forestry industries. Labor forces have declined due to aging, and there has been a population decrease in rural and mountainous areas; thus a shortage of workers able to manage forests has arisen. Moreover, some plantation forests were not well managed before the FIT system was introduced for timber production. The management rate of these forests was approximately 45% (Amano, 2007).

Forests have various ecological functions, and their benefits to human society have ecosystemic importance (ecosystem services). The functions of forest ecosystems include prevention of sediment discharge, headwater conservation, water purification, carbon absorption, timber and forest product supply, and biodiversity conservation. These functional issues are affected (quantitatively and qualitatively) by forest management and the degree of forest conservation. Well-managed forest ecosystems exhibit higher carbon absorption rates (Hiroshima & Nakajima, 2006) and improved photosynthesis rates after thinning (Han & Chiba, 2009). In contrast, soils in unmanaged forests have lower water-holding capabilities and exhibit erosion (Miyata et al., 2009).

Those conditions currently prevail because of the increased demand for biomass power plants. Because clear-cutting is simpler to implement than thinning, and reforestation is difficult due to economic and labor factors, resource depletion could potentially occur due to the lack of adequate systems for achieving a managed degree of logging and reforestation in the affected forests. In addition to the amount of resources available, the effects of ecosystem functions have major impacts on environmental issues such as disaster prevention.

In 2019, the Forestry Agency launched the New Forest Management System, which established distinctions between forest ownership and forest management, thereby encouraging harvesting by operators interested in promoting municipal forest management (Forestry Agency of Japan, 2020; Uchiyama & Kohsaka, 2020). Currently, an economic and sustainable framework for forestry at the municipality level needs to be developed as soon as possible, considering the advantages of that system.

3. Renewable Energy and Regional Circulation

3.1 Renewable Energy in Japan

After the first oil crisis (1973), Japan’s dependence on foreign energy sources became evident along with environmental issues due to the use of fossil fuels (air pollution and greenhouse gas emissions). Thus development of novel energy sources was initiated, aiming to solve those problems. “New energy” is a term used in Japan in a unique context because it refers to non-fossil fuels under the Act on the Promotion of New Energy Usage (New Energy Act). Currently, the definition by law is similar to that of the renewable energy concept, including biomass, solar thermal energy, snow and ice thermal energy, along with geothermal, wind and solar power generation.

The Great East Japan Earthquake and consequent nuclear disaster in 2011 became an opportunity for Japan to reconsider its energy sources. In addition to the existing trend in “fossil-free” sources for international security reasons, Japan considered renewable energy at that time as a means of decentralizing energy and managing local resources well autonomously. In addition, international treaties related to climate change have progressed, and promoting renewable energy is consistent with global agreements to phase out carbon energy and reduce future climate risks, according to the Paris Agreement. Although solar power was initially considered as a potential source of renewable energy, power generation from un-utilized woody resources has attracted attention, as it also maintains a relatively high purchasing price under the current system.

3.2 Regional Use of Woody Biomass and its Constraints

Historically, woody biomass has been used not only as construction material but also as an energy source. In Japan, firewood and charcoal were widely used as energy sources before households turned to fossil fuels in the first half of the 20th century (Totman, 1995). Additionally, firewood forests were located around populated areas. Currently, however, profits from woody biomass as an energy source have not returned to their earlier values.

Households need energy for a variety of purposes and high amounts of energy are consumed. In the past, the energy demand in Japan arose primarily for warmth, hot water, and cooking. Nowadays, there is also demand for cooling, equipment operation and transportation, which are powered by electricity and fossil fuels (diesel and gasoline). Consequently, energy demand in the past was low compared to current requirements. For instance, the annual electricity consumption in Fukushima Prefecture is 17,207 × 10^6 kWh (as per the 2010 record before the earthquake), which represents 6.757 × 10^6 tons of woody biomass in terms of heat demand. That amount is approximately four times the joint timber volume from plantation forests in the five towns and villages around Mishima. Togawa et al. (2019) also indicate such large demands (14,000 tons/y in the case of maximum use of woody biomass) that is supplied only to Mishima.
compared to the potential supply of woody biomass (4,000 tons/y). Converting that volume of resources into energy would lead to forest depletion in less than three months. In contrast, approximately 40 years would be required before harvesting a standard cedar forest.

One difficulty with woody biomass energy applications is the geographical limitation caused by the need for transporting materials from the supply area to the production area. To benefit from regional resources, including forest reserves, we should consider a “circulation radius” (Fig. 1) that is socioeconomically viable. The radius has been studied in the context of waste collection areas (e.g., Fig. 5 in Ohnishi et al., 2016). Although the present study area has an abundance of forest resources, there is a maximum limit regarding transportation distances of raw biomass corresponding to 50–125 km based on previous studies (e.g., for large-scale power plants in Hokkaido, Sakai et al., 2017). Furthermore, when a resource is considered an energy source, the range that electricity generated from it can reach using self-operated power lines is limited to a few kilometers due to economic constraints (Agency for Natural Resources and Energy, 2019; e.g., for case studies, Shima & Nose, 2014; Haruta & Muraki, 2017).

Similarly, the supply range when using self-operated pipes for thermal energy is a few hundred meters. Regarding electricity, it is possible to transport power generated by a small local power plant through a power grid owned by a regional power company that operates across a larger area. Grid-use fees, however, would be included in the retail electricity price, which would not be economical for consumers. Obtaining profits from regional resources requires socioeconomic principles that maintain this “circulation radius.” On a temporal scale, the life spans of local resources should be also considered. For example, electricity must be consumed immediately after power generation, while woody biomass in forest stands can be saved (or grown) for the long term.

Therefore, utilizing forest resources is not enough to resolve forest and energy issues entirely in a modern society. That conclusion, however, is based on an assumption of unrestricted forest usage and energy consumption in an environment where only market competition exists. We have derived that it may be possible to construct a system that can provide solutions to biomass usage and forest issues according to two constraints described as follows:

1. The geographic and temporal range that allows for resource circulation is limited.
2. Facilities of feasible size within that range are limited.

These constraints were not explicit at the beginning of our research in local areas but rather were established more clearly as our research progressed.

4. Case Study: Mishima Town

4.1 Location and Forests

Oku-Aizu and Mishima in Fukushima Prefecture are snowy areas located in the southwest region of Aizu, close to the border with Niigata Prefecture (Fig. 2).
According to the Automated Meteorological Data Acquisition System (AMeDAS) in Kaneyama (a town located next to Mishima), the average annual temperature in the area is 10.4°C, the annual rainfall is 2,020 mm, and the maximum snow depth is 177 cm. Because Mishima has a robust water supply due to snowmelt, the Tadami River has been used as a power source since the end of World War II. At that time, Mishima’s population was over 7,000. Its current population, though, is less than 1,600, and Mishima exhibits one of the highest aging rates (53.0%) in Fukushima Prefecture.

The general environmental issues of Japan also affect Mishima, as forests cover 88% of its total area. While the town has a wealth of forest resources, cedar forests, which account for almost all of the privately-owned forest land, are often owned by small-scale owners. There is also a lack of clarity regarding the ownership of these lands. Timber prices have remained low for approximately 50 years, and not enough thinning or materials production have been conducted. Furthermore, the timber produced in the Aizu region presents issues, such as bending or excessive knots, rendering it a low-quality product in Japan.

The results of a questionnaire survey on forest-related awareness in Mishima (Nakamura & Togawa, 2020) showed that local people perceive that a combination of issues, such as the delineation of boundaries to subdivide forests and unclear ownership, leads to forest degradation. The details of this survey are discussed below.

Some areas of Mishima have adopted the Fukushima Forest Restoration Project (Fukushima Prefecture, 2018), which was implemented by the prefecture after the earthquake and nuclear accident. Future benefits from assessment of knowledge on forest boundaries through the project are expected.

4.2 Toward Renewable Energy from Forests

Aiming to promote forest management and profits from woody biomass, Mishima formulated the Mishima New Energy Vision Program in February 2006 and the Detailed Mishima New Energy Vision Program the following year. In particular, these programs proposed replacing petroleum-based boilers and stoves with units that can handle easy-to-use pellets as combustible sources to make use of the town’s abundant forest resources. In cooperation with nearby towns and villages (Yanaizu, Kaneyama, Showa and Tadami), the Oku-Aizu Five-Towns Revitalization Council was established in April 2010 to achieve biomass utilization. However, the Tohoku Earthquake in 2011 and major damage from torrential rains in Niigata and Fukushima have contributed to decreased biomass processing.

The chambers of commerce of 13 cities, towns and villages in the Aizu area worked together to establish the Aizu 13 Project Council in 2016, with the participation of Mishima Town and its Chamber of Commerce. The goal of the project was to expand production of materials from the Aizu area, obtaining high-performance plywood materials, and additionally biomass as energy fuel sources. The project is currently being managed and actively implemented by both the Aizu Forest Resource Utilization Promotion Council and the Aizu Forest Utilization Organization, based on collaboration with the national governmental. Our project was affected indirectly by the Aizu 13 project, but it was not directly connected to the project.

4.3 Research Activities and Their Outputs

The Fukushima branch of the National Institute for Environmental Studies (NIES) holds surveys and performs studies which are assessed primarily by regional development researchers. It also conducts collaborative research with specialists from other universities and institutes. To ensure and promote regional research, NIES signed a collaborative agreement (memorandum of understanding) with Mishima Town in 2017.

With constraints [1] and [2] in mind, the research team listed problems in Mishima and the surrounding area, initiatives to solve those problems, the effects of the initiatives, and details regarding the research required to address those effects (Table 1).

Further details on the research activities in Table 1 are provided below.

4.3.1 Detailed Survey of Forest Resources, Questionnaire Survey on Forest-related Awareness

The first problem that arises in forest resource usage is that forest boundaries are frequently not well-defined or geographically accurate, as required for forestry practices. Furthermore, most forests are unmanaged, and the actual timber volume of the forest is unknown.

To reconfirm forest boundaries and estimate amounts of resources, we used a drone to take aerial images and laser measurements. We studied a forest area of approximately two hectares in a commonly owned forest in the Mishima area, contributing to understanding by the residents. The aerial images and laser measurements were taken in August 2019, whereas the field studies were conducted in February and May of 2020 (Fig. 3). With the cooperation of the Graduate School of Engineering at Osaka University, we used 3D-point cloud data to estimate tree top positions and crown sizes for each tree through machine learning. After its use in an initial analysis and validation, this technique continued to be improved for accuracy. These data show the amount of each type of tree located in each owner’s forest and the available timber volume. In addition, the detailed aerial images and point cloud data may also be useful in defining boundaries of forest ownerships and planning forest practices. Data are currently being compiled for presentation to the residents of the town and the region.
This will also lead to higher consolidation and better forest land management.

Additionally, a questionnaire survey on forest-related awareness was conducted in 2018 (Nakamura & Togawa, 2020). We randomly selected 599 Mishima residents (aged 18 or older) and obtained responses from 264 people (44.1% response rate). The results showed that 76% of the respondents knew the location of the forest they owned, and only 58% were aware of its boundaries, indicating a need to reconfirm boundaries. However, because most owners did not manage their forests, when asked about owners’ management difficulties, they mentioned “low timber prices” as the most frequent response, followed by “lack of manpower,” “undeveloped work roads,” and “unclear boundaries.” Another common response was “aging of the population.” When asked about subsidies they would need to keep managing their own forests, we obtained several answers related to financial issues (timber prices/supply chain: 56 responses, logging/transportation subsidies: 30 responses), as well as 80 responses related to boundary definition/forest road development.

This survey received significant attention from residents regarding disaster prevention and reduced forest functionality. Although the Great Tohoku Earthquake and nuclear disaster in 2011 had little impact on the region, torrential rain and flooding occurred in the same year. The relationship between forests, landslides and floods is understood well in this region, and biomass utilization plans should be considered.

### 4.3.2 Estimation of the Production Potential and Resource Circulation Area

A study on the biomass potential of privately owned forests in the Oku-Aizu area (Ooba et al., 2018) produced a cost analysis of chip production to obtain energy (including logging and transportation). It demonstrated that, for forestland with extremely low management rates (percent of area managed annually: 0.36% per year), chip production to obtain energy was not possible from an economic viewpoint. However, the study showed that it might be possible to produce chips at a cost of 7,000 JPY/m³ or less (in a scenario where the amount harvested was increased by conducting extensive thinning) and that future production could be ramped up to approximately 10,000 m³.

### 4.3.3 Energy Conversion Technology, a Detailed Survey on Energy Demand

The feasibility of implementing a biomass energy system was also studied at typical hot spring facilities in the region (Togawa et al., 2018). Based on data from a survey jointly conducted with Mishima, energy demand by season and time was estimated in facilities along the Tadami River. It was demonstrated that a small biomass co-generation system (operating continuously during all seasons) would consume approximately 700 tons/year of...
woody biomass. However, when the economics of this scenario were analyzed, there were concerns about profitability.

We installed Home Energy Management Systems (HEMS) in Mishima Town, which are currently studying the actual energy consumption of houses in the cold Oku-Aizu region and modeling that consumption. From these data, energy charts for each community in Mishima (Togawa et al., 2019) were prepared and efforts to estimate the distributed energy systems’ potential in terms of demand were conducted (Fig. 4).

Based on this research, Mishima used a subsidy for promoting smart communities from Fukushima Prefecture to conduct a foundational study (pre-feasibility study, FS) in 2017 with a company, Nippon Koei Co., Ltd., on energy production for local demand using local resources, such as woody biomass in Mishima. In a study performed by a different welfare institution, a scenario in which electricity was sold to an electric company under the FIT system resulted in a profitable business and an estimated biomass consumption of approximately 800 tons/year.

4.3.4 Social System Theory and Research on Future Social Scenarios

Constraints [1] and [2], as well as the research described above, suggested that in Mishima, woody biomass materials can only be produced as fuel sources at a relatively small scale. This implies that the town needs a community system centered on introducing CHP systems with an electricity output of 50 kW or less. In addition, we may surmise that it would be realistic to start the project up relying on the current FIT system to some extent to ensure business revenues.

As a starting point for social implementation, in 2018, Mishima Town implemented small initiatives as a first step towards promoting woody biomass utilization. One of those initiatives was a Tree Station-style program, which has also been conducted by many municipalities and non-profit organizations, collecting firewood in December. In Mishima, 1 m$^3$ of logs can be exchanged for 4,500 JPY in local gift certificates. The heating and cooling system of the Mishima Local Crafts Museum, a core institution that shares the town’s braided handicrafts tradition, was switched to a system based on a wood-fired boiler. This fuel is produced from firewood collected in Mishima using the method mentioned above.

The research team has not only promoted collaborative-scientific research in Mishima but has also held collaborative research meetings with civil engineering, architecture and regional policy officials at least once a month. Additionally, we have also provided our research results to the Mishima Town Forestry Policy Development Committee, through on-demand lectures in Mishima and public meetings that brought stakeholders together.

To address the implementation of an energy system, in 2019, the NIES proposed that Mishima establish a council. This council would divide tasks related to woody biomass utilization issues into forest/energy production-related (supply-related) and energy-consumption tasks, and form working groups with stakeholders comprised of both local and external parties that could consolidate the opinions of the higher-level coordination council and make decisions. Therefore, Mishima and four surrounding
Promoting local revitalization to solve issues on degraded forests in Japan: a case study in Oku-Aizu, Fukushima

The Fifth Basic Environmental Plan approved by the Cabinet in 2018 focuses on the concept of “regional circular and ecological spheres” (regional CESs, MOE, 2020). Contributing to that plan, the Ministry of the Environment has elaborated several projects based on model cases of regional CESs. This concept can be considered an integrative version of conventional social-consciousness environmental goals, such as low-carbon or decarbonizing societies, recycling-oriented societies, and harmonious relationships with nature. The achievement of regional CESs infers the embodiment of the SDGs. Woody biomass usage, as presented by this project in Mishima and the Oku-Aizu region, has the potential to create a society that can achieve such goals (Fig. 5).

In addition to academic and technological support, this project will require public-private partnerships. Several businesses and non-profit organizations in Mishima are enthusiastic about renewable energy and woody biomass usage. Creating more effective and sustainable biomass, as well as regional economic circulation, will require higher logging than predicted from the energy center studies and FSs conducted so far. The amount of wood available for logging is limited, however, (and the energy demand is predicted to be significant). Local operators using local resources will conduct this biomass supply project; therefore, we would assume that the energy system the town might install could be a relatively small one and that the service area could be a district of Mishima (a community). Although it is small-scale, implementing this community revitalization energy project will not only ensure economic profits for the community, but also have definite secondary effects in terms of the development of industrial and human resources and stable local employment. This project would have a significant impact as a local service and could also be an initial step towards promoting future projects addressing a wider range of social services, similar to Germany’s Stadtwerke project (Ando, 2019) and responding to the problems of depopulation and aging. This demonstrates the potential of the project to scale into a major sector in the rural regions.

We plan to continue our research on sustainable regions like regional CESs, ensuring that the local needs are considered through their potential environmental effects, which allows for an integrated approach. Furthermore, a thorough estimation of future full-scale biomass utilization is required, considering its impacts on the Oku-Aizu forests, where the vegetation has remained unchanged for several decades. We are also planning to begin research on adaptation to climate change in the Oku-Aizu region, including a survey aimed at creating hazard maps for landslides and other disasters, while actively providing information to local governments.

Fig. 5 Sustainable revitalization inside Oku-Aizu through the regional circulation of local resources from production to distribution and consumption as the goal of “regional circular and ecological spheres” (CESs).
References


Makoto Ooba
Dr. Ooba heads the Environmental Renovation Laboratory at the Fukushima Branch of the National Institute for Environmental Studies, Japan. From 2007 to 2012 and from 2014 to the present, he has participated in a study on spatial assessment of Japan’s regional forests using process-based models and remote sensing by NIES. Based on these studies, he has analyzed sustainability of forestry and harvested wood products. He has also worked at Osaka University, Nagoya University and the Tokyo University of Agriculture. He holds a Ph.D. in environmental science from Hokkaido University, 2002.

Shogo Nakamura
Shogo Nakamura is a researcher in the Regional Environmental Renovation Section of the National Institute for Environmental Studies, Fukushima Branch. He holds a Ph.D. in agricultural science. He has played a central role in developing the energy monitoring systems in Shinchi as well as many other areas in Fukushima. Recently his interests have led him to participate in the Environment-Economy-Society Integration Research program.

Takuya Togawa
Takuya Togawa is a senior researcher at the National Institute for Environmental Studies, Fukushima Branch. He received his doctorate in engineering from the Graduate School of Environmental Studies, Nagoya University in 2010. He is engaged in research on mechanisms for realizing disaster recovery and regional revitalization by effectively utilizing local environmental resources.

(Received 10 October 2020, Accepted 29 December)
Smart Community Recovering from the Tsunami-Disaster: Case Study of the Community Energy Supply Project in Shinchi Town, Fukushima

Yujiro HIRANO1*, Shogo NAKAMURA1, Takuya TOGAWA1, Tsuyoshi FUJITA2 and Kenichi ADACHI3

1 Fukushima Branch, National Institute for Environmental Studies
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
2 Center for Social and Environmental Systems Research, National Institute for Environmental Studies
16-2 Onogawa, Tsukuba-shi, Ibaraki, 305-8506, Japan
3 Japan Environment Systems Co., Ltd.
5-5-5 Koishikawa, Bunkyo-ku, Tokyo, 112-0002, Japan
*E-mail: yhirano@nies.go.jp

Abstract

The present study was aimed at investigating urban reconstruction development in Shinchi Town, which is located on the northeastern coastal edge of Fukushima Prefecture. Shinchi Town experienced major damage from the Great East Japan Earthquake in 2011. Thereafter, an environmentally friendly community energy supply system was planned and introduced as a core project for reconstruction of the town. The National Institute for Environmental Studies, Japan, provided academic support for designing and planning of systems, determining energy conservation and CO2 emission reduction, and feasibility studies. As a part of the project, a community-based energy organization, named Shinchi Smart Energy, was newly established near the town’s rebuilt railway station. This organization supplies electric power and heat energy in the area undergoing redevelopment around the station. Shinchi Smart Energy employs a cogeneration system that uses waste heat from electricity generation for heating and hot water provision and an absorption chiller (Genelink), which uses waste heat to chill water for air conditioning, enabling high-efficiency energy management. Evaluation of the project reveals that it is being properly operated at this stage, although the facilities on the demand side have not been fully completed since the arrival of COVID-19 and the resulting socioeconomic impacts. Future studies will focus on furthering the introduction of renewable energy and expanding the area receiving the power supply in Shinchi Town, as well as spreading the knowledge gained from this town to other areas.

Key words: CO2 emission reduction, cogeneration, community energy management, distributed power source, district heating and cooling, reconstruction town development

1. Introduction

The Great East Japan Earthquake (GEJE), which occurred in 2011, was the first major disaster experienced by Japan since its population began declining. After previous similar disasters, urban reconstruction plans were made, aimed at extensive urban expansion with the goal of providing substitutive town functions to the damaged districts. The GEJE, however, accelerated the depopulation trend, especially outmigration, from disaster areas that were already scarcely populated even before the GEJE, resulting in further population decline in the region. It has already been argued that in Japan, population decline is causing deterioration of central districts and sprawling decentralization of towns and cities, which increases their CO2 emissions per capita and makes them less carbon efficient; these observations have been confirmed in the case of municipalities in disaster-prevalent areas. Hence, municipalities undergoing reconstruction focus on developing compact cities characterized by higher traffic efficiency and higher housing density, thereby increasing efficiency in terms of reducing air conditioning load and optimizing the heat supply. Furthermore, CO2 reduction is also attained via efficient local energy systems employed for cooling and heating buildings. A number of disaster-affected municipal governments have created a basis for residential and commercial activities in the reconstruction process by
redeveloping into compact cities with more efficient energy supply and demand in the local system (Hayashi, 2014; Kitakaze, 2016).

The situation regarding energy use has changed significantly since the GEJE (Komiyama & Fujii, 2012; Benjamin, 2014; Zhang and McElhan, 2014). Before the GEJE, reducing CO₂ emissions was an important policy issue for medium-to-long-term global warming countermeasures. After the event, however, not only have global warming countermeasures been considered, but also policy issues on energy. The government has implemented several power-saving measures to mitigate peak loading of the power system; these include: addressing issues associated with nuclear power generation, imposing a renewable energy feed-in tariff, liberalizing power retailers, and separating power production from power distribution and transmission. This is because the large-scale energy supply network, which previously served the entire nation, was obviously vulnerable. The supply network for power and gas was disrupted during the GEJE and the energy supply was interrupted in several areas, even in the areas that were relatively less affected. This led to a keen interest in renewable energy as an emergency power source during disasters, in addition to its contribution toward a decarbonized future. The Fukushima Daiichi Nuclear Power Station accident (Hall, 2011; Yamane et al., 2013; Suzuki, 2014) further complicated the perspective. To mitigate peak loading of the power system, in a situation where a nuclear power plant lost function, it was found that rolling blackouts and legally binding power usage restrictions needed to be implemented. Radioactive contamination led to a large-scale evacuation order for residents in various localities that had social and economic impacts, leading a large number of citizens to reconsider their perceptions regarding energy supply issues. From the perspective of both disaster prevention and environmental re-creation, coordinated management of energy supply and demand has become more efficient at the local scale through the introduction of distributed power supplies and construction of autonomous energy networks (Iwamura, 2015).

Against this backdrop, efforts to develop towns in which distributed community energy management was introduced have been promoted in the process of disaster recovery in Shinchi Town, Fukushima Prefecture. In the districts around the JR Shinchi Station, reconstruction from severe damage by the tsunami following the GEJE has been progressing, and various facilities have been constructed thus far (Fig. 1). A high-efficiency community energy system has started to supply electricity and heat energy to facilities built in the vicinity of JR Shinchi Station.

In this study, the planning and evaluation process of the community energy supply project were evaluated via collaboration among the local government of the town of Shinchi, private companies and research professionals. This paper is organized as follows: Chapter 2 gives an overview of Shinchi Town, and the process of reconstruction after the GEJE in conjunction with cooperation from the National Institute for Environmental Studies (NIES). Chapter 3 outlines the community energy supply project. As this community energy supply project cannot be evaluated using full-year data, Chapter 4 introduces the results of evaluating environmental performance at the planning stage. Chapter 5 reports the results of an evaluation using the actual data currently available. Lastly, Chapter 6 provides a summary of the findings and introduces future perspectives.

2. Post-Disaster Reconstruction Process in Shinchi Town

Shinchi Town is a small municipality with a population of about 8,000 and a total area of 46.53 km², located near the border between Miyagi and Fukushima Prefectures, at the northern end of Fukushima Prefecture on the Pacific Ocean side (Fig. 2). It is approximately 300 km north of Tokyo. The temperature is low as compared to that in Tokyo, and the winters are especially cold (Fig. 3). The population of this town peaked in 1995 and has declined since, owing to reduced birthrate and ageing of the remaining population; this is the case for most Fukushima localities.

In Shinchi Town, the number of casualties was approximately 120 in the GEJE and subsequent tsunami. The tsunami inundated a large land area below the elevation of 10 m, with the flooded area encompassing...
about 20% of the town. As a result of the tsunami, 516 houses were damaged, and JR Joban Line Shinchi Station was destroyed, while 40% of the agricultural land (420 ha) was inundated.

For the post-disaster reconstruction of Shinchi Town, the town’s government presented “a smart hybrid town concept” to increase the values of the environment, economy and society. The aim of this concept was to reconstruct the area by combining information and communication technology (ICT) with the social mechanisms that support the community. This concept proposes a new community information infrastructure for local residents networked with the municipal government, research facilities and business sectors and involves a bidirectional information system of sharing information on the local environment and lifestyle. Based on this concept, Shinchi Town, as a disaster-affected site, was selected as a “future city” by the Prime Minister’s Cabinet Office in December 2011. With its selection as a “future city”, discussion on cooperation with NIES toward the reconstruction of the town started, and in March 2013, a basic agreement on cooperation was drawn up between the Shinchi Town government and NIES. Based on research knowledge resources such as social communication, NIES has supported the planning of future visions of the town, and aided in investigations and formulation of the local comprehensive plan and local reconstruction plan (Fujita & Hirano, 2016; Hirano et al., 2017a). We developed an information system that serves as a residential interface for the information infrastructure, and it is presently in the phase of social demonstration experiments (Hirano et al., 2018). Various functions of this information system such as visualization of energy use on the demand side are already available. Community energy conservation campaigns have already been implemented using this information system, contributing to improved awareness regarding energy conservation and a more active community (Otsuka et al., 2019). The energy-saving campaign was a demonstration experiment, involving implementation of energy conservation activities; meaningful results were obtained on provision of energy conservation information and added economic incentives for residents.

As part of this reconstruction and community development support, we have put forth proposals and planning support for regional energy management linked to community development (Togawa et al., 2013; Togawa et al., 2014). This effort has progressed, and the social implementation of the regional energy supply in the reconstructed community has been achieved. As a core project of the urban reconstruction project around JR Shinchi Station, a community energy center, i.e., Shinchi Energy Center, was constructed, with local heat conduits, a community power grid, and CO2 supply pipes being installed (Fig. 4). Details on the project are provided in the next chapter.

Fig. 2 Location of Shinchi Town.

Fig. 3 Variations in air temperature in Shinchi and Tokyo in January and July.

Fig. 4 Shinchi Energy Center.
3. Outline of the Community Energy Project

In February 2018, a community-based energy organization, named Shinchi Smart Energy, was newly established by 12 entities comprising the local government of Shinchi Town and multiple companies and organizations. In November 2018, the Shinchi Energy Center, which provides a highly efficient energy supply, was completed. The Shinchi Energy Center is a community energy supply facility that supplies electricity and heat to facilities around JR Shinchi Station by utilizing cogeneration systems, solar panels, storage batteries and a heat source equipment system. Figure 5 shows an energy flow chart of the system, and Fig. 6 shows photographs of the main equipment. The Shinchi Energy Center has five gas engine cogeneration systems with a power output of 35 kW (175 kW in total) that utilize liquefied natural gas (LNG); the systems are regulated by the number of units in operation depending on energy demand. The cogeneration system utilizes waste heat from power generation to increase the total energy efficiency. LNG, an energy source, is supplied to the center via an LNG pipeline that branches off from the Soma LNG terminal. In addition to utilizing LNG, the center also has solar panels with a rated output of 50 kW installed, providing effective use of renewable energy. Electricity and heat are supplied from the Shinchi Energy Center to facilities in the area through private lines and heat supply conduits. In the energy supply area (the area supplied with electricity and heat), a hotel and hot bath facility with relatively high heat demand have been constructed for commercial use, and hot water supplied by the cogeneration systems is effectively utilized in these facilities. In addition, cooling during summers by operating the cogeneration system is also a feature of this project. In Japan, power peaks occur during summer when air conditioners are in use; thus, to reduce peak loads, cooling technology using gas with absorption chiller heaters has come into widespread use. What is called “Genelink,” is a set of waste heat recovery absorption chiller heaters that produce cold and hot water using waste heat from power generation, such as from gas engines. Some cogeneration systems obtain steam using gas turbines. Because the scale of this project is small, however, it uses gas engines, and the waste heat provides only hot water. Therefore, in the Shinchi Energy Center, cooling and heating are performed with hot wastewater from power generation using Genelink.

Energy began being supplied to consumers in March 2019 (Fig. 7). All the facilities in the supply area shown in Fig. 7 were newly constructed after the tsunami disaster. In addition, the Shinchi Energy Center functions as a regional base for energy distribution. For example, in the event of a power outage during a large-scale disaster, it will be possible to provide an uninterrupted power supply to the energy supply area of the center.

A community energy management system (CEMS) provides integral management of these facilities as well as energy utilization. One of the functions of CEMS is to provide the information necessary for community energy center management. Management is required for when the cogeneration equipment is combined with multiple auxiliary heat sources and power purchased from existing power companies (grid power), thus reducing excess heat while not exceeding the contract power from the grid. In this case, the prediction of demands and power generation via solar power, which depends on climate conditions, becomes essential. Under such complex conditions, information necessary for energy management personnel to make appropriate decisions is provided, contributing to more efficient operations.

![Energy Flow Chart](image)

Fig. 5 Electricity/heat supply system and energy flows in the Shinchi Energy Center.
We are conducting research on evaluating and improving the efficiency of community energy supply and demand management around JR Shinchi Station. We aim to improve energy efficiency and reduce CO₂ emissions in this region and generalize knowledge about efficient operation methods for applications in other regions. However, due to delays in the construction of community centers and agricultural facilities, as well as the socioeconomic impact of COVID-19, the energy supply record at Shinchi Energy Center is currently inadequate, and investigations using available data are incomplete. For this reason, we first present the results of a study based on the master plan (Shinchi Town et al., 2016). In this case study, although the data and calculation conditions are primarily based on the master plan, the capacity of the solar panels has been modified to correspond to practical conditions and recalculated accordingly.

Energy simulations were used to calculate electricity and gas consumption. In the simulations, input data were provided, and calculations were conducted for the load allotment of various heat sources based on input data and operational priority settings. Subsequently, city gas and electricity consumption were calculated based on the coefficient of performance (COP) of the heat source equipment, efficiency data and other factors. Based on these results, the energy savings, CO₂ reduction, and costs of this system were calculated. The various facilities shown in Fig. 7 were considered in the energy demand, and the demand pattern was set based on the existing energy consumption intensity data. (The supply system for the energy center and the assumed energy demand are shown in Fig. 5.) Then, the operating conditions of each item of equipment for supply were evaluated, as shown in Fig. 8.

Based on the above conditions, we calculated the total yearly CO₂ emissions when all facilities were in operation (Fig. 9). We also calculated the CO₂ emissions...
in the case of a conventional system being installed in each building for comparison. The results show that a CO₂ reduction of approximately 20% can be expected by modifying the community energy system based on the highly efficient community energy supply provided by the Shinchi Energy Center. In addition, the seasonal and time-dependent operation patterns of each device were also comprehensively examined. For example, various improvements have been made: approximately 10% of power consumption can be supplied by solar power generation during daytime peak hours and approximately 30% of cold heat consumption can be supplied by a Genelink using cogeneration exhaust heat (figures omitted).

5. Energy Evaluation Based on Available Data

We are conducting energy conservation diagnosis at the Shinchi Energy Center as part of developing technology for planning and evaluating community energy utilization. This is a tentative evaluation result, however, because the expected number of consumers assumed during the planning stage has not yet been achieved.

As an example of the midsummer season, Fig. 10 shows the recorded electricity, cold heat and warm heat supplies for August. In August, cold water was supplied to consumers at 381 GJ and hot water at 222 GJ; although mainly cold water was supplied, one-third of the total demand was for hot water. The number of operational cogeneration units was reduced during the night, but the overall cogeneration system operated 24 hours a day. For the power supply, along with solar power generation, distributed power sources provided approximately half of the local power demand. Energy for cooling was supplied by Genelink, which used exhaust heat from cogeneration, for more than 60% of the total demand. Owing to the demand for hot water in the public bath facilities and hotels, there was some heat demand in summer. Cogeneration exhaust heat and a boiler were used to meet this heat demand.

Fig. 11 shows the energy supply in December as an example of winter conditions. Because there was almost no demand for cold water in December, this aspect was not included in Fig. 11. On the other hand, the demand for hot water increased to 877 GJ owing to its use in both water and space heating. Based on the results of our energy conservation diagnosis, the operation of the cogeneration system was modified in November, and the cogeneration system was stopped during the midnight power time zone of the grid power system. This operation contributed to cost reduction and grid power load smoothing. Correspondingly, heat was supplied from the cogeneration exhaust heat and boiler during day and from the boiler during night.

Fig. 12 shows the cogeneration operation results based on the practical supply and demand data for the seven months from June to December 2019. Since the

---

**Fig. 10** Hourly energy supply in August.

**Fig. 11** Hourly energy supply in December. The abbreviations in the legends are the same as in Fig. 10.
6. Summary and Future Perspective

This paper describes a case study on the planning and evaluation of an environmentally friendly energy supply project that is being developed in the central area of Shinchi Town. This project is being carried out as part of reconstruction of the town after considerable damage caused by the tsunami following the GEJE. In this project, the Shinchi Energy Center was constructed to supply energy to the facilities around JR Shinchi Station. Although the current evaluation is tentative, the overall efficiency of cogeneration is approximately 70%, and the utilization efficiency of exhaust heat is approximately 80–90%, confirming that it is in good operating condition. In the future, we plan to evaluate its environmental performance using practical data as the surrounding facilities on the demand side are completed and the supply records are collected.

Our subsequent goal is to apply the knowledge obtained in Shinchi Town to other regions. Therefore, we are currently working on developing a general-purpose evaluation system for evaluating the feasibility of a community energy supply system in accordance with various regional conditions. In this system, in addition to the data on energy supply and demand management realized at the current Shinchi Energy Center, various models for energy demand forecasting and optimal operation forecasting will be incorporated to evaluate efficient energy management. For the residential sector, we have constructed an energy demand forecast model using energy monitoring data in Shinchi Town (Lubashhevskiy & Hirano, 2018) and estimated the electricity demand distribution to calculate the potential for introducing a community energy supply. For the commercial sector, because the data available on facilities in Shinchi Town are insufficient for obtaining generalized knowledge, we are investigating forecasting methods based on regional climate conditions using existing databases (Hirano et al., 2017b). Based on these results, we aim to conduct data analysis and evaluation for horizontal expansion in other regions, and study methods for evaluating renewable energy as well as the potential for introducing cogeneration by incorporating demand forecasting.

Acknowledgements

The project introduced in this paper is being carried out under the smart community adoption promotion project with NIES acting as the academic advisor, based on the Basic Cooperation Agreement, for supervising Shinchi Town with the cooperation of related companies.
Feasibility assessment of the use of power plant-sourced waste heat for plant factory heating considering spatial configuration. Journal of Cleaner Production, 81, 60–69.


Yujiro Hirano
Yujiro Hirano is a senior researcher at the Regional Environmental Renovation Section of the National Institute for Environmental Studies, Fukushima Branch. He holds a doctorate of engineering and has long been engaged in research on low-carbon lifestyles remote sensing of urban surfaces, urban heat island countermeasures and urban energy system. His recent research interests are in modeling and analysis of regional energy system for environmental renovation plans.

Shogo Nakamura
Shogo Nakamura is a researcher in the Regional Environmental Renovation Section of the National Institute for Environmental Studies, Fukushima Branch. He holds a Ph.D. in agricultural science. He has played a central role in developing the energy monitoring systems in Shinchi as well as many other areas in Fukushima. Recently his interests have led him to participate in the Environment-Economy-Society Integration Research program.

Takuya Togawa
Takuya Togawa is a senior researcher at the National Institute for Environmental Studies, Fukushima Branch. He received his doctorate in engineering from the Graduate School of Environmental Studies, Nagoya University in 2010. He is engaged in research on mechanisms for realizing disaster recovery and regional revitalization by effectively utilizing local environmental resources.

Tsuyoshi Fujita
Tsuyoshi Fujita is a principal researcher at the Center for Social and Environmental Systems Research, National Institute for Environmental Studies. He is concurrently a professor in the Department of Urban Engineering, University of Tokyo. His main fields of interest are the regional SDGs, regional circular and ecological systems, and urban industrial symbiosis. He is also a registered professional engineer in the field of civil engineering and architecture.

Kenichi Adachi
Kenichi Adachi is director of Japan Environment Systems Co., Ltd. He graduated from the Faculty of Engineering, Yokohama National University. He is currently engaged in research and planning related to architecture, energy and the environment in cities and regions, particularly on the themes of district heating, low-carbon community development, smart communities, microgrids and hydrogen utilization supply chains.

(Received 7 September 2020, Accepted 21 December 2020)
Longitudinal Evaluation of Energy-saving Effects and Their Implication Using Electricity Monitoring Data in Shinchi Town, Fukushima

Ayami OTSUKA1* Yujiro HIRANO2 Shogo NAKAMURA2 Tsuyoshi FUJITA3 and Daisuke NARUMI1

1 Faculty of Social Sciences, Waseda University
1-6-1 Nishi Waseda, Shinjuku-ku, Tokyo 169-8050, Japan
2 Regional Environmental Renovation Section, Fukushima Branch, National Institute for Environmental Studies
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
3 Center for Social and Environmental Systems Research, National Institute for Environmental Studies
16-2 Onogawa, Tsukuba-shi, Ibaraki, 305-8506 Japan
4 Faculty of Environmental and Information Sciences, Yokohama National University
79-7 Tokiwadai, Hodogaya-ku, Yokohama-shi, Kanagawa, 240-8501 Japan
*E-mail: aotsuka@aoni.waseda.jp

Abstract

This study evaluated the energy-saving effects of electricity consumption monitoring and energy-saving campaigns in Shinchi Town, Fukushima, Japan, where a community energy management system was introduced as part of recovery efforts after the Great East Japan Earthquake of 2011. First, a longitudinal evaluation through all six energy-saving campaigns conducted since 2014 illustrates that the first campaign showed the highest energy-saving effect, indicating the energy-saving potential brought by visualization of one’s own energy consumption by home energy management systems (HEMS). Declining trends in energy-saving were observed over time. In addition, the correlations between the effects of energy-saving campaigns and trends in longer-term electricity use were noted to be minimal, indicating that the effects of energy-saving campaigns did not continue beyond the campaign period. It appears, however, that electricity consumption rates were restrained during each campaign implementation period. The fact that repeated appeals for energy savings were met with responses by the study target each time provides good prospects for demand-response processes that incorporate consideration of renewable energy usage.

Key words: electricity monitoring, energy-saving campaigns, residential sector, supply-demand balance

1. Introduction

The 2015 Paris Agreement was signed in response to an increased need to tackle global warming. To accomplish the aims of the Agreement, saving energy and promoting a low-carbon society are issues of utmost urgency. Under the Paris Agreement, Japan pledged to reduce CO2 emissions in the residential and commercial sectors by 26% compared to 2013 levels. Of this, approximately 22% is to be reduction of CO2 originating from energy use, wherein the residential sector is to reduce CO2 emissions by approximately 40% (Global Warming Prevention Headquarters, 2020).

Providing information to energy consumers is considered essential for promoting energy-saving activities. One means of doing so is to develop home energy management systems (HEMS) that enable “visualization” of energy usage. A variety of efforts, including energy-use diagnostics, offering advice regarding energy conservation, and various ways of making energy “visible” within the home, often conducted as part of smart-city empirical social experiments, have been performed using HEMS data for promoting energy-saving.

The Great East Japan Earthquake (GEJE) of 2011 made Japan’s citizens more inclined to save energy in general. It also changed the situation surrounding energy issues in Japan. A fixed-price feed-in-tariff (FIT) system for renewable energies, for instance, was put in place. Progress was also made toward liberalizing electrical power retailing.

Amid these changes, energy demand-and-supply management on a regional scale is becoming increasingly important. Indeed, 13% of the targeted 40% reduction for the household sector under the Paris Agreement concerns low-carbonizing of electrical power, increasing anticipations of more aggressive introduction of renewable energy (Global Warming Prevention...
Headlines. Community energy-management systems centered on renewable energies are essential to enable active transformation of energy demand to meet the fluctuating output levels of renewable energy, which is highly dependent on weather conditions, and this is a key means of ensuring stability in the power supply-and-demand balance.

This demand-response (DR) method can be defined as inducing leveling of electricity demand by shifting electricity consumption patterns via such measures as electricity price setting or payment of incentives, as summarized under the terms used by the Agency for Natural Resources and Energy (2020). In other words, DR is a mechanism by which energy consumers can contribute to balancing of supply versus demand for electricity. During “smart city” social demonstration experiments conducted shortly after the Earthquake, a number of studies were conducted regarding peak-cut effects in times of “tight” supply and demand for seasonal reasons, namely air-conditioning and heating. In Yokohama City, a maximum 15% peak-cut (compared to the past performance baseline) was reportedly observed for seasonal demand in the household sector (City of Yokohama, 2017). A study in Kitakyushu City also showed 10%–20% peak-cut effects via price setting (New Energy Promotion Council, 2014). On the other hand, concurrent with the more widespread use of renewable energy in the future, increased needs for DR are likely, particularly for balanced-adjustment effects with regard to weather-induced fluctuations of supply. However, there is a lack of knowledge on this issue since there have been few case studies on regional energy systems, especially with regard to the establishment of small smart communities in rural areas.

A broadly common issue in promoting energy conservation to counter global warming and energy supply/demand (S/D) management is that changes in energy demand depend on the behavior of energy consumers, that is, individuals in society. In this regard, knowledge about ways of inducing energy-saving behavior can provide cues for evaluating future energy-demand flexibility. In fact, Shimoda et al. (2020) state that there is a need to accumulate more research and knowledge in energy demand science, a new interdisciplinary science that integrates natural, behavioral and data science, whereby two conflicting requirements for promoting energy saving while at the same time seeking to increase energy demand flexibility should be effectively addressed.

In this regard, the aims of this paper are three-fold. The first is to present a longitudinal evaluation of the results of six energy-saving campaigns conducted using electricity usage data from HEMS in Shinchi Town, Fukushima Prefecture. This system was established as a smart-community development project, part of the town-revitalization plan aimed at recovery from the damage caused by the Earthquake. The second is to attempt to evaluate electricity-consumption trends over a longer term, also using HEMS data. The final aim is, by combining the results of the above-mentioned two sets of longitudinal evaluation, to draw implications for controlling electricity demand towards introduction of low-carbon community energy systems.

2. Overview of the Study

2.1 Study Target

In this paper, a case study from Shinchi Town, Fukushima Prefecture is presented. Shinchi is a small municipality with a population around 8,000, located at the northernmost tip of the Fukushima coastline, bordering with Miyagi Prefecture to the north and west, Soma City to the south, and the Pacific Ocean to the east (Fig. 1). It is approximately 300 km north of Tokyo.

In Shinchi, around 20% of the town area was damaged or destroyed during the Earthquake of March 2011. In December 2011, Shinchi was selected as an “environmental future city” under the Japanese government’s “FutureCity” Initiative. Since then, the “Smart Hybrid Town” concept has been applied as part of the town’s redevelopment efforts to enhance its environmental, economic and societal values. A local information network system (regional ICT system) was established to disseminate information about energy-conservation activities in the area, provide regional information and bulletin boards and support the daily lives of senior persons among other functions. Energy usage has been made visible from 2014 through smart meters and electronic display terminals under the “Shinchi Daily Life Assistance System (SDLAS)” utilizing this ICT system. In addition, with the long-term vision of meeting a portion of the region’s energy needs by local energy companies using thermal power and natural energy, Shinchi Smart Energy, a special purpose company, was established in February 2018 to supply energy locally. It began supplying energy to a certain part of the redeveloped areas by the end of the 2018 fiscal year (FY). Subsequently, it has aimed to perform S/D adjustment via DR during actual operations (Shinchi

Fig. 1 Location of Shinchi Town.
The target of this study is the households that have volunteered to be monitored under the above-stated SDLAS. Energy monitoring started from June 2014 in the order of the participants’ selection. While the number of households peaked at 75 during FY2015, data from 68 households were used in this study, due to withdrawal from the program and system connection status. Figure 2 presents the main demographic attributes of the households, summarized from responses to a questionnaire survey conducted at the time of volunteer recruitment. As shown in the figure, characteristics of households in Shinchi differed from those of urban area households, in that many were three-generation households with a large number of family members, and that they frequently used kerosene for heating and water-heating purposes. Although not described in the figure due to sample-number differences, Shinchi residences characteristically had large houses with 5–15 rooms each (38 of 39 households covered in a lifestyle survey conducted in December 2014). While it is not clear how the target households of this study had been affected by the Earthquake, it is reasonably presumed that physical damage to their houses was not so severe, judging from the fact that a majority continued to live in houses constructed before the Earthquake.

### 2.2 Electricity Monitoring

The HEMS units used in Shinchi were installed in the monitors’ existing detached homes. Each household participating as a monitor under SDLAS chose six lines for monitoring whereby visualization of electricity was enabled. The six measuring points, therefore, differed according to household: some chose individual lines such as air-conditioning in each room, whereas others chose six rooms such as kitchen, bedroom, child room, etc. In this respect, the electricity monitoring system in Shinchi differed from the standardized HEMS collectively installed in newly built apartments where what was monitored was consistent for all households. Total values for each monitoring line, as well as the total electricity consumption for the entire household, all measured hourly, were stored on a cloud server. A tablet computer was distributed to each household to provide information on energy consumption and other life-related details described above.

Table 1 summarizes the daily average electricity consumption per household by number of persons and by season, according to the HEMS monitoring data.

<table>
<thead>
<tr>
<th></th>
<th>Spring</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2 persons</td>
<td>12.98</td>
<td>14.97</td>
<td>11.47</td>
<td>18.69</td>
</tr>
<tr>
<td>3-4 persons</td>
<td>12.30</td>
<td>13.43</td>
<td>11.08</td>
<td>20.05</td>
</tr>
<tr>
<td>5-6 persons</td>
<td>16.57</td>
<td>19.19</td>
<td>15.67</td>
<td>24.20</td>
</tr>
<tr>
<td>&gt; 7 persons</td>
<td>24.02</td>
<td>27.38</td>
<td>24.30</td>
<td>38.66</td>
</tr>
</tbody>
</table>

(unit: kWh/day)

The seasonal data comprised the following from 2015 to 2017: spring and fall, i.e., two-week periods with low variability in average temperatures; summer, i.e., a two-week period with higher average temperatures with the least fluctuation; and winter, i.e., a two-week period with lower average temperatures and the least variability. While demand increased during summer and winter due to air-conditioning and heating, considering that Shinchi is located in a coastal district, a comparatively cooler climate meant that summer peaks were lower compared to those for the Tokyo Metropolitan Area. Conversely, while there was comparatively little snowfall in the area despite its location in the Tohoku region, the winters were cold, leading to high peaks in demand for heating and kerosene. Households having a larger number of inhabitants (especially for households of seven or more persons) typically had higher electricity consumption. The exception was that households with one to two persons had higher electricity consumption in all seasons other than winter compared to households with three to four persons. This was possibly because one-to-two person households in urban areas often have one or both adults working and not home during the daytime. Meanwhile, one-to-two person households in Shinchi would have higher consumption given the characteristics of rural towns in Japan with their higher elderly population ratios, where either one or both adults are already retired and staying home during daytime, leading
to higher electricity consumption. In addition, in terms of hourly electricity usage, data from the monitoring system were characterized by a morning peak at around 6 a.m. and a nighttime peak from around 6 p.m. and thereafter.

2.3 Energy-saving Campaigns

Since the establishment of the monitoring system and start of measurement, six different electricity-saving campaigns have been promoted (Table 2). In campaigns 1–3, the top-ranking households were awarded coupons for local shopping. However, no such incentives were offered during subsequent campaigns.

In the first two campaigns (campaigns 1–2), real-time assessment of power consumption was enabled in individual households as details of power consumption (including rankings that allowed comparisons between households) were made “visible” to householders (Masuda et al., 2018). In the four subsequent campaigns (campaigns 3–6), in addition to the above information, households were provided paper-based reports titled “Shinchi Energy Savings Newsletter (kawara-ban)” containing advice and suggestions (Fig. 3). Information was provided in Japanese and customized for each household, including consumption percentages by the hour of day and system type. Moreover, other general information on energy saving tips was provided, such as the amount of energy-conservation expected from replacing existing electrical devices with more energy-efficient equivalents.

With the exception of Campaign 5, where no verification was made of per-household energy-savings effects, in each campaign, the average energy-savings effects of participating households ranged from –5.0% to +2.9% (Shiraki et al., 2016; Nakamura et al., 2017; Masuda et al., 2018). The negative figure of –5.0% indicating an increase in electricity use for Campaign 2 was reportedly due to “wear-out” effects, according to Shiraki et al. (2016), as the first and the second campaign took place only one month apart from each other. It should be noted, however, that as evaluation methods differed by campaign, no overall comparisons across the six campaigns were possible.

2.4 Methods of Longitudinal Evaluation for Electricity Consumption and Energy-savings Effects

A suitable method was needed to evaluate energy-
Longitudinal evaluation of energy-saving effects and its implication using electricity monitoring data

savings effects longitudinally across the past campaigns as well as changes in energy consumption over time after introduction of the electricity monitoring system. For this, following the method used in the most recent campaign (Campaign 6), a prediction formula was employed that was derived from temperatures and actual electricity consumption of each household.

The daily electricity consumption of each household against the daily average outside temperature for Shinchi Town as published by the Japan Meteorological Agency (2017) was plotted for the period from June 2014 through August 2017. Quadratic polynomial approximation lines were then drawn on the scatterplot for each fiscal year, and the derived equation was used as the prediction formula for per-household electricity consumption for each fiscal year (Fig. 4). Hence, scatterplots and prediction formulas were created for all the selected 68 households.

To assess electricity consumption over time, year-to-year changes were first computed for three values of temperature representative of each season, viz. 5°C (winter), 15°C (spring and fall) and 25°C (summer). For assessing change rates over time, the change rates for each fiscal year, and change rate between FY2015 and FY2017 were calculated to assess the changes over a longer period of time. Then, to assess the effectiveness of past energy-saving campaigns, actual daily average temperatures were included in the prediction formulas for the fiscal years wherein the campaign was conducted. Subsequently, the differences between the predicted values (from which temperature effects were excluded) and actual measured values within the campaign period were considered “energy-saving effects” (or, vice versa, energy-increase effects).

It is noteworthy that for evaluating energy-saving campaigns, the use of randomized controlled trials (RCTs, which involve the random allocation of test subjects to the control group) is recommended for greater accuracy. However, it is also often considered difficult to perform strict RCTs (Bhushan et al., 2018) for any experiment involving the household sector, largely because of costs, and secondarily because it often requires voluntary participation in questionnaire surveys to enable researchers to understand background factors for behavioral changes. This conflicts with the nature of RCTs. There is a commonly recognized need for more appropriate evaluation methods in cases where RCTs cannot be performed (Bhushan et al., 2018; Vine, 2014). The same issue was shared in this study: the participating households were originally voluntary, and it was difficult to include non-monitored households to serve as a control. Hence, in the present study the method used was based on actual data from each household and predicted values estimated using the formula.

However, the prediction accuracy (i.e. $R^2$ value of the prediction equation) varied by fiscal year. In the case of households in Fig. 4, the $R^2$ value for the same household varied from 0.47 to 0.79. This variation was considered due to limited data availability: for FY 2014 and FY 2017, the data used for analysis included only specific periods, possibly lowering $R^2$. Moreover, factors that could potentially explain increases in electricity consumption in particular fiscal years (e.g., FY 2014) are unknown. Although questionnaire surveys aimed at identifying factors that could potentially influence electricity consumption (e.g., purchase of energy-saving household electrical appliances, or changes in family composition) were conducted, but it proved difficult to ascertain all factors. These limitations were taken into consideration during the analysis and attempts were made to estimate energy-saving and increase effects from electricity monitoring data and the results of the energy-savings campaigns.

![Fig. 4 An example of scatterplots and prediction formulas.](image-url)
3. Results and Discussions

3.1 Longitudinal Evaluation of the Energy-saving Campaigns

Results of longitudinal evaluations of the past six energy-saving campaigns are indicated in Fig. 5. The horizontal axis depicts the campaign period and the preceding and succeeding two-week periods. However, as noted in the discussion regarding Table 2, the horizontal axis is not continuous, as there was more than one year’s gap between campaigns 4 and 5.

It is evident that the effect of the energy-saving campaign was up to 7.7% for subject household averages during one campaign period (Campaign 1). The corresponding values for campaigns 2, 3, and 4 were, respectively, 6.8%, 0.8%, and –3.9%, i.e., a continuous decline in its energy-saving effects. (Notably, in Campaign 3, since there were no data available to identify the participating households and their energy data, the figure indicates the average measurement values for all households). With respect to the above declining trend, and considering that only volunteer households participated in campaigns 1 and 2 during the early period of the electricity monitoring system, the results suggest that the effects of making energy usage “visible” to users were large, as these were new and of novel interest. As for Campaign 4, the large consumption increase was likely due to the fact that the campaign period covered the year end and New Year’s period. This season is associated with substantial changes in normal daily-life patterns (e.g., household members spending a longer time at home, and relatives and guests coming to visit from outside). For campaigns 5 and 6 these figures were 0.1% and –1.3%, respectively. While these indicate improved energy-savings rates compared to those for Campaign 4, these figures showed a slight increase vis-à-vis predicted values used for longitudinal evaluation, i.e., prediction values from which atmospheric temperature effects were excluded. Energy-savings effects were particularly evident during the period following the end of Campaign 6. This campaign was designed such that upon its conclusion the participants were provided individualized information concerning results from the campaign period (Masuda et al., 2018). It is possible that the effects of presenting this information were thus delayed until after the campaign.

As mentioned earlier, repeated requests to the same study subjects to save energy showed a trend of progressively weaker responses to such appeals. Yet, we found that electricity consumption was lower during campaigns compared to the periods before and after each campaign.

3.2 Trends in Electricity Consumption over Time

During the energy-saving campaigns, households were provided with various information to promote behavioral changes. One example of such information is advice on replacing electricity-consuming household appliances with energy-efficient ones. With the purpose of measuring the rate of application of information in the daily life of householders, changes in electricity consumption after the introduction of the monitoring system were analyzed.

The frequency distributions of change rates of each household at each of the three air temperature values: 5°C (winter), 15°C (spring and fall), and 25°C (summer) are presented in Fig. 6. Here, negative figures in change rates indicate increases in electricity use. According to the figure, the most frequent change rates were in the range of 0%–5% decreases for winter, at 5°C, for all FY

![Fig. 5 Results of longitudinal evaluation.](image-url)
periods. The mode value for spring and fall, at 15°C, changed from a 0%–5% increase for FY 2014–2015 to 0%–5% decrease for FY2015-2016, which again shifted to a 5%–10% increase in FY2016-2017. As for summer, mode values showed divergent results in the early period after system introduction (FYs 2014–2015), i.e., a 0%–5% decline followed by a 5%–10% increase. More recent trends in FY2015-2016, and FY2016-2017 show even more divergence among the households, where the mode is within the 0%–5% increase range while the number of households with decreasing trends have also increased.

The average electricity consumption change over time for all households at the same air temperature of 5°C, 15°C, or 25°C, presented in Fig. 7, indicates these trends more clearly. Considering the comparably longer period from FY2015 through FY2017, average change rates showed a slight increase in electricity use by 1.2%–2.3% for all three temperatures. The trends in change overtime varied by season, however. In winter, they started with a decline in the FY2014 and FY2015 periods, which turned into an increase subsequently. That increase was especially large in the more recent period from FY2016 to FY2017. The trends in spring and fall were opposite: starting with a large increase in the beginning which then turned into a gradual decrease. The trend in summer indicated mixed results: an initial large increase turning into a decrease, as in spring and fall, but it shifted to an increase again more recently in the FY2016-FY2017 period, yet the increase is somewhat restrained. An overall increasing trend on average, with particularly large increases during winters, suggests that the average values were impacted by households that showed large increases, despite there being a number of households showing a decreasing trend, as discussed regarding Fig. 6 above.

3.3 Correlation between the Two Energy-saving Effects

From these results, the relationships between previous energy-saving campaigns and changes in over-time electricity consumption rates were explored by a series of correlation analyses. For instance, in Fig. 8, the vertical axis represents change over time rates (at 5°C) from FY 2015 to FY 2017, while the horizontal axis shows average energy-saving effects for each household during campaigns 1 through 6. This figure suggests that the energy-saving effects (reduction rates) of campaigns and electricity consumption change rates over time were mostly uncorrelated. The same was observed for other temperatures (at 15 °C and 25 °C), or for individual analyses by each campaign. In other words, the effects of each energy-saving campaign did not translate to steady, long-term energy-saving effects.

The probable reasons for this are as follows. Reduction effects from energy-saving campaigns appeared to be due, in a relatively pure fashion, to changes (reductions) arising from engagements during the campaign period. Meanwhile, rates of changes over time are likely to have been more strongly impacted by factors other than purely energy-saving effects, such as, changes in household member configurations. This is
family size as well as age of the house, normally known from the aftermath of the Earthquake. Important for this study, which looks at redevelopment "prospects for Shinchi Town" were something unique but cognition, whereas variables "life satisfaction" and "behavior" was used here to represent such conventional behaviors. The variable "actively taking energy-saving change people's cognition and/or awareness and energy-saving campaigns the purpose of which is to consider important to include similar cognitive variables. The link between the increase in energy consumption is indeed related to the in-situ (i.e., self-produced) use of solar power, it is not necessarily a problem as it represents a low-carbon energy source, especially if the solar-powered electricity is used as a variable indicating practices in replacing appliances to back-up this reasoning, the fact that this variable was included as an influencing factor for spring and fall (at 15°C), when the increased sample number (n=68) was used without the inclusion of cognitive variables, may reasonably imply such a possibility, especially given the overall trend in the decreasing change rate at 15°C as discussed earlier.

It is also noteworthy that cognitive variables such as "actively conducting energy-saving behavior" and "having good prospects for town redevelopment in the future" contribute to energy-saving. This is especially true for winter, when the cognitive variable "actively taking energy-saving behavior" shows the strongest influence on the change (decrease, in this case) rate. The fact that the age of the house is the second most influential factor (in the increasing direction) in winter highlights the need for promoting better insulation. This is in line with the current energy-saving promotion policy in Japan, and will be an important agenda to raise, given the location of Shinchi in the Tohoku region with a cold winter climate. Implementation of such measures for existing houses poses a challenge, however, as it is something not simply achievable through behavioral changes in everyday life.

On the other hand, “installation of solar panels” has been one of the factors pointing toward increased electricity consumption over time in summer. The same trend for having solar panels was observed in other seasons, at both 5°C and 15°C, when the analysis was conducted with a larger sample number (n=68) without cognitive variables. The link between the increase in electricity consumption and having solar panels per se is not necessarily a problem as it represents a low-carbon energy source, especially if the solar-powered electricity is used towards enabling net-zero electricity in a house. If the increase in electricity consumption is indeed related to the in-situ (i.e., self-produced) use of solar power, it then makes the challenge of effective S/D management a reality. There is a need to investigate this relationship further with increased samples, though it was not possible in this study due to limited availability of data. It is also noted that a new awareness arising for DR in terms of climatic fluctuation is necessary. Again, that “actively taking energy-saving behavior” was also associated with an increase, rather than decrease, in electricity consumption in summer poses a challenge, but the fact

Table 3 Factors influencing rate of change over time.

<table>
<thead>
<tr>
<th>Name of variables</th>
<th>Standardized β</th>
<th>5°C</th>
<th>15°C</th>
<th>25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Family size</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Family size (increased)</td>
<td>0.328</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Family size (decreased)</td>
<td>-0.205</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of persons at home (weekday)</td>
<td>-0.260</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of persons at home (weekend)</td>
<td>0.356</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residence area</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (at application)</td>
<td>0.281</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age of family (infants)</td>
<td>0.383</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age of family (juniors)</td>
<td>-0.729</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age of family (&gt;65)</td>
<td>-0.205</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occupation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Family income</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year built</td>
<td>0.366</td>
<td></td>
<td>0.507</td>
<td></td>
</tr>
<tr>
<td>Solar panel installed</td>
<td>0.507</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All electric</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air-conditioning type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of air conditioners</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of heating units</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of elec. appliances</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of lights</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active in energy-saving behavior</td>
<td>-0.452</td>
<td></td>
<td>0.396</td>
<td></td>
</tr>
<tr>
<td>Life satisfaction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prospect for Shinchi Town</td>
<td>-0.299</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjusted R2</td>
<td>0.432</td>
<td>0.171</td>
<td>0.515</td>
<td></td>
</tr>
</tbody>
</table>

*p < 1%, 5%, 10%. Step-wise regression analysis was used: empty cells in the Table therefore mean that these were not identified as influencing factors although these were also included in the analysis. There are no VIF figures, suggesting multicollinearity among the variables.

Indeed indicated in the results of a series of step-wise regression analyses (Table 3). Here, the rates of change over FY2015 to FY2017 at each temperature were used as dependent variables, whereas households' demographic and housing attributes, partly presented in Fig. 2, were used as independent variables. People’s subjective cognition on energy issues as well as general well-being obtained from a survey conducted during one of the energy-saving campaigns, namely Campaign 4, were also included in the analysis (though limiting the sample size, i.e., 35). Cognition of energy-issues, such as societal responsibility and efficacy, is known to have certain influences on energy-saving behaviors and thus energy consumption (e.g., Otsuka et al., 2017), so it was considered important to include similar cognitive variables as this study directly addresses the effect of energy-saving campaigns the purpose of which is to change people’s cognition and/or awareness and behaviors. The variable “actively taking energy-saving behavior” was used here to represent such conventional cognition, whereas variables “life satisfaction” and “prospects for Shinchi Town” were something unique but important for this study, which looks at redevelopment from the aftermath of the Earthquake.

The results show that changes (increase/decrease) in family size as well as age of the house, normally known to be factors affecting energy consumption, are found to be have an influence with statistical significance. The number of electric appliances was associated with a negative influence (i.e., decrease in change rate) – the opposite of what is normally expected. One of the reasons for this could be that it gave opportunity for people to replace these appliances with more efficient ones according to the energy advice given during the energy-saving campaigns. Although there were no data available which could be used as a variable indicating practices in replacing appliances to back-up this reasoning, the fact that this variable was included as an influencing factor for spring and fall (at 15°C), when the increased sample number (n=68) was used without the inclusion of cognitive variables, may reasonably imply such a possibility, especially given the overall trend in the decreasing change rate at 15°C as discussed earlier.
that people’s attachment to locality as shown in the prospects for the future of the town contribute to an energy-saving effect gives hope in terms of community energy-management systems.

4. Conclusion

This study used electricity monitoring data for independent households within Shinchi Town, Fukushima Prefecture to investigate: 1) energy-(electricity)-saving effects during energy-saving campaigns and, 2) long-term changes in electrical power consumption, in an aim to learn from them and assess the implications of S/D balancing effects in the future. The conclusions drawn from the results are summarized as follows.

The energy-saving effects due to the implementation of each energy-saving campaign showed declining trends over time. It appears, however, that electricity consumption rates were restrained during each campaign implementation period.

With regard to changes related to over-time electricity consumption tendencies beyond the period of the energy-saving campaigns, while there was an increasing tendency overall, there were also numerous households that showed a declining tendency. This was apparent when considering changes during each fiscal-year period and changes within individual households. There were also households that showed restraint in their increase of electricity consumption. Notably, however, the effects of energy-saving campaigns were limited and mostly did not continue beyond the campaign period. Hence, it follows that measures are required, especially regarding seasonally increased electricity consumption trends, to promote and stabilize further energy savings.

To summarize the study’s findings, considering that the effects produced during the energy-saving campaigns did not translate into long-term effects, it can be said that even stronger engagement and educational/awareness-raising efforts are needed. In doing so, new issues such as building insulation, noted to be quite influential during wintertime, may need to be addressed. Moreover, given the fact that households responded to repeated appeals for energy savings, it sheds light on future prospects that requests made to consumers via processes such as demand-response (DR), that are likely to be long-term, continuous and more frequent within community energy management systems than in the energy-saving campaigns used as the case study in this paper will also be responded to by the targeted consumers, implying that consumers are ready to make changes when so requested. This gives further positive prospects that the results of the energy-saving campaigns would have been more positive if evaluation by randomized control tests had been available.

With regard to further work in the target area of the present study, this study was limited to covering only the electricity usage in the households. Given the climatic conditions, where heating is often conducted using energy sources other than electricity as well as warmer summer temperatures in the most recent years, it would be worthwhile to study people’s behavioral responses to similar requests regarding heating as well as in hotter summers.

Further, similarly to energy-saving campaigns conducted in the past, it is also important to investigate and verify the people’s responses and behavioral changes in settings whereby actual demand-and-supply balance adjustment requests, although virtual, are given that incorporate considerations for renewable energy usage.

References


A. OTSUKA et al.

Daisuke Narumi is a professor at Yokohama National University. He received his PhD in engineering from Osaka University in 2003. His doctoral thesis was titled, "Study on the Planning Methods of Urban and Architectural Environment in Harmony with Surrounding Climate Characteristics." His specialty is urban and architectural environmental engineering, and he has been working in research on a wide range of subjects, from energy consumption in cities and buildings to analysis of the environmental impacts associated with energy consumption. His major awards include the Encouragement Prize from AIJ and Paper Award from the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan.

Tsuyoshi Fujita is a principal researcher at the Center for Social and Environmental Systems Research, National Institute for Environmental Studies, University of Tokyo. His main fields of interest are in regional SDGs, regional circular and ecological systems, and urban industrial symbiosis. He is also a registered professional engineer in the field of Civil Engineering and Architecture.

Yujiro Hirano is a senior researcher at the Regional Environmental Renovation Section of the National Institute for Environmental Studies, Fukushima Branch. He holds a doctorate of engineering and has long been engaged in research on low-carbon lifestyles remote sensing of urban surfaces, urban heat island countermeasures and urban energy system. His recent research interests are in modeling and analysis of regional energy use for environmental renovation plans.

Shogo Nakamura is a researcher in the Regional Environmental Renovation Section of the National Institute for Environmental Studies, Fukushima Branch. He holds a Ph.D. in agricultural science. He has played a central role in developing the energy monitoring systems in Shinchi as well as many other areas in Fukushima. Recently his interests have led him to participate in the Environment-Economy-Society Integration Research program.

Ayami Otsuka is an assistant professor at the Faculty of Social Sciences, Waseda University. Holding a Ph.D. in environmental studies, she served as a visiting research fellow at the National Institute for Environmental Studies from October 2017 to March 2019. Her main research interest lies in integrating energy research and social sciences, with a particular focus on citizens’ roles in realizing a sustainable society.

(Received 23 September 2020, Accepted 25 December 2020)
Impact of TEPCO Nuclear Accident and Associated Evacuation to the Demography in Fukushima

Kei GOMI

Fukushima Branch, National Institute for Environmental Studies
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
*E-mail: gomi.kei@nies.go.jp

Abstract

The nuclear accident at Tokyo Electric Power Company’s Fukushima Daiichi Nuclear Power Station resulted in evacuation orders being issued for the surrounding municipalities. These have been lifted one by one, and people have begun to return to their hometowns. When considering the reconstruction and long-term development of these areas, population recovery is the most fundamental factor. In this study, I analyze the demographics of these areas, including how the inhabitants’ return is proceeding, from multiple statistical sources. The results show that out-migration according to official registration has returned to its previous trend again since 2013, that progress in evacuees’ return after the lifting of the evacuation order varies from region to region, and that the proportion of women of reproduction age is low among residents in the areas where the evacuation orders have been lifted.

Key words: demographic transition, disaster recovery, evacuation, nuclear accident

1. Introduction

The accident at Tokyo Electric Power Company’s (TEPCO’s) Fukushima Daiichi nuclear power plant following the Great East Japan Earthquake in 2011, resulted in evacuation orders being issued for the surrounding areas. Since then, as the accident was brought under control and radiation levels dropped, the evacuation orders have been lifted one by one. In areas where the orders have been lifted, residents who had been evacuated are now returning to their hometowns. For areas forcibly evacuated due to the disaster, population recovery is the most basic element of reconstruction. Therefore, it is important to understand the demographics of these areas so as to plan for future recovery. It remains unclear, however, how many people will eventually return to the areas affected by radioactive contamination, as we have no experience in recovery from such large-scale evacuations and the longer the evacuation period, the more settled the residents will become in their evacuation sites. For example, according to a survey conducted by the Reconstruction Agency and local governments, more than half of the people in some areas have decided not to return (Reconstruction Agency, 2020). In this study, we will investigate the demographics of the evacuation areas from the time of the disaster to the present situation, analyze trends by factor, clarify the actual circumstances and identify issues from the perspective of recovery.

Morita et al. (2018) analyzed the evacuation behavior of people in Minamisoma, Japan, when the evacuation orders were issued in the month after the disaster, and found that (1) males were more likely to have stayed there against the evacuation orders than females, and (2) residents aged 40–64 years old were more likely to have stayed there than were those aged 75 years or older. Heuer et al. (2020) analyzed population migration patterns from the affected areas before and after the disaster on a prefecture-by-prefecture basis by comparing evacuees (those who remained registered at their original address) and out-migrants (those who had registered in other prefectures). Their results showed that the composition of the areas to which the out-migrants had moved had not changed from before the disaster, while the evacuees, unlike the out-migrants, chose to live in more neighboring areas. Higuchi et al. (2012) analyzed a variety of statistics for the first ten months after the disaster and found the number of excess out-migrants from the three affected prefectures to be four times greater than in 2010, with the largest number in April 2011, nearly 80% of the total number of the excess, was people moving out from Fukushima Prefecture, with the largest number of people moving to Tokyo. Hashimoto and Kawakami (2015) conducted an analysis of population movement by municipality based on the Basic Resident Registration System (BRRS) and found that the higher the average income and the greater the degree of damage,
the higher the out-migration rate tended to be, and that even after adjusting for economic factors and the degree of earthquake and tsunami damage, the out-migration rate was higher from municipalities in Fukushima Prefecture than from the other two (Iwate and Miyagi). In relation to deaths, it has been noted that Fukushima Prefecture had a higher incidence of disaster-related deaths than other areas affected by the Great East Japan Earthquake due to the nuclear disaster (Kubo et al., 2017). It has also been shown that among the elderly in the same affected areas in Fukushima, the mortality rate was higher among the evacuees than among those who did not evacuate (Nomura, 2016).

Based on the fact that several more years have passed since the previous studies above, and that evacuation orders have been lifted and people have been returning to their hometowns in the meantime, this study targets the areas affected by the nuclear disaster, with a special focus on the areas where evacuation orders had been issued, and clarifies the overall demographic picture, including progress in evacuees’ return, from multiple statistical sources. We present the results in Chapter 3 and discuss their implications from the perspective of recovery in Chapter 4.

2. Method

2.1 Target Areas and Periods

The target area was the 11 municipalities where evacuation orders had been issued. The scope and type of evacuation orders changed several times since immediately after the disaster. The following three zones, some of which were in place for a relatively long time and some of which are still in place today, were established in August 2013: Zones in preparation for the lifting of the evacuation order (herein, Zone 1), restricted residence areas (herein, Zone 2), and difficult-to-return zones (herein, Zone 3). In Kawauchi Village, all villagers were evacuated in 2011 after the accident and then began to return to their homes on January 1, 2012, except for some areas (later becoming zones 1 and 2), and then in 2016, evacuation orders for Zones 1 and 2, which together accounted for about 10% of the village’s population, were lifted. Because of this history and the lack of detailed population information from the town, we treat the entire town as one area without distinguishing between the evacuation zones. Table 1 lists these municipalities and the populations of the evacuation zones, the timing of the lifting of the evacuation orders, and the scope of analysis of evacuees’ return in this study. In principle, the period covered is until the end of June (or July 1, 2019). This is because, in Japan, the new fiscal year begins in April and many people relocate between March and April, and this kind of movement is thought to have settled down by the end of June. However, different time periods may be used in the individual analyses. In such cases, the periods are indicated in each item. In addition, most of the evacuation orders for Zones 1 and 2 had been lifted by that time.

2.2 Information Sources and Analytical Methods

Currently, there are four main sources of information for determining the population of the evacuated areas. The BRRS, national census, resident population according to municipalities’ tallies, and mobile phone location information. Each of these has its own strengths and weaknesses, but by combining them, we can see the

<table>
<thead>
<tr>
<th>Table 1 Basic profile of target municipalities in this study.</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study examines the 11 municipalities that appear in this table. They have different proportions of the three categories of evacuation zone (Zones 1, 2 and 3).</td>
</tr>
<tr>
<td>Population (July 31, 2013)</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>Minamisoma City</td>
</tr>
<tr>
<td>Iitate Village</td>
</tr>
<tr>
<td>Kawamata Town</td>
</tr>
<tr>
<td>Katsurao Village</td>
</tr>
<tr>
<td>Tamura City</td>
</tr>
<tr>
<td>Namie Town</td>
</tr>
<tr>
<td>Futaba Town</td>
</tr>
<tr>
<td>Okuma Town</td>
</tr>
<tr>
<td>Tomioka Town</td>
</tr>
<tr>
<td>Naraha Town</td>
</tr>
<tr>
<td>Kawauchi Village</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

All residents evacuated in 2011. Return started on January 1 2012 except for Zone 1 and Zone 2. The rest was lifted in June 4 2016.
whole picture. Table 2 summarizes the advantages and
disadvantages of each statistical source and how they are
used in this study. The details of each statistical source
and method of survey and analysis in this study are
discussed below.

The BRRS is municipality-based, middle-frequency
and detailed. It contains basic demographic statistics that
provide a complete picture of births and deaths by sex
and age, and are usually compiled by local governments
on a monthly basis, while annual reports are made
available to the public by the central government of
Japan. However, because the data are based on
registration by residents, people are sometimes registered
in a different place from where they currently live. For
this reason, it is not possible to obtain the actual
population of areas from which residents have evacuated
and begun returning to in this study. In addition, BRRS
does not have information on the daytime population
because it does not include information on where people
work and go to school. Therefore, for example, if a
business has reopened in the area due to reconstruction,
but the employees do not live in the area but commute to
work there from outside the area, it is not possible to
determine the daytime demographics of the area from the
BRRS. In this study, from the BRRS, we obtained the
total population, net social change, net natural change and
composition by sex and age on an annual basis. We
compared pre-disaster trends between municipalities
designated as evacuation areas and the rest of Fukushima
Prefecture, focusing on 2011 and covering seven years
before and after the disaster (2004–2018). However, due
to municipal mergers within the region, social changes
are calculated from 2007 to 2018, the year after the
merger (as it is not possible to determine retrospective
movements between merged municipalities). Regarding
the composition of the population by sex and age, we
compare the residential data for each municipality on
January 1, 2018 with the composition of the number of
residents in the area based on mobile spatial statistics (see
the following chapter).

The number of residents in the municipality tally
was compiled by the local governments in whose areas
the evacuation orders had been lifted, and they asked
returning residents to report on the status of their return.
Many of the municipalities publish the population and
number of households present as well as those still
evacuated monthly on their websites. This information is
very important for identifying the actual situation of
people living in the evacuated areas. Each municipality,
however, differs in whether it publishes the information,
how long it is available on the websites, the details on
age, sex and location of the population, and whether it
classifies people who have moved into the area from
outside after the disaster. In addition, because the system
is not as enforceable as BRRS, there may be residents
who do not report their immigration status or return to
their hometowns, or residents who report their
immigration status but actually live outside the area. In
this study, we collected the number of residents and
evacuees published by each municipality from the month
when the evacuation order was lifted until June 30 (or
July 1) 2019 to calculate the rate of return. The rate is
defined as the sum of the number of residents in the area
where the evacuation order was lifted plus the number of
registered evacuees in the area, divided by the number of
registered residents in the same area, and is calculated for
the area and time period for which the information is
available. To confirm progress toward population
recovery and differences in rates, we show changes in the
rate over time. We also briefly examine the factors behind
the differences.

The census is the most fundamental source of
statistics in the nation on a municipal basis. In the case of
the evacuation in question, an individual is counted
in a different place from where they currently live. For

Table 2: Comparison of information sources on population in the target areas.

Four different statistical information sources were adopted in this study to get an overall picture of the demography in the target area. Each of them has strengths and weaknesses as shown in the table, so it is necessary to combine them.

<table>
<thead>
<tr>
<th>Use in this study</th>
<th>Census</th>
<th>Basic Resident Registration System (BRRS)</th>
<th>Municipality tally</th>
<th>Mobile phone information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal resolution</td>
<td>Low (every 5 years)</td>
<td>Middle (monthly, yearly)</td>
<td>Middle (monthly)</td>
<td>High (hourly)</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>Low (municipality)</td>
<td>Low to Middle (sub-municipality)</td>
<td>Middle (municipality, evacuation area)</td>
<td>High (500m mesh)</td>
</tr>
<tr>
<td>Demographic profile resolution</td>
<td>High (sex, age, working status, marriage status)</td>
<td>Middle (sex, age)</td>
<td>Low (total only in many cases)</td>
<td>Middle (sex, age)</td>
</tr>
<tr>
<td>Availability</td>
<td>High (provided on Web)</td>
<td>High (provided on Web)</td>
<td>Middle (varies by municipality)</td>
<td>Low (fee for use)</td>
</tr>
<tr>
<td>- Comparison of nighttime and daytime population and gender ratio in the municipalities before and after disaster (2010 and 2015)</td>
<td>- Indicators of basic demographic dynamics of each municipality (social and natural increase, birth and death rate) on an annual basis</td>
<td>- Progress of return to the areas where evacuation orders were lifted - Analysis of differences in progress between areas</td>
<td>- Analysis of gender and age structure in the areas where evacuation orders were lifted - Comparison of age and gender composition against BRRS</td>
<td></td>
</tr>
</tbody>
</table>
As a population estimate based on mobile phone location data, we used mobile spatial statistics in this study. Mobile spatial statistics are population estimates from NTT DoCoMo, Inc. based on the location of their own mobile phone users. They have a high spatio-temporal resolution and are provided in hourly, administrative boundary or 500-meter mesh units. Since they are based on the number of mobile phone users who were present at a given location at a given time, it is possible to estimate the daytime population and also to capture temporary increases in the number of people due to stays or events. On the other hand, the estimates are uncertain because they are based on the percentage of mobile phone subscribers of that company. This is especially true in areas with small populations. The same is true for younger and older people, who are less likely to have mobile phones. In addition, it should be noted that the number of residents who are staying in the area without being registered is also estimated (e.g., employees of businesses involved with work such as decontamination, decommissioning of the nuclear plant and interim storage of decontamination waste). With this information, in this study, the total number of people in December 2017 (average at night between 18:00 and 8:00 a.m.) is compared with the BRRS data (January 1, 2018). The profile of residents in the area (composition ratio by sex and age) is compared between BRRS and mobile spatial statistics to identify relatively greater or fewer people by sex and age using the Jaccard distance. The Jaccard distance is an application of the Jaccard coefficient, which was proposed by Jaccard (1912) as a method of comparing the size of the common parts of two sets, and it has been applied in various ways since then. To determine the similarity of two vectors, we compute the Jaccard distance $Jd$ using the formula below. This indicator is for two non-negative vectors of the same dimension. It ranges from 0 to 1, taking the minimum value 0 when the two vectors coincide perfectly. The larger the value, the greater the difference between the two vectors. Here, $i$ is the population profile (by sex and age), $x_i$ is the population composition ratio based on mobile spatial statistics, and $y_i$ is the population composition ratio based on the BRRS.

$$Jd(x, y) = 1 - \frac{\sum_{i} \min(x_i, y_i)}{\sum_{i} \max(x_i, y_i)} \quad \ldots (1)$$

3. Results

3.1 BRRS Data

Figure 1 shows the total population (ratio to that of January 1, 2011). The population of most areas had been decreasing even before the disaster (the exception being Okuma Town), and after a significant decrease from 2011 to 2012, the pre-disaster trend of population decline resumed again. However, the post-disaster population of most of the 11 municipalities has declined at a greater rate than in the rest of Fukushima. The social growth rate (Fig. 2) has been negative in most areas, including the rest of Fukushima, for most of the period since before the disaster. An exception is Okuma town. Before 2011, relatively young workers were constantly migrating to the town because of steady growth in industries related to the nuclear power plants (Okuma Town, 2016). In 2011, in seven out of 11 municipalities, the rate was lower than that of the rest of Fukushima. After a significant drop in 2012, the rate of natural increase remained stable in the rest of Fukushima. Nine of the 11 municipalities, except for Okuma and Tomioka, had a lower rate of natural increase in 2012 than did the rest of Fukushima. More municipalities had lower natural growth rates than rest of Fukushima in other periods as well. Although the crude birth rate has been declining over the long term, there are large year-to-year fluctuations in each of the municipalities involved, so a clear trend cannot be readily discerned from the figure. In the rest of Fukushima, because of the smoothing effect of aggregation of many municipalities, there is a clear trend toward lower birth rates in 2012 and 2013 than in the other years. This may be because people were discouraged from having children due to the 2011 disaster. Crude mortality rates had been increasing overall since before the disaster, with an overall increase in 2011 and an even higher rate in 2012. The increase in mortality rates in 2012 compared to 2011 was higher in all 11 municipalities in the study area than in the rest of Fukushima Prefecture.
Demographic impact of TEPCO nuclear accident

Fig. 1 Time-series of registered population in target municipalities and rest of Fukushima Prefecture. The registered population of the target area in the Basic Resident Registration System shows that the 11 municipalities experienced a faster population decline than rest of Fukushima Prefecture.

Fig. 2 Factors in population changes before and after 2011 in BRRS. Out-migration from Fukushima was larger in 2012 than in other years. The main contributor to the natural decrease in year 2012 was a high death rate, rather than a low birth rate. Death rates in 2012 in the target municipalities were higher than in the rest of Fukushima, indicating that evacuation from the nuclear accident caused excess deaths among the evacuees.
Table 3 Population living in the evacuated areas.
Local governments in the target area have reported the numbers of residents living in the areas where evacuation orders have been lifted. Progress in population recovery varies significantly region by region. Large differences are found in the populations reported by local governments and estimates from mobile phone information.

<table>
<thead>
<tr>
<th>Local government</th>
<th>Registered population in the evacuated area</th>
<th>Population living in the evacuated area</th>
<th>Ratio</th>
<th>Months since evacuation order lifted**</th>
<th>Average increase in ratio of population in the area per month</th>
<th>Population living in the evacuated area</th>
<th>Nighttime population by mobile phone information (average of December 2017)</th>
<th>Difference in demographic composition (Jaccard distance)***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minamisoma</td>
<td>9,542</td>
<td>4,161</td>
<td>43.6%</td>
<td>34</td>
<td>1.28%</td>
<td>2,798</td>
<td>4,841</td>
<td>0.156</td>
</tr>
<tr>
<td>Iitate</td>
<td>4,240</td>
<td>1,324</td>
<td>31.2%</td>
<td>26</td>
<td>1.20%</td>
<td>602</td>
<td>2,487</td>
<td>0.376</td>
</tr>
<tr>
<td>Kawamata</td>
<td>1,022</td>
<td>480</td>
<td>47.0%</td>
<td>26</td>
<td>1.81%</td>
<td>279</td>
<td>1,413</td>
<td>0.218</td>
</tr>
<tr>
<td>Katsurao</td>
<td>1,570</td>
<td>421</td>
<td>26.8%</td>
<td>34</td>
<td>0.79%</td>
<td>267</td>
<td>640</td>
<td>0.439</td>
</tr>
<tr>
<td>Tamura</td>
<td>277</td>
<td>225</td>
<td>81.2%</td>
<td>36</td>
<td>2.26%</td>
<td>230</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Namie</td>
<td>16,074</td>
<td>729</td>
<td>4.5%</td>
<td>26</td>
<td>0.17%</td>
<td>291</td>
<td>3,131</td>
<td>0.326</td>
</tr>
<tr>
<td>Tomioka</td>
<td>12,905</td>
<td>1,064</td>
<td>8.2%</td>
<td>26</td>
<td>0.32%</td>
<td>358</td>
<td>6,689</td>
<td>0.316</td>
</tr>
<tr>
<td>Naraha</td>
<td>6,881</td>
<td>3,761</td>
<td>54.7%</td>
<td>44</td>
<td>1.24%</td>
<td>2,203</td>
<td>5,924</td>
<td>0.282</td>
</tr>
<tr>
<td>Kawauhci</td>
<td>2,677</td>
<td>2,165</td>
<td>80.9%</td>
<td>63</td>
<td>1.28%</td>
<td>2,197</td>
<td>1,852</td>
<td>0.288</td>
</tr>
<tr>
<td>Total</td>
<td>55,188</td>
<td>14,330</td>
<td>26.0%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9,225</td>
<td>26,976</td>
</tr>
</tbody>
</table>

* August 31, 2019 in Kawauhci.
** Months by the ratio of population living in the region exceeds 80%.
*** Comparison of sex and age composition between registered population in BRRS and mobile phone information.

Fig. 3 Progress in population recovery in areas where evacuation orders were lifted.
The figure shows the share of population living in the area of the population registered there after the evacuation order was lifted. A “jumping” increase occurs in March or April, when the new fiscal and school year starts in Japan. The rate of recovery (slope of the lines) varies region-by-region, and is especially low in Namie and Tomioka, which are near to the nuclear power plant and experienced severe contamination.

3.2 Municipality Tally Data
Table 3 shows the status of the percentage of people living in the area at the end of June or beginning of July 2019. The changes in the percentage of people living in the area are shown in Fig. 3. The left side of the figure shows the rate by each year and month, and in Tamura and Kawauhci, where the evacuation orders were lifted early, it has recently leveled off at about 80%. A large increase in March or April is common, probably because in Japan, the new fiscal year and school year start on April 1, so the evacuees are expected to return in March or April. The right-hand side of the figure shows the percentage of people living in the region according to the number of months after the evacuation order was lifted. The larger the slope, the greater the increase in the rate of settlement per given period, and the faster the return and recovery of the population. There is considerable variation in the progress in population recovery by region (see also the “Average increase of …” column in Table 3). The variation might be explained partly by the
Demographic impact of TEPCO nuclear accident

3.3 Census Data

Discussion is provided later in this paper.

The order of lifting evacuation orders is beyond the scope of this study, but more is observed between the areas where the order was lifted at the same time (e.g., the rate was much higher in Iitate than Namie, even though the orders were lifted at the same time in both areas). A detailed quantitative analysis of the variation in progress is beyond the scope of this study, but more discussion is provided later in this paper.

3.3 Census Data

Table 4 provides the main information from censuses: areas with zero nighttime population in 2015, and areas with significantly fewer employees than in 2010, also have a decent sized daytime population. In 2015, the sex ratio in daytime was greater than 1 in all municipalities but Tamura, i.e., more males than females were there during the day. Especially in municipalities near the nuclear plant, the ratio was quite large (nearly 30 in Okuma and 18 in Futaba). Figure 4 shows the resident locations of employees by municipality to facilitate analysis of commuting OD. In Minamisoma, Kawamata, Tamura and Kawauchi, where the evacuation orders were lifted early, many employees commuted to work in their own municipality. On the other hand, in the areas where the evacuation orders had not been lifted or where they had been issued later, many people commuted from other areas. The total of seven specific municipalities with a particularly low or no daytime population are shown in the same figure. Many of the employees in these areas were commuting from nearby towns where no evacuation orders had been issued. This is especially true in Iwaki City, the southernmost coastal city and the most populated city in the prefecture.

### Table 4: Basic Statistics from Censuses of 2010 and 2015

<table>
<thead>
<tr>
<th>Nighttime Population</th>
<th>Daytime Population</th>
<th>Daytime/Nighttime Sex Ratio (nighttime)</th>
<th>Sex Ratio (daytime)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minamisoma</td>
<td>70,878</td>
<td>57,797</td>
<td>0.82</td>
</tr>
<tr>
<td>Iitate</td>
<td>6,209</td>
<td>41</td>
<td>0.01</td>
</tr>
<tr>
<td>Kawamata</td>
<td>15,569</td>
<td>14,452</td>
<td>0.93</td>
</tr>
<tr>
<td>Katsurao</td>
<td>1,531</td>
<td>18</td>
<td>0.01</td>
</tr>
<tr>
<td>Tamura</td>
<td>40,422</td>
<td>38,503</td>
<td>0.95</td>
</tr>
<tr>
<td>Namie</td>
<td>20,905</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Futaba</td>
<td>6,932</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Okuma</td>
<td>11,515</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tomioka</td>
<td>16,001</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Naraha</td>
<td>7,700</td>
<td>975</td>
<td>0.13</td>
</tr>
<tr>
<td>Kawauchi</td>
<td>2,820</td>
<td>2,021</td>
<td>0.72</td>
</tr>
<tr>
<td>Total</td>
<td>200,482</td>
<td>113,807</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Timing of lifting of the evacuation orders. In short, the rate is higher in Tamura (where the order was lifted in 2014) and Naraha (2015) than Namie and Tomioka (both in 2017). However, variation is also observed between the areas where the order was lifted at the same time (e.g., the rate was much higher in Iitate than Namie, even though the orders were lifted at the same time in both areas). A detailed quantitative analysis of the variation in progress is beyond the scope of this study, but more discussion is provided later in this paper.

3.4 Mobile Phone Location Information

There are differences in the numbers of people living in each area between the municipality tally and the nighttime population based on mobile spatial statistics (Table 3). In some areas, the latter is significantly higher than the former. This suggests the presence of reconstruction-related workers, temporary outsiders, residents who return without reporting to the municipality and residents who live primarily outside the area but frequently visit their homes or other places of residence. The Jaccard distance, an aggregated indicator of variations in demographic composition between two information sources, was the highest in Katsurao (0.439), followed by Iitate (0.376). It was lowest in Minamisoma (0.156) followed by Kawamata (0.218). These results indicate that the difference tends to be larger in areas where the ratio of people living in the evacuation area is lower (Table 3). Figure 5 shows the population pyramids for a total of the eight regions based on BRRS data (for
According to a comparison of mobile spatial statistics with BRRS data, males are more likely to be there than females, and the working-age population is more likely to be there than the other age groups. The ratio of the composition of the two information sources is shown in Fig. 6. A higher value indicates a higher proportion of the resident population in each age and sex group in the mobile phone information compared to the registered population. There is considerable variation among regions. Among the working-age population, there are more males and females between the ages of 45 and 59. Among the younger age groups, there are more males than females in the same respective age group.

The figure indicates the population in a total of eight municipalities that have areas where evacuation orders had been lifted by the end of 2017. The age and sex composition in the former evacuation area (left) versus the whole municipality (right) are significantly different. In sex compositions, more males are found than females in most of the age groups in the left figure, while there are more females in the right.
4. Discussion

From the results presented above, in general, we can say that the demographic phenomena are not uniform among the different municipalities. In this chapter we discuss implications of the above results to the recovery and sustainable development of this region.

4.1 Changes in Registered Population

It has been pointed out that the Earthquake, tsunami and accident have had an impact on the population decline in Fukushima Prefecture as a whole. The 11 municipalities that had been designated as evacuation zones have been affected more heavily than others. As for social changes, the tendency to move out of the areas evacuated has been higher in many areas than in the rest of Fukushima Prefecture. However, this trend was clear only until 2012. The number of registered residents declined significantly immediately after the disaster but has not changed much since 2013. This suggests that many people decided to move out in the first two years after the disaster, but from the third year onwards, the trend has been the same as it was before the disaster. In terms of natural increase or decrease, the 2012 mortality rate increase was higher in municipalities with evacuated areas than in the rest of Fukushima. This is consistent with the facts reported by Nomura (2016).

4.2 Population Composition

Fewer young people living in the area are in their teens or younger; there are more men in their late 40s to 50s, and fewer women in their 20s to 30s. This suggests that households with children to care for and women of childbearing age have tended not to return. If this structure does not change in the future as the number of residents increases, the long-term demographic structure of the area will be one of extreme aging, followed by a sharp decline in population. This may have a significant impact on communities’ sustainability in the future.

4.3 Progress in Evacuees’ Return

In Tamura and Kawauchi, the percentage of people living in the region has remained almost unchanged at around 80%. This value is nearly identical to the combined total of “want to return” and “have not decided” in an opinion survey by the Reconstruction Agency (2015). Whether this applies to other regions as well is not clear at this time, but it may serve as a reference or a benchmark for the long-term population outlook. From the comparison of progress in evacuees’ return and timing of the lifting, as we mentioned above, it has been suggested that the timing of lifting of the evacuation orders may be a factor affecting differences in the progress in evacuees’ return (i.e., increase in the annual rate of residence in the area). Among the areas where the evacuation orders were lifted at the same time, the towns of Namie and Tomioka have town centers close to the nuclear power plant, and in Namie, where progress has been slower than in Tomioka, the proportion of Zone 3 areas is higher than in Tomioka in terms of both area and population (actually it is the highest of the all 11 municipalities). The same discussion may apply to Tamura, where contamination was relatively low and evacuation was ordered for only a small part of the city. These conditions suggest that factors that slow progress may include proximity to the nuclear power plant and large proportions of residents in areas that have not yet had their orders lifted. We think this is an important finding for predicting the progress in evacuees’ return to the towns of Okuma and Futaba, which were not included in the analysis of evacuees’ return, as well as to other specific centers for reconstruction and rehabilitation in Zone 3.

4.4 Commuting Structure

Where evacuation orders have been lifted, in general, many people commute from the outside, instead of living in those areas. Results of a survey by the Reconstruction Agency (2020) may explain the reason for that. Many respondents reported that a lack of medical and shopping facilities and support for housing were the main barriers hindering their return. From our results and the survey, even though economic activity has recovered thanks to policy initiatives, without such facilities and support, the nighttime population may not recover. Based on comparison of the areas where the evacuation orders have been lifted so far, though, the percentage of commuters from outside the areas is expected to decrease as the population recovers. However, especially in the areas where the evacuation orders have been lifted or will be later, many commuters will continue to commute from the outside until the population recovers. To mitigate this, it is important that those who wish to return should be able to do so as soon as possible. In addition, among those who work in the region, some were not residents before the accident, but arrived because new industrial development led by the government necessitated different expertise among employees compared to before the disaster. It will be necessary to remove obstacles for people moving into the area and joining the community.

5. Concluding Remarks

In this study, migration and return to the areas affected by the nuclear power plant accident were investigated using multiple sources of data to clarify the demographic situation. Each source had its own inherent limitations, and care needed to be taken in interpreting the results. Analysis using mobile spatial statistics is particularly subject to uncertainty: since the estimates are scaled up according to the percentage of subscribers to NTT DoCoMo’s mobile phone service, deviations from the true values may be large, especially in small areas. In addition, in many areas, there is no differentiation among people living in the evacuation zone, evacuees and newcomers. Therefore, this study has not been able to
discern how many of the residents in the area are returnees.

The information we have been able to obtain so far in this study is limited, and many issues remain to be addressed in analyzing the population of the evacuated areas. First, it will be necessary to continue to survey the situation among newer returnees, including those to areas where the evacuation orders have been lifted very recently. Next, quantitative analysis of factors affecting regional differences in the progress in evacuees’ return could help project future progress of their return and identify what is needed to enable residents who wish to return to their homes to do so more quickly. Once these issues are addressed, many of the insights needed for estimating the future of the population over the long term will be available, allowing for a long-term socioeconomic outlook that explicitly takes uncertainty into account.

References


Kei Gomi

Dr. Kei Gomi is a senior researcher in the Regional Environmental Renovation Section of the National Institute for Environmental Studies, Fukushima Branch. His research activities have focused on integrated modeling for climate action and sustainable society scenario development in municipalities across Japan and in other Asian countries. Since 2014, he has been involved in research toward recovery and renovation from the Great East Japan Earthquake and Tsunami of 2011. His recent research interests are integration of the SDGs into planning processes and comprehensive recovery from nuclear disasters. He received his Ph.D in global environmental studies from Kyoto University in 2010.
A Study on Sustainable Energy Systems for Small Villages in Fukushima

Takuya TOGAWA¹*, Yi DOU², Shogo NAKAMURA¹ and Makoto OOBA¹

¹Fukushima Branch, National Institute for Environmental Studies
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
²The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan
*E-mail: togawa.takuya@nies.go.jp

Abstract

We investigated the design and operation of distributed energy systems for the central area of Mishima Town in the Oku-Aizu area of Fukushima Prefecture. These systems were tailored to the characteristics of the region. Although we found that the deployment of an energy system utilizing forest biomass resources was desirable from the perspectives of CO₂ emissions and economic circulation based on local natural resources, the cost of energy was relatively high. Based on these results and related information, we considered the processes required for implementing energy systems utilizing forest biomass resources. Our results show that to create sustainable communities based on renewable energy in rural areas with low population density, it is important to integrate energy system development with community development from a medium- to long-term perspective.

Key words: autonomous distributed system, mathematical optimization, mixed integer linear programming, regional revitalization, renewable energy

1. Introduction

Interest in renewable energies has grown against the backdrop of global environmental issues, with the Great East Japan Earthquake revealing the vulnerabilities of large-scale centralized electric power supply systems. These two considerations have led to increased nationwide momentum to promote the introduction of distributed energy systems utilizing renewable energies (Nakata, 2015). In addition, frequent abnormal weather events such as heavy rains and snowfalls in recent years further have spurred this trend. This is particularly of great concern in Fukushima Prefecture, Japan, which is now suffering from all of these problems, necessitating a comprehensive solution for revitalization.

Up to now, however, technology and policies related to resources and energy have been regarded as national and global issues and, therefore, “given conditions” that could not be altered at the level of local living and economies. Adverse impacts have arisen due to the large gap between the given conditions and local situations. For example, in mountainous and other remote areas, energy supply infrastructure such as gas pipelines has not been sufficiently developed. Thus energy prices have tended to be higher there than in urban areas. Rural communities have been unable to implement effective measures to address such situations. Especially in cold regions where there is great demand for space heating and hot water supply, utility costs are a burden for households. Furthermore, inadequate space heating and hot water supply systems along with poor building insulation lower residents’ quality of life.

Meanwhile, Japan’s 5th Basic Environmental Plan has advocated maximizing the vitality of regions by using regional resources to build self-reliant, decentralized societies based on the characteristics of regions and, to this end, proposes the concept of regional circular and ecological spheres that complement and support regional resources. The introduction of renewable energy is regarded as a substantive measure that will contribute to the creation of such regional circular and ecological spheres (Shirai, 2018a; Shigeto et al., 2018). Effective use of forest resources has been recognized as a key issue for revitalizing local economies and sustainable regional development in rural communities especially in mountainous areas (Uragami & Itoh, 2007). In addition, development of technologies such as small biomass cogeneration systems for converting forest resources into energy are being actively promoted (Japan Woody Bioenergy Association, 2017a, b).
Previous studies related to sustainable community development in mountainous areas have been carried out at the village or regional scale comprising single or multiple local governments. Research at the village scale has focused on specific energy projects and their impacts (Asano & Takaguchi, 2015). A number of studies at the regional scale have focused on regional circulation effects of biomass and other resources (Sumitomo et al., 2015; Miura et al., 2018; Nakamura & Shibata, 2013). However, since these previous studies have been carried out in parallel at each scale, inter-scale effects—for example, the impact of village-scale energy systems on resource circulation at a regional scale—have not been adequately investigated.

Therefore, this study examined the feasibility of transition to next-generation energy systems utilizing local resources in mountainous villages of Japan, and quantified the impacts of introducing such systems on the balance of resource supply and demand, as well as on the regional environment and socio-economy.

2. Study Area and Data

2.1 Study Area

This study targeted the central area of Mishima Town in the Oku-Aizu area of Fukushima Prefecture. According to the 2015 census, the population of Mishima was 1,792, and the proportion of the population 65 or older had already reached 49% (compared to the average for Japan of 26.6%). The main industries included construction and electric power connected with a local Tohoku Electric Power hydroelectric power plant (maximum output 94,000 kW), followed by agriculture, forestry and tourism. The area of the town is 1,518 km² with approximately 80% of that area being forested. Therefore, regional development based on effective utilization of woody biomass resources as energy has become a goal of public policy. The use of woody biomass resources, however, has been limited to the introduction of wood pellet stoves and firewood stoves in some public facilities and houses.

Figure 1 and Table 1 provide an outline of the study area. The area inside the dotted line in Fig. 1 is the central area of Mishima Town, which is the subject of this study. Facilities such as the town hall, prefectoral hospital, Aizu Miyashita Station and welfare facilities are located centrally and play a central role in the town. Solar panels have been installed on the welfare facilities. Although housing accounts for only a small proportion of buildings in the central area of the town, that area has the town’s largest population concentration.

We estimated spatial information for the area that was required for energy system assessment. This included the length of the heat distribution pipes that would be required for deploying district heating and the area of land where solar panels could be installed. The pipe length was assumed to be the length of the shortest road network required to connect the buildings in the area. It was assumed that solar panels would be installed on the roofs of buildings in the central area of the town. However, since roof area data were not available, the built-up area was assumed to be the roof area. Building data were estimated based on information from Zenrin Tatemono Pointo (2014 version) and road network data based on Zenrin Data Zmap-Town II (2015 version) using GIS.

2.2 Establishing the Renewable Energy Supply Potential

Since the renewable energy supply potential depends on the characteristics of the region, we set assumptions regarding the biomass resources and photovoltaic power generation potential required for subsequent analysis. The NEDO estimate (2011) for available biomass resources (forest residuals from harvesting and trimming) is 4,085 tons/year for Mishima Town and 43,746 tons/year if the resources of the four nearby towns and villages (Tadami Town, Yanaizu Town, Kaneyama Town, and Showa Village) in the Oku-Aizu area are included. This value is referenced in the evaluation of the regional circular sphere. The photovoltaic power generation potential was set based on monitoring data collected by the authors in Mishima Town. Figure 2 shows the power generated by a 1 kW solar panel. The figure shows hourly data for one week from January 1 to 7 as well as monthly data. The Oku-Aizu region is a heavy-snowfall area that receives approximately 60 cm of snow annually in the winter.
effect of this snowfall is confirmed as reduction of power generation during the winter months in Fig. 2. It is assumed that the solar panels were covered with snow from Jan 3 to 6. These data are referenced in subsequent analyses as the potential amount of photovoltaic power generation.

2.3 Energy Demand

Hourly energy demand data were set for the study area for the following use categories: electric power, cooling, heating and hot water supply. First, annual energy demand was calculated by multiplying the floor area for each use in each neighborhood by the energy load intensity. Then, hourly energy demand was calculated by multiplying the annual energy demand by the monthly and hourly proportions. The values reported by Kashiwagi (2008) were used for the ratio of energy load intensity and for monthly and hourly proportions; to reflect circumstances in the Tohoku region for energy load intensity, we used the correction coefficient from Japan District Heating & Cooling Association (2002).

Regarding the housing sector, the authors monitored energy consumption at 12 all-electric homes in Mishima for one year from October 2017 to September 2018. Hourly and monthly electric power consumption was measured by meters for each use category, and power consumption for each use category was corrected using the measurement results. Figure 3 shows the calculated energy demand results (hourly values for the week of January 1 to 7 and monthly values for the year) for the study area.

3. Model

3.1 Overview of the Planning Process Model

To examine the effect of introducing alternative energy systems, it is necessary to evaluate detailed system designs and optimal operation of each general system type comparatively. In this study, the planning process model reported in previous studies (Togawa et al. 2017; Togawa et al., 2020a) was used to determine the conditions resulting in minimal cost for design and operation. The basic structure of the planning process model is shown in Fig. 4.

An energy system converts power supplied by the grid or fuel from outside the system (gas, kerosene, biomass resources, etc.) into electric power, heating and cooling, and hot water supply for use on the demand side. First, we set up an energy system study framework. Figure 4 shows a general structure including all candidate energy systems that is referred to here as the
“superstructure,” following the nomenclature used in previous research (Yokoyama, 2014). The superstructure is represented by the subsystems that represent the candidate devices that make up the system and the potential flows of energy between them (input/output relationships).

Next, we simultaneously specified the system configurations that minimize the cost function, which combines flow values such as fuel consumption with stock values, such as installed capacity, and the operating plans for each season and time period. Fuel consumption was calculated by multiplying the energy demand of the buildings shown in Fig. 3 by the energy conversion efficiency of the equipment. Depending on the purpose, a subsystem can be selected from the superstructure, and the equipment to be operated and the input/output level for operation can be specified for each season and time for the selected equipment. For this reason, equipment that needs to be operated even once must be selected at the design stage and the capacity of the equipment must be greater than or equal to the annual maximum output value.

However, for this study, because the calculation load would be prohibitively high if the analysis were performed for 8,760 hours a year, the calculations were performed for 2,016 hours based on the data for one week extracted from each month. It was also assumed that the same type of energy system was installed in all the buildings in the study neighborhood.

3.2 Establishing the Superstructures

Taking into consideration the availability of resources and technological progress (Nakamura et al., 2018) in mountainous areas, we assessed the impact of three different cases involving introduction of alternative energy systems that combine biomass-related technologies and photovoltaic power generation with the currently deployed system. Figure 5 shows the superstructure of the system. Here, the energy systems were treated as an aggregated unit for a given neighborhood; the capacity of each component of the energy systems could be set from continuous variables except in the case of biomass cogeneration (BCHP: Biomass Combined Heat and Power), which has a relatively large capacity per unit.

Case 1: Conventional System
Room air conditioners, kerosene heaters and gas water heaters are used for cooling, heating, and hot water supply, respectively. The energy supply sources are grid power, kerosene, and LPG (liquefied propane gas). According to survey results, this is the most common system configuration in the study area (Nakamura et al., 2018).

Case 2: Photovoltaic Power Generation + All-Electric System
All energy is supplied by the grid and solar panels. Room air conditioners and heat pump water heaters are used for cooling, heating, and hot water supply. The installation of storage batteries and heat storage tanks is possible. As mentioned above, the maximum installation

![Fig. 5 Energy system alternatives.](image-url)
A study on sustainable energy systems for small villages in Fukushima

area for solar panels equals the building roof area. In recent years, all-electric houses, which are considered to be one of the directions for future energy system conversion, have been constructed in the study area (Mishima Town, 2018).

Case 3: Photovoltaic Power Generation + Biomass Heat Supply System

Although grid power and solar photovoltaic panels are used as in Case 2, stoves and boilers that use biomass pellets as fuel are used for heating and hot water supply. Given that the stoves and boilers are installed by each customer, installation of heat distribution pipes is not necessary. This scenario assumes the deployment to each customer of photovoltaic power generation and biomass heat supply systems that have already been installed in some buildings in the study area.

Case 4: Biomass Combined Heat and Power System (BCHP)

The BCHP system generates the necessary electric power and uses the waste heat for heating, cooling and hot water supply. Therefore, a heating pipe network is required for the district. BCHP assumes the deployment of a 10 to several hundred kW-class system similar to those being developed mainly in Europe. The available BCHP devices are shown in Table 2, with up to two units being selectable for each system. This scenario proposes the introduction of leading-edge technology of which only a few examples exist in Japan.

The set values of other components required for each energy system were specified based on vendor catalogs, and the unit prices for electricity, kerosene and LPG were set based on the prices in the study area (Togawa et al., 2017).

4. Results

4.1 System Design and Operating Plans

Table 3 gives a summary of the system designs for each case and lists the installed capacity of major components of the energy systems shown in Fig. 5. First, we confirmed the capacity of the solar photovoltaic systems for Cases 2 and 3. In Case 2, a photovoltaic system with a capacity equivalent to about 60% of the installable area (building roof area) was selected. The capacity of the photovoltaic system in Case 3 was slightly smaller than in Case 2 due to the lower electricity demand for heating and hot water, which were covered by wood pellets instead. Next, we examined factors for determining the capacity of the pellet stoves and the pellet boilers in Case 3 by comparison with the demand shown in Fig. 3. The installed capacity of the pellet stoves was set at 3,853 kW, which corresponds to the peak heating demand in winter (January). For the week shown in Fig. 3, the peak heating demand was about 3,000 kW. However, as the peak times for residential and business systems differ, the combined total of the peak heating demands is about 3,853 kW. On the other hand, the installed capacity of the pellet boiler was set at 475 kW, which is about half the peak demand for hot water supply in winter (January) (about 800 kW for the week shown in Fig. 3). Given the high cost of biomass boilers, it was assumed that heat storage tanks would be installed to optimize the systems and minimize boiler size.

4.2 Operating Plans

Next, to confirm how the systems operated, we examined the energy supply and demand by hour and month (Fig. 6). The supply and demand data for electricity and hot water for each case are presented. The upper graph for each case shows the hourly data (for one week in January) while the lower figure shows the monthly data. The equipment used to supply energy in response to demand is shown. Negative values for the supply from storage batteries and hot water tanks in the hourly diagrams indicate energy is being stored. First,
Fig. 6 Supply and demand data for electricity and hot water in each case. The upper graph for each case shows the hourly data (for one week in January). The lower figure shows the monthly data. Negative values for the supply from storage batteries and hot water tanks in the hourly diagrams indicate energy is being stored.
from the electric power supply and demand for Cases 2 and 3, it can be seen that photovoltaic power generation exhibits substantial seasonal and daily fluctuations, with the amount of power generation in winter being particularly limited. Furthermore, from the hourly supply and demand for hot water supply in Case 2, it can be seen that the heat pump water heater is operated using low-cost nighttime electricity. In addition, from the hourly supply and demand for hot water supply in Case 3, it is evident that hot water is stored during the low-demand period with the 475 kW biomass boiler operating at full capacity, which is lower than the peak demand; the stored hot water is consumed during the peak demand period in the evening. Similarly, from the results for Case 4, it can be seen that the BCHP system operates steadily at 870 kW throughout the year, storing surplus electricity at night when demand is low and distributing the stored electricity during peak daytime demand periods when the BCHP system output is lower than demand. As above, appropriate system designs and operating plans were derived for each case.

4.3 Impacts of System Deployment

Figure 7 shows the results of estimating energy costs for the entire study area for each case. The energy cost including equipment associated with Case 1 was approximately 300 million JPY. The energy cost reductions associated with Cases 2 and 3 were on the order of 20%. However, Case 4 resulted in a 34% increase in cost.

Next, we examined the effect of system deployment on economic circulation. In Cases 1 and 2, most of the economic benefits are thought to flow out of the region. The items that are likely to contribute to regional economic circulation (personnel costs, maintenance costs, pellet charges, chip charges) amounted to 52 million JPY for Case 3 and 175 million JPY for Case 4. These costs only accounted for approximately 1% in Case 3 and 3% in Case 4 of Mishima Town’s total production, which is 6.1 billion JPY (Ministry of the Environment & Value Management Institute, 2013). These results indicate the importance of expanding measures beyond the central area to the surrounding areas if they are to have an impact on revitalizing the regional economy.

Figure 8 shows the impact of each case on CO₂ emissions and emissions reduction. Cases 2 and 3 reduced CO₂ emissions by 28% and 43%, respectively, compared to Case 1. In Case 4, CO₂ emissions were zero because energy from fossil fuels was not used. Using a CO₂ transaction price of 4,355 to 8,710 JPY/ton-CO₂ (40 to 80 USD/ton-CO₂) from the World Bank (2019), the economic value of these CO₂ reductions is estimated to be 6 to 47 million JPY. In all cases, the value is about 10% to 40% compared to the increase/decrease in direct energy costs, indicating the importance of taking the value of environmental benefits into account when selecting energy systems.

Next, we examined the consumption of biomass resources. Here, the amount of woody biomass resources used as raw materials was evaluated in a unified manner. We assumed that both pellets and chips were produced from woody biomass resources with a moisture content of 50%, which is equivalent to that of raw wood, and converted biomass mass into energy units assuming 1 kg = 2.33 kWh. The results are shown in Fig. 9 together with the available woody biomass resources in Mishima Town. In Case 3, the consumption of biomass resources was approximately 40% of the amount available to Mishima
Town, while the consumption in Case 4 greatly exceeded available resources. However, in all cases, the amount consumed was small compared to the total annual biomass resources available in the Oku-Aizu area (48,736 tons/year according to NEDO, 2011). Thus, we believe that the use of biomass energy can contribute to revitalization of forestry in Mishima Town and the Oku-Aizu area.

5. Discussion

As shown in Fig. 7, we found that it would be difficult to introduce neighborhood energy systems based on BCHP due to the substantial initial investment associated with neighborhood BCHP systems. However, the system is expected to have a positive regional effect (Figs. 8 and 9). Also, these results are based on the current socio-economic situation. It is important to take into consideration that technological development of small-scale energy supply systems suitable for neighborhood energy systems is actively progressing (Murugan & Horák, 2016). In particular, small 10 kW-class biomass cogeneration system units have been developed and are being deployed mainly in Europe. In Japan, studies have been carried out addressing component technologies related to biomass power generation. Yanagida et al. (2015) analyzed the relationship between the break-even point and raw material procurement cost for biomass power generation businesses at various output scales. They found that, even if a relatively high feed-in-tariff purchase price is assumed, the amount of power generated must be 5 MW or greater to be profitable. Sasauchi (2015) examined the technical characteristics of steam turbine power generation, gasification with gas engine power generation, and ORC (Organic Rankine Cycle) power generation, which are typical power generation methods for woody biomass, and reviewed the profitability of small-scale projects for each method. They found that the steam turbine method is not profitable for small-scale power generation businesses of about 2 MW. However, profitability is greatly improved for gasification with gas engine power generation and ORC power generation, which can supply heat along with power, indicating the business potential of such systems. Similarly, Kuboyama et al. (2016) and Komata et al. (2016) point out the need for cogeneration when using small-scale biomass generators. As described above, technologies for practical distributed energy systems that can contribute to local economies by utilizing forest resources in mountainous areas are being developed. The output of the 870 kW BCHP examined in this study was less than half that of the 2 MW-class systems evaluated in the above studies. Moreover, as can be seen from Fig. 6, the efficiency of heat utilization is not always high. These points along with those mentioned above indicate that increasing demand and improving heat utilization efficiency are challenges that must be overcome.

Based on the above, the key to implementing local energy systems is improving energy utilization efficiency through cogeneration. However, as the ability to transport thermal energy is limited, efforts must be integrated with regional development plans that include, for example, concentrating energy consumers. In a previous study (Shirai, 2018b) field studies were conducted in eight pioneering examples of integrated energy business and community development, clarifying the roles played by stakeholders such as local companies, citizen networks, regional organizations and universities. It has also been pointed out that these examples are not based on top-down deployment but, rather, the result of co-creative processes by diverse stakeholders in a community. A case study conducted by the authors in Shiwa Town, Iwate Prefecture, which is an environmentally leading municipality, found that budding efforts in resource circulation that started around 2000 have spawned other activities including the development of various spaces by diverse stakeholders through co-creative processes (Togawa et al., 2020b). These results show that to create sustainable communities based on renewable energy in rural areas with low population density, it is important to integrate energy system development with community development from a medium- to long-term perspective. However, no general design schemes that can be applied to different complex problems have been sufficiently developed, and past approaches have tended to rely on local experience. In our research as well, we examined a top-down method for designing a distributed energy system. Frameworks for bottom-up design of sustainable communities that complement this top-down approach need to be developed.

In addition, various social benefits associated with deployment of distributed systems have also been identified. These include the stabilization of employment by building energy supply systems in local communities, enhanced continuity of the energy supply in the event of a disaster, and improved safety and security of the region (Nakata 2015). Therefore, it is important to develop systems that are competitive in function with large scale systems while also being tailored to the unique circumstances of each community through co-creative processes and multidimensional perspectives that cover the environment, economy and society.

6. Conclusions

In this study, we developed designs and operating plans for and evaluated the deployment potential of alternative energy systems taking into account the structure of the neighborhoods that made up the area and the supply characteristics of renewable energy. Our findings were as follows:
Based on hourly energy supply and demand, we developed a planning process model that can simultaneously derive optimal energy system design and operating plans and conducted analyses using data obtained through monitoring in the actual community.

We conducted analyses using models based on information that we had obtained for the central area of Mishima Town, Fukushima Prefecture, which has characteristics typical of the mountainous areas of Japan. Our results showed that it is possible to reduce energy costs by introducing a fully electrified system that uses photovoltaic power generation. We also showed that the introduction of biomass boilers and biomass cogeneration systems that utilize forest biomass resources is desirable from the perspective of CO₂ emissions reduction and local resource circulation.

We considered issues for implementation of regional energy systems in rural areas with low population densities. We found that a framework was necessary for comprehensively designing sustainable local communities that incorporates regional development in the surrounding area with selection of appropriate distributed energy systems that are tailored to regional characteristics.

References


Togawa, T., Ohnishi, I. S. and Fukushima, H. (2020b) Description of the co-creative process found in leading cities for environmental and community development. Japan Society of Civil Engineers Infrastructure and Planning and Management Fall Meeting Proceedings, 62. (in Japanese)


Yanagida, T., Yoshida, T., Kuboyama, H. and Jinkawa, M. (2015) Relationship between feedstock price and break-even point of


**Takuya Togawa**

Takuya Togawa is a senior researcher at the National Institute for Environmental Studies, Fukushima Branch. He received his doctorate in engineering from the Graduate School of Environmental Studies, Nagoya University in 2010. He is engaged in research on mechanisms for realizing disaster recovery and regional revitalization by effectively utilizing local environmental resources.

**Yi Dou**

Yi Dou is a project researcher for the Presidential Endowed Chair for “Platinum Society,” University of Tokyo. He received his doctorate in engineering from Nagoya University in 2019, and his research interests are closely related to urban sustainable development, especially focusing on promoting circular economies and proliferation of emerging technologies through regional energy planning.

**Shogo Nakamura**

Shogo Nakamura is a researcher in the Regional Environmental Renovation Section of the National Institute for Environmental Studies, Fukushima Branch. He holds a Ph.D. in agricultural science. He has played a central role in developing the energy monitoring systems in Shinchi as well as many other areas in Fukushima. Recently his interests have led him to participate in the Environment-Economy-Society Integration Research program.

**Makoto Ooba**

Dr. Ooba heads the Environmental Renovation Laboratory at the Fukushima Branch of the National Institute for Environmental Studies, Japan. From 2007 to 2012 and from 2014 to the present, he has participated in a study on spatial assessment of Japan’s regional forests using process-based models and remote sensing by NIES. Based on these studies, he has analyzed sustainability of forestry and harvested wood products. He has also worked at Osaka University, Nagoya University and the Tokyo University of Agriculture. He holds a Ph.D. in environmental science from Hokkaido University, 2002.
Survey on Household Wood Biomass Use and Energy Consumption in the Oku-Aizu Region

Shogo NAKAMURA* and Takuya TOGAWA

Fukushima Branch, National Institute for Environmental Studies
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
*E-mail: nakamura.shogo@nies.go.jp

Abstract

We surveyed and analyzed the current status of household energy consumption and use of firewood and other wood biomass in the town of Mishima, Fukushima Prefecture for the purpose of building a supply chain model for forest resource use in mountainous regions. The number of questionnaires returned was 341, with a response rate of 48.6%. The survey results revealed that approximately 9% of households were using wood biomass combustion devices. Annual firewood consumption per household was 3 m³, and over 90% of the raw logs used were procured inside the town. The difference in the ages of the houses of firewood users and non-users suggests that building structure may have influenced this result.

Key words: firewood, household energy consumption, mountainous area, questionnaire survey, wood stoves

1. Introduction

Ascertaining the status of wood biomass utilization for household wood stoves and other wood-burning is important from the perspective of utilizing regional forest resources and tackling climate change. Although cold mountainous regions tend to be sparsely populated, per capita energy consumption for heating is likely to be high and, therefore, deserves detailed investigation.

Several studies have already been conducted on the use of wood biomass from the viewpoint of solving environmental problems simultaneously. Nemoto et al. (2017a, b) investigated household use of wood biomass combustion devices from a nationwide view. Regionally, Hatanaka et al. (2011, 2012) surveyed household use of wood-burning devices in 10 municipalities in Nagano Prefecture from the viewpoint of effects of carbon emissions reductions. From the viewpoint of promoting usage of unused biomass, Ogasawara et al. (2017) investigated the use of firewood in fruit-producing areas and found higher use of wood stoves and other wood-burning devices than in other areas owing to the ready availability of tree prunings. Many case studies at a local scale have also been conducted, for example, Izumi et al. (2018) conducted a random electoral-register-based sampling survey to ascertain the level of firewood use in Shiwa Town, Iwate Prefecture. Harashima et al. (2014) researched the utilization of wood stoves and other wood-burning devices and firewood consumption in the Minowa district of Ina, Nagano Prefecture, through a visual survey and questionnaire. Uezono (2018) also conducted a questionnaire survey on household energy consumption in both mountainous and urban areas of the San’in region in western Honshu. These studies indicated that currently the consumption of firewood is stable in both mountainous and urban areas, but the amount of firewood consumption is very limited compared to the rich potential of this resource from domestic forests. The role of woody biomass energy should be reconsidered compared to other energy (electricity, gas, and so on) based on reliable field surveys with promotion to a suitable environmental policies such as transformation to a decarbonized society.

With regard to energy consumption in the residential sector, the Ministry of Internal Affairs and Communications’ Family Income and Expenditure Survey (2018) includes data on household expenditures for electricity, kerosene, gas and other energy sources broken down by city classification, drawn from a subset of the survey sample. Data on household energy consumption by city classification nationwide are also available in the form of estimates for the residential sector in the Agency for Natural Resources and Energy’s Energy Consumption Statistics by Prefecture (2018) and the Ministry of the Environment’s Statistical Survey of Residential Sector CO₂ Emissions (2018).

Few studies, however, have looked specifically at the level of wood biomass use in relation to household consumption of various energy resources in mountainous regions. The town in Fukushima Prefecture that was selected as our studied area decided to promote usage of woody biomass and started to survey the current situation...
of forest and biomass consumption inside and near the town. In this study, in collaboration with the town, we conducted a questionnaire survey of all households in a mountainous district to shed light on the trends and characteristics of household energy consumption and use of wood biomass, which is a forest resource. This study provided the town the basic information on instituting environmental policy regarding woody biomass as energy.

2. Survey and Analysis Methods

2.1. Study Area

The mountainous location chosen for this study was the town of Mishima in the Oku-Aizu region of Fukushima Prefecture (Fig. 2 in Ooba et al., 2020). The Oku-Aizu region is colder than Aizuwakamatsu City and other locations at the same latitude, with mean temperatures approaching those of northern Tohoku, the northernmost region of Japan’s main island of Honshu. Depending on the year or month, Oku-Aizu can receive more than double the snowfall of Aizuwakamatsu. Mishima is a small municipality with a population of about 1,600 people living in approximately 750 households scattered among 18 villages. Its elderly ratio (percentage of the population aged 65 or older) is 54.1% (Fukushima Prefecture, 2020). At its peak during the development of the Tadami River hydroelectric dam, Mishima’s population topped 7,700; since then, however, the population has steadily declined, prompting the town to launch various initiatives to attract young residents from other parts of Japan and otherwise curb depopulation. Given that it has a forest coverage of 88% (Forestry Agency, 2018), the town is also considering measures for exploiting its forest resources, including the use of wood biomass energy in public facilities and subsidies for using firewood.

2.2 Survey Method

We conducted a questionnaire survey of 702 households, representing all of the households in Mishima except occupants of homes for elderly people requiring special care. The survey was conducted from October 20 to November 6, 2017, with questionnaires being distributed to each household by the town through ward chiefs and returned by postal service. The number of questionnaires returned was 341, with a response rate of 48.6%.

The questionnaire, which was to be filled in by the head of each household, asked about type of house, use of heating equipment, use of wood biomass combustion devices, consumption of electricity, kerosene, and other sources of energy, and household attributes. Table 1 shows the items surveyed in the questionnaire. We went through these by hand, and based on the questionnaire responses, identified the characteristics of households using wood biomass combustion devices and compared them with households not using such devices.

For converting the amount of firewood used into wood biomass consumption, we assumed that 1 m$^3$ of firewood = 800 kg and that one bundle = 13 kg.

3. Results and Discussion

3.1 Use of Wood Biomass Combustion Devices

Figure 1 shows a breakdown of devices owned by households using wood biomass. Approximately 9% of the households were using wood biomass combustion devices (wood stoves, fireplaces, cookers, boilers) at the time of the survey. Although this was lower than values found by previous studies (13.5%: Izumi et al., 2018; 27.4%: Yasumura et al., 2011). Wood stoves and boilers (firewood-heated baths etc.) accounted for most of the wood biomass combustion devices being used, with 11%
of firewood-using households using more than one type of device.

The number of years since households started using firewood combustion devices varied from several decades to several years prior; of these households, 28% started using these devices in 2010 or later. Looking at the relationship with house renovation/rebuilding and wood biomass utilization, although 17% of firewood-using households installed devices when renovating or rebuilding, no such relationship was observed in most households. Among households not currently using wood biomass, approximately 19% of all respondents indicated that they intended to use firewood combustion devices in the future subject to availability of cheap firewood and subsidies for installing devices. This indicates that, combined with existing users, a potential 27% of households may use firewood combustion devices given the right conditions.

Most existing users obtained their firewood either by producing it themselves or procuring it for free from acquaintances rather than purchasing it from vendors. Over 90% of the raw logs used were procured in Mishima Town, either from the users’ own forest plots or from the plots of acquaintances.

3.2 Number of Heating Devices

Table 2 shows heating device ownership of households in Mishima Town. The percentage of households equipped with air conditioners was relatively low in Mishima, with most households using kerosene stoves and fan heaters for heating purposes. A comparison of the number of other heating devices owned by users and non-users of wood stoves and fireplaces shows that users of firewood for heating purposes owned fewer kerosene stoves and fan heaters than non-users. However, ownership of other heating devices such as kotatsu or heated floors was higher among firewood users than non-users, albeit only slightly. Among households using wood stoves, all but one household owned only one stove. This suggests that almost all of the households using wood biomass also used fossil fuels or grid electricity for heating purposes. The percentage of household energy consumption used for heating is a matter for future investigation. The sample size of firewood users for this question was small, and statistical tests found no significant differences in mean values.

3.3 Household Energy Expenditure

Table 3 shows the mean household energy expenditure in Mishima and other locations in Japan’s Tohoku region in 2017. Energy expenditure in Mishima was high compared with mean values in the Tohoku region, indicating high energy consumption for heating purposes. Kerosene and electricity consumption tended to be lower among firewood-using households (Table 4), while consumption of LPG (Liquid Petroleum Gas) was almost double compared to the amount consumed by non-users. These differences, however, were not found to be statistically significant (t-test, \( p < 0.05 \)), and a more detailed statistical analysis would be needed such as factor analysis (covariance structure analysis or statistical causal analysis) according to the building age of the house related to the performance of thermal insulation.

### Table 2 Heating device ownership and mean number of devices owned.

<table>
<thead>
<tr>
<th>Device type</th>
<th>Ownership as a percentage of all households (%)</th>
<th>Mean number of devices owned by firewood users</th>
<th>Mean number of devices owned by firewood non-users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene stove/fan heater</td>
<td>93.8</td>
<td>2.23</td>
<td>3.10</td>
</tr>
<tr>
<td>Kotatsu</td>
<td>80.4</td>
<td>1.31</td>
<td>1.08</td>
</tr>
<tr>
<td>Air conditioner</td>
<td>42.2</td>
<td>0.62</td>
<td>0.75</td>
</tr>
<tr>
<td>Electric stove/oil heater</td>
<td>26.4</td>
<td>0.15</td>
<td>0.39</td>
</tr>
<tr>
<td>Heated floor</td>
<td>6.2</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>Wood stove</td>
<td>3.5</td>
<td>1.08</td>
<td>*</td>
</tr>
<tr>
<td>Gas stove</td>
<td>1.8</td>
<td>0.00</td>
<td>0.03</td>
</tr>
</tbody>
</table>

*This question was not asked of firewood non-users

### Table 3 Mean annual household energy expenditure (unit: JPY/year)

<table>
<thead>
<tr>
<th>Energy (per month)</th>
<th>Firewood use</th>
<th>Number</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td>User</td>
<td>13</td>
<td>9,700 (94.8%)</td>
<td>16,000</td>
</tr>
<tr>
<td></td>
<td>Non-user</td>
<td>278</td>
<td>10,000 (100%)</td>
<td>9,900</td>
</tr>
<tr>
<td>LPG</td>
<td>User</td>
<td>11</td>
<td>8,900 (172%)</td>
<td>15,000</td>
</tr>
<tr>
<td></td>
<td>Non-user</td>
<td>254</td>
<td>5,200 (100%)</td>
<td>5,400</td>
</tr>
<tr>
<td>Electricity</td>
<td>User</td>
<td>13</td>
<td>9,800 (89.7%)</td>
<td>5,300</td>
</tr>
<tr>
<td></td>
<td>Non-user</td>
<td>306</td>
<td>11,000 (100%)</td>
<td>9,300</td>
</tr>
</tbody>
</table>

* Source: Family Income and Expenditure Survey 2016 (Ministry of Internal Affairs and Communications, 2018)
3.4 Wood Biomass Consumption and Substitution Effect

Annual firewood consumption per household was 3 m$^3$. Assuming this firewood was used in wood stoves, the amount of heat generated by burning this amount is 6.55 GJ, which is equivalent to 208 L of kerosene or 31.5% of mean annual household kerosene consumption (660 L) in Mishima. In terms of costs, almost all firewood in Mishima was either self-procured by felling trees or obtaining logs for free from acquaintances. Only one household surveyed purchased firewood, but at the extremely low price of JPY 200/m$^3$. Assuming that the firewood used in Mishima households lowered kerosene use by 208 L at the prevailing price of JPY 89/L and that no costs were incurred in firewood procurement, use of firewood reduced annual household heating costs by approximately JPY 18,500.

3.5 Wood Biomass Use and Energy Expenditure

We conducted independent sample t-tests to compare energy expenditure for kerosene, LPG, and electricity between firewood-using households and non-using households (Table 4). Although mean energy expenditure between the two groups differed, this difference was not statistically significant. The lack of differences may be due to other factors such as the small sample size, differences in usage of heating and hot water supply, or differences in household attributes.

3.6 Wood Biomass Use and Household Characteristics

To investigate the reasons for no statistically significant difference being found between the energy costs of firewood-using households and non-using households, we conducted independent sample t-tests on the difference in means with building age, floor area, number of buildings, number of rooms, renovation/rebuilding history of the households surveyed as separate dependent variables and use/non-use of firewood as the independent variable. The homes of firewood-using households tended to be older (Table 5).

As shown in Fig. 2, we also compared the number of people per household. Only mean building age was found to differ between firewood-using and non-using households at the $p < 0.05$ level (Table 5), with the homes of firewood-using households tending to be older. Owing to poor insulation and other factors related to house structure in firewood-using households, energy expenditure would likely be even higher than in

<table>
<thead>
<tr>
<th>Table 5 Use/non-use of firewood and household attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firewood use</td>
</tr>
<tr>
<td>Building age (years)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Floor area (m$^2$)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Number of rooms</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Persons per household</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Persons at home during the day (weekdays)</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 Persons per household in relation to number of heating devices owned for use/non-use of firewood.
households procuring their own firewood for free. Annual firewood consumption per household was 3 m$^2$, assuming this firewood was used in wood stoves, the amount of heat generated was equivalent to 31.5% of the mean annual household kerosene consumption in the town. Usage of firewood is economical, bringing a reduction in annual household heating costs of approximately JPY 18,500. These findings showed firewood still to be major heat resource in this town, and this trend is the same as was seen in previous studies (e.g., Izumi et al., 2018). Total demand for firewood inside the town can be self-supplied from the forest resources (Ooba et al., 2020).

In 2019, Mishima Town installed a new air conditioner system using fire-wood boilers in one of the town’s public facilities, Seikatsu Kogei-Kan (Mishima Local Crafts Museum), referring to our policy suggestion based on this study and other studies conducted by our project team (e.g., Ooba et al., 2020). This boiler system was coupled with the startup of a new small-scale firewood supply chain inside the town. Local companies in the town with the potential to provide more firewood intend to expand the biomass supply (personal communications). In the future, suppliers need to be matched with consumers of firewood at the local scale. Additionally, to transform this heat resource from a depletable to a renewable energy to achieve a decarbonized town, more detailed field surveys and analyses of related policies for not only biomass but also house building and renovation should be conducted.

4. Conclusions

We conducted a questionnaire survey of all households, the town of Mishima, Fukushima Prefecture to shed light on wood biomass use and household energy consumption in a mountainous region. The survey results revealed that approximately 9% of households were using wood biomass combustion devices, with most such households where firewood was not used, but further research and analysis would be required to identify exactly which factors are important.

Figure 3 shows the relationship between firewood use and energy expenditure. Although we found no decrease in energy consumption as a result of firewood use, the relationship between building structure and firewood use shown in Fig. 4 indicates that firewood use may be effective in reducing energy consumption in wooden houses, which require higher energy consumption.

References


---

**Shogo Nakamura**

Shogo Nakamura is a researcher in the Regional Environmental Renovation Section of the National Institute for Environmental Studies, Fukushima Branch. He holds a Ph.D. in agricultural science. He has played a central role in developing the energy monitoring systems in Shinchi as well as many other areas in Fukushima. Recently his interests have led him to participate in the Environment-Economy-Society Integration Research program.

**Takuya Togawa**

Takuya Togawa is a senior researcher at the National Institute for Environmental Studies, Fukushima Branch. He received his doctorate in engineering from the Graduate School of Environmental Studies, Nagoya University in 2010. He is engaged in research on mechanisms for realizing disaster recovery and regional revitalization by effectively utilizing local environmental resources.

(Received 21 December 2020, Accepted 28 December 2020)
Community Governance in Decontamination Policy after the Fukushima Nuclear Accidents: Two Case Studies from the Naka-dori Region, Fukushima, Japan

Takashi TSUJI*, Shogo NAKAMURA and Makoto OOBA

Regional Environmental Renovation Section, Fukushima Branch, National Institute for Environmental Studies
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima, 963-7700, Japan
*E-mail: tsuji.takashi@nies.go.jp

Abstract

The aim of this study is to explore the influence of community governance on the determination and implementation of decontamination policies in local communities, focusing on Miharu Town and Koriyama City in the Naka-dori region of Fukushima Prefecture. This study is based on fieldwork undertaken in Miharu Town and Koriyama City. Data were gathered from local documents and interviews. Interviews were conducted with the municipal administrations and neighbourhood associations in charge of post-accident decontamination policies. The results showed that the procedures and contents of the resulting decontamination policies were formulated on the basis of organizational cooperation among municipal administrations and neighbourhood associations in both municipalities. Immediately after the accident, neighbourhood associations participated in the process of determining the decontamination policies of these two municipalities. Networks comprising several neighbourhood associations tackled decontamination in educational facilities and along school routes. In some districts, neighbourhood associations participated in decisions on location and management of temporary storage yards for waste generated by decontamination work. In addition to these institutional factors, land-use-related factors in the spaces used in daily life influenced the procedures and contents of the decontamination policies. These defined the differences between methods of establishing temporary storage yards in Miharu Town and Koriyama City. Our findings suggest that the relationship between community governance and land use deserves more attention in this case, as in the case of other environment problems.

Key words: community governance, decontamination policy, Fukushima nuclear accident, Naka-dori region

1. Introduction

Decontamination is one of the main methods for eliminating radioactive contaminants and reducing radiation exposure in areas used in daily life. After radioactive materials escaped and spread as a result of the Fukushima Daichi Nuclear Power Station accident in March 2011, the Japanese government legislated a legal framework for decontamination, and the Act on Special Measures concerning the Handling of Radioactive Pollution came into operation from January 2012. Based on ICRP standards, the act set guidelines for decontamination aiming to reduce exposure doses. The Japanese government has overseen decontamination policies in these areas directly. Meanwhile, Intensive Contamination Survey Areas (ICSA) were established outside the evacuation zones, where the radiation doses were relatively low level.

As shown in Fig. 1, 102 municipalities in eight prefectures were designated as ICSA on December 28, 2011. In ICSA, decontamination was left up to the stakeholders in the local communities. The Japanese government argued that decontamination by the these local communities themselves would be most effective because the administrative functions were present, the residents were living there, and it was easy for them to understand the circumstances and the residents’ needs (Basic Policy for Emergency Response on Decontamination Work, published by Japanese Nuclear Emergency Response Headquarters on August 26, 2011).

The municipalities designated as ICSA, however, had few experts in radiation and radioactive materials and...
few people with experience in decontamination, which is the method of removing radioactive materials. Therefore, decontamination was promoted while learning about radioactivity and radioactive materials through trial and error based on collaboration and cooperation among stakeholders such as municipal administrations, neighbourhood associations, citizens’ groups and experts. These stakeholders determined the procedures and contents of the decontamination policies.

Against this background, the content of and progress in decontamination projects differed between municipalities. Kawasaki (2016) noted that there were differences in the formulation and implementation statuses of decontamination implementation plans among municipalities designated as ICSA. According to data from his questionnaire survey on municipalities designated as ICSA, of 40 that carried out decontamination, 12 had completed decontamination (30%) and 28 were in the course of decontamination (70%) as of the end of September 2015 (Kawasaki, 2016). Sato and Abe (2013) noted that policies on building temporary storage yards for radioactively contaminated soil differed from one municipality to another. In some municipalities such as Fukushima City, no temporary storage yards were set up to begin with. Decontamination waste was stored at the decontamination sites. In other municipalities such as Kawauchi Village, temporary storage yards were set up and radioactively contaminated soil was amassed in several places (Sato & Abe, 2013).

Decontamination is a sensitive issue not only for residents, but also municipal officials. Hence, it is difficult for the stakeholders to build consensuses and work together when dealing with decontamination programs (Edgington, 2017; Isono, 2015). In ICSA, because there may be discrepancies in awareness among stakeholders inside and outside the local communities regarding the implementation of decontamination procedures and the provision of temporary storage sites, measures may not proceed smoothly. In the decontamination policy-setting process, miscommunications and conflicts among stakeholders have been common in local communities since the Fukushima nuclear accident. In some local communities, however, decontamination has been implemented smoothly, and consensuses among stakeholders have ensured they are conflict-free. Based on the above, it is conceivable that collaboration among various stakeholders involved in decontamination programs may determine their content and quality in the local community.

In other words, it is important to focus on community governance to get a clear view of the institutionalization of decontamination policies in local communities. The aim of this study is thus to explore the influence of community governance on decontamination policy determination in local communities, focusing on Miharu Town and Koriyama City in the Naka-dori region of Fukushima Prefecture.

2. Brief Review of Community Governance

Literature and Decontamination Case Studies

In this study, we focused on the local community as a place of political decision making where governance is built during disaster recovery. Peters and Pierre (2016) defined governance as a process, where each group of different types of stakeholders congregates towards some collective goal. Above all, local governments play an important role in setting collective goals. Banner (2002) claimed that in recent years, local governments had been shifting their role from administrative to political leadership in civil society. In this study, community governance was regarded as a political process by which various stakeholders—including local governments as a political leader—converged toward the collective goal of decontaminating the local community.

When decontamination is regarded as a political process, it is necessary to pay attention to how risk
Community governance in decontamination policy after the Fukushima nuclear accident

Community governance in decontamination policy after the Fukushima nuclear accident is intimately connected with risk communication in the local community. Some research and theories suggest that there are pitfalls to risk communication in a ‘top down’ mode. A ‘top down’ mode of risk communication may miss what the public and stakeholders feel they need to know about environmental radioactivity (Mabon & Kawabe, 2018). In the decontamination policy process, a ‘bottom up’ mode of risk communication is required. Regarding how to formulate a ‘bottom up’ mode of risk communication in the decontamination policy process, Kinoshita notes that risk communication is not limited to issues of information transmission from administrative authorities to the public and stakeholders. He suggests that it is essential to focus on collaboration and coordination among the various organizations involved in the risk (Kinoshita, 2008).

Previous studies have focus on organizational communication by various stakeholders in local decontamination policy processes. Some studies have focused on communication with municipal administrations and community organizations. These studies have affirmed that municipal administrations and community organizations should communicate starting from the occurrence of the accident until formulation of the decontamination implementation plan is complete, ensuring that the decontamination policy proceeds smoothly. For example, Isono notes that municipal administrations that lacked communication with neighbourhood associations at the decontamination implementation planning stage met opposition from the neighbourhood associations and residents when setting up temporary storage yards and were unable to proceed with decontamination as planned (Isono, 2015).

Some studies emphasize the role of experts in mediating communication between municipal administrations and various community organizations in the local decontamination policy process. In Kashiwa City, Chiba Prefecture, an ICSA, a round table meeting was organized in collaboration with the municipal administration, agricultural groups and consumers associations with the support of sociologists prior to implementing decontamination. They examined radiation dose measurement methods for agricultural land and set voluntary standard values for the radioactivity of agricultural products (Igarashi & Anshin Anzen no Kashiwa San Kashiwa Shou Round Table, 2012). In the decontamination implementation phase, Kashiwa City administrative officials called on neighbourhood associations, to cooperate in decontamination and set up a “decontamination advisor” to assist these associations in implementing decontamination from an expert’s standpoint (Fukuda & Akita, 2014; Nakano & Deguchi, 2014; Iimoto et al., 2018). Kashiwa City is known as a successful case in which decontamination was able to proceed smoothly through collaboration among the municipal administration, community organizations and experts.

These studies suggest that the ability of municipal administrations to coordinate and the support of experts are required to facilitate decontamination policy. However, little attention has been given to structural conditions surrounding the community organizations and the ability of community organizations to coordinate in previous studies. To get a clear view of the institutionalization of decontamination policy, it is important to consider the role of community organizations for building consensus among stakeholders from the occurrence of the accident until the implementation of the decontamination policy.

3. Methodology and Case Study Areas

Miharu Town and Koriyama City are located in the central Naka-dori region of Fukushima Prefecture, about 45–60 km from the Fukushima Daiichi Nuclear Power Station (Fig. 2).

Miharu Town has a population of around 18,200, with a satoyama landscape and historic townscape of an old castle town. Koriyama City has the second largest population of any municipality in Fukushima Prefecture, with around 335,000 persons (Table 2). This city is the financial capital of Fukushima Prefecture. Urban functions and industries are concentrated and citizen groups and research institutes are gathered here.

Radioactive fallout contaminated the area as a result of the accident.
of the accident. Miharu Town and Koriyama City are specified municipalities among the ICSA, and decontamination has been carried out according to a decontamination implementation plan formulated at the end of 2011. There was a slight difference in the extent of radioactive contamination between Miharu Town and Koriyama City. In Miharu Town, the environmental radiation dose rate varied by district. In some districts, it exceeded 0.23 μSv/h, which was set by the national government as the post-decontamination numerical target for FY2016. In Koriyama City, the environmental radiation dose rate was relatively higher than that in Miharu Town. Especially in the central area of the city, radiation contamination of over 2.0 μSv/h was recorded. In accordance with the scale of these municipalities, the number of cases of decontamination also differed between the two. Koriyama City had the largest number of decontamination cases listed in the decontamination implementation plan in Fukushima Prefecture.

There was also a difference between the procedures and contents of the decontamination policies. In Miharu Town, a temporary storage yard was set up in each of the seven districts of the town. In Koriyama City, on the other hand, basically no temporary storage yards were set up, but decontamination waste was stored at the decontamination sites, meaning at each household.

By using qualitative research methods, we investigated the policy processes involved in implementing decontamination policy in Miharu Town and Koriyama City, focusing on policy networks formed after the accident. Based on fieldwork conducted in 2017 and 2018, the following survey methods were used in the current study.

The first was a document analysis. In this study, we analysed regional data before and after the nuclear accident. The local documents analysed included newspaper articles (from Fukushima Minpo and Fukushima Minyu), administrative council minutes, local governmental public relations magazines and various materials concerning local organizations. Materials available about community organizations from before the nuclear accident were collected without setting a target period. Meanwhile, materials issued in the six-year period from March 11, 2011 to March 31, 2017 were collected as materials from after the nuclear accident.

The second survey method was by interview survey. In this study, interviews were held with administrative department officials in charge of decontamination policies in Miharu Town and Koriyama City, and leaders of community organizations such as town planning associations, neighbourhood associations and agricultural groups.

### 4. Decontamination Policy Process in Miharu Town

From this chapter, the time between the accident and the ICSA designation of Miharu Town and Koriyama City is classified as the “emergency phase” and the time thereafter as the “reconstruction phase” and an overview is provided on how community governance functioned in the stream of decontamination policy processes in the two municipalities.

#### 4.1 Emergency Phase in Miharu Town

In Miharu Town, the “First Representative Ward Mayors Meeting” was held on March 12, 2011, the day after the accident. This meeting doubled as an autonomous disaster prevention association meeting, and information on the damage status and number of evacuees in the town’s seven districts was exchanged. It was decided that a “district disaster response headquarters” would be set up in each of the seven districts of the town, and the community development associations (machizukuri kyokai) in each district would manage them. In addition, the representative mayors of each neighbourhood association (gyousei-ku) became members of the town disaster response headquarters, and a system for collaboration between the town hall and each district was established.

Miharu Town’s administration collected information on the situation, namely the release of radioactive materials into the atmosphere due to damage to the nuclear reactor, and on March 15, unilaterally decided to distribute a stable iodine agent that was effective in reducing thyroid exposure to residents aged below 39 (7,269 people), without instruction from the government or prefecture (Miyazaki, 2013). Although the decision on the stable iodine agent was made by the upper level of the town administration, two district disaster response headquarters meetings were held before its distribution, and the district disaster response headquarters played a leading role in sharing information prior to the distribution and its related administrative procedures. This suggests that the community development
associations, which were responsible for operating the district disaster response headquarters, were at the core of community governance in Miharu Town immediately after the nuclear accident before the decontamination policy was launched.

Thereafter, the protection of children from radiation became an urgent issue in Miharu Town, as in other areas of the prefecture. The town administration conducted a radiation dose investigation of the schoolyards and playgrounds of the elementary and junior high schools and kindergartens of the town on May 14, 2011, and it was decided that the topsoil would be removed at 16 facilities in the June 23, 2010 fiscal supplementary budget.

In addition, to reduce the radiation dose from radioactive materials in spaces used in daily life such as school roads and parks, where children spend a lot of time, Fukushima Prefecture decided to implement a “Dose Reduction Activity Support Project (DRASP).” In Miharu Town, this project was utilized by residents voluntarily to decontaminate school roads in each district from November 6 to December 8, 2011. The main stakeholders in implementing this voluntary decontamination were the community development associations, neighborhood associations and parent-teacher associations (PTAs) in each district.

In the case of voluntary decontamination, the community development associations played the role of coordinator for the administration and each regional organization. In Sawaishi district, a rural area in the northern part of the town, the community development association conducted the “Sawaishi District Environmental Protection Measures Meeting” on October 18, 2011 to discuss the implementation system and contents of the DRASP in the district.

However, during the emergency phase in Miharu Town, emergent collaboration involving experts outside the region was also seen. After research volunteers specializing in radiation physics at the Tohoku University Graduate School of Science lobbied experts in the town, and it appeared in the mass media, the “Miharu Misho project” was launched on June 20, 2011. A town subsidy was used to cover the operating costs of the project, and the town’s General Affairs Section (Planning Information Group) served as the secretariat. In the project, a survey of individual cumulative doses among elementary and junior high school students (around 1,700 people) using a badge type dosimeter was conducted along with a soil radiation dose survey at the educational facilities.

4.2 Reconstruction Phase in Miharu Town

On August 26, 2011, the Nuclear Emergency Response Headquarters formulated Guidelines for Decontamination by Municipalities. Subsequently, after the enactment of the Act on Special Measures, the Ministry of the Environment formulated and announced Decontamination Guidelines on December 14, 2011. These guidelines provided policies on radiation dose survey measurement methods and decontamination methods for buildings, roads, soil, plants and trees. Since then, whole-area decontamination became the focus of measures against radioactive materials in the ICSA. Based on these guidelines, Miharu Town’s administration formulated a decontamination plan on December 1, 2011. The town administration held discussions with the resident representative (union organization of neighbourhood associations, Gyousei-kuchokai) and the town council prior to formulating the decontamination plan. When formulating the decontamination implementation plan, however, they had no opportunity to inform the residents of the plan and hear their requests.

Miharu Town established a policy of proceeding with decontamination from the areas where the temporary storage yards for decontamination waste such as soil generated by decontamination were located. In this instance, the community development associations were responsible for determining the location of the temporary storage yards and carrying out routine management in each district. Some community development associations in the town established departments and committees within the association for sharing information on surface decontamination and determining and managing the location of temporary storage yards.

In Iwae district in the western part of the town, the “Iwae District Decontamination Promotion Council” was established on June 27, 2012 within the association to share information on the decontamination implementation plan from the town’s Decontamination Measures Section and hold discussions on the location of temporary storage yards.

The officers included representatives of the town council and landowners, in addition to the head of the neighbourhood associations. The technical conditions (required area, land lease fees, etc.) of the temporary storage yards presented by the town administration were aligned with the residents’ interests (inclinations of landowners and reactions by surrounding residents) (Fig. 3).

To realize consensus building for the construction of temporary storage yards, it was important to focus on the
role of community development association leaders. They found suitable private land in their district and negotiated with the landowners for construction of temporary storage yards. One of the study interviewees, a representative of Iwae district’s community development association, described the actual state of communication among stakeholders such as neighbourhood associations and landowners in the temporary storage yard construction process as follows:

“We decided where to put the waste from decontamination. In our Iwae district, there was no suitable public land for temporary storage yards. So we held a meeting of the community development association, where presidents of the neighbourhood associations exchanged information about private land with each other.

In the end, we argued over details, negotiated with the landowners and got approval.”

(Source: Interview of Iwae Community Development Association representative, on December 22, 2017.)

His narrative indicated that there were many chances for discussion among the leaders of the community development associations. They persistently negotiated with landowners to construct temporary storage yards. This was possible because leaders of the community development associations were familiar with the ownership of private land in their districts.

Figure 4 illustrates the decontamination policy process in Miharu Town. The vertical columns list the decontamination policy items of each fiscal year on the horizontal axis. It is necessary to focus on the emergence of an organization in each district. This row shows that even immediately after the accident, community organizations were involved in the decontamination policy process. They consistently cooperated with the town government starting from just after the accident.

5. Decontamination Policy Process in Koriyama City

5.1 Emergency Phase in Koriyama City

After the accident occurred, Koriyama City’s administration launched topsoil removal from schoolyards at 15 public elementary and junior high school and playgrounds at 13 public nursery schools before any other municipality from the end of April 2011 (Fukushima Minyu, April 26, 2011). However, the city administration faced resident’s strong opposition in its briefing session held on April 27, 2011 for residents who were candidates for hosting storage yards for removed soil.

Koriyama City’s administration failed to build a consensus for decontamination with residents from the beginning of the decontamination policy process. According to an evaluation of the city administration officials, the radioactive substances contained in the removed soil did not reach a level that would impair the environment or health. However, not only the residents but also the city administration officials lacked sufficient knowledge and technical skills regarding radioactivity at that time. It is assumed that uncertainty regarding radioactivity then may have generated this consequence.

On the other hand, there was a swift response from the private sector regarding decontamination. From April 2011, community organizations such as neighbourhood associations (Chounai-kai, Gyousei-ku) and PTAs launched decontamination work and radiation dose surveys in areas used in daily life such as school roads.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergence of an organization in each district</td>
<td>Study sessions on the Great East Japan Earthquake (2011.5.5 – 2012.5.29 / 4 times)</td>
<td>Briefing session for residents about topsoil removal at schoolyards (2011.6.2–)</td>
<td>Briefing session for residents about the construction of temporary storage yards (2012–2013)</td>
<td>Decontamination Promotion Committee</td>
<td></td>
</tr>
</tbody>
</table>

Source: Authors, referring to Fukushima Action Research on Effective Decontamination Operation (FAIRDO), 2013.
and school facilities. Table 3 indicates that the main voluntary decontamination related activities in each district had multi-organizational cooperation.

In Koriyama City, community organizations had already launched their decontamination activities before the city government released its manual on decontamination to the citizens on October 1st, 2011. In addition to that, their decontamination activities were not based on the city administration’s requests.

5.2 Reconstruction Phase in Koriyama City

Koriyama City’s administration formulated a decontamination plan on December 27, 2011. The city administration held briefing sessions for all households and districts to formulate a decontamination plan. In this plan, the city administration promoted a policy of carrying out the decontamination program in collaboration with residents, neighbourhood associations, PTAs, volunteers and local companies (Murayama et al., 2015).

Utilizing the DRASP, Koriyama City’s administration gave grants to community organizations for decontamination activities in areas used in daily life. A total of 919 community organizations applied for the grants in three years: 622 in 2011, 264 in 2012 and 33 in 2013. It was the neighbourhood associations—who were the main parties responsible for voluntary decontamination—that utilized the grants. Before the accident, Koriyama City had 662 neighbourhood associations. Of these neighbourhood associations, 385 (58.2%) applied for the grants. DRASP was carried out throughout the city, but there were some districts where it was not possible to construct temporary storage yards because no suitable land could be found.

In some districts, decontamination wastes generated by the community decontamination activities were stored in parks and open spaces of their respective districts after coordinating among the city administration and community organizations. In Kikuta district in the northern part of the city, decontamination wastes were buried underground in public land (city-owned land) at a sports park (Fig. 5). The city administration proposed this method to the leaders of community organizations (Kikuta-machi Kucho-kai, the chounai-kais and PTAs).

The city administration and community organizations cooperated with the construction industry association in implementing storage of decontamination waste by this method. The fact that the leader of the construction industry association lived in the Kikuta district and was friends with the leader of the community organization also helped facilitate adoption of this method. The background to realization of this method of decontamination and temporary storage of decontamination waste is the existence of collaboration among city administration, neighbourhood organizations and the construction industry association.

In some districts, decontamination wastes were buried underground in private land. In Kurume district in the central part of the city, around 5,000 square meters of shrine-owned land was designated a temporary storage yard for the soil removed during decontamination of a residential area after mutual consultation between the residents.

The district’s federation of neighbourhood associations (Kurume-machi Choukai Rengokai) had responsibility for overall land use management for the construction of temporary storage yards. The federation set up a countermeasures headquarters within the association to carry out decontamination. The headquarters conducted voluntary decontamination activities in coordination with 13 neighbourhood associations and PTAs. After the voluntary decontamination was completed and the decontamination of residential areas was launched by the city administration, the leader of the federation negotiated with organization owning the land (the shrine association), decontamination contractor and city administration.

Table 3 Voluntary decontamination activities in Koriyama City.

<table>
<thead>
<tr>
<th>Date</th>
<th>District</th>
<th>Organizations</th>
<th>Contents</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 April 2011</td>
<td>Saikon Elementary school</td>
<td>Decontamination work</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>11 March 2011</td>
<td>Tomita PTA</td>
<td>Decontamination work</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>16 June 2011</td>
<td>Akagi Voluntary disaster prevention organization</td>
<td>Radiation dose survey</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>9 July 2011</td>
<td>Houzan Neighborhood associations</td>
<td>Radiation dose survey</td>
<td>Decontamination work</td>
<td>—</td>
</tr>
<tr>
<td>Late September, 2011</td>
<td>Citywide Small-scale enterprises PTAs</td>
<td>Radiation dose survey</td>
<td>Decontamination work</td>
<td>50</td>
</tr>
</tbody>
</table>

Source: Fukushima Minnu, Fukushima Minpou and Public Relations Koriyama (Kouhou Koriyama).

Fig. 5 Work to bury waste generated by decontamination of school roads in city-owned land (sports park) in Kikuta district, Koriyama City. (Photo by Kikuta-machi kucho-kai)
administration. The background to realization of this land use management for construction of temporary storage yards was the leadership of the federation uniting the district’s community organizations. Since the president of the federation also served as an officer in the community organizations in the district, it was easy to coordinate with the leader of each organization.

Figure 6 illustrates the decontamination policy process in Koriyama City. It is necessary to focus on consensus building between the city administration and residents, which was difficult in the emergency phase. It also bears repeating that, voluntary decontamination activities by community organizations preceded administrative efforts in Koriyama City.

6. Conclusions and Discussion

In this paper, we explored the influence of community governance on the determination of decontamination policies in local communities, focusing on Miharu Town and Koriyama City. The findings of this paper can be summarized in three points.

First, the procedure and contents of decontamination policies in Miharu Town and Koriyama City were formulated based on continuous organizational cooperation among municipal governments and community organizations starting from immediately after the accident. As shown in the case of Kashiwa City, opportunities and venues to coordinate the interests of multiple stakeholders before the details and policies of the measures for radioactive materials are determined and implemented are also required (Igarashi & Anshin Anzen no Kashiwa San Kashiwa Shou Round Table, 2012). By necessity, the procedure and contents of decontamination policies in local communities are determined based on limited information on radioactivity, and it is necessary for stakeholders to share awareness when making decisions and implementing measures. The state of consensus building on topsoil removal from the schoolyards in Koriyama City during the emergency phase suggests as much.

Second, the procedure and contents of the decontamination policies of Miharu Town and Koriyama City were formulated based on land ownership in local communities. When public land is used as a temporary storage yard for removed soil, coordination between the municipal administration that owns the land and the community organization that represents the residents is required. On the other hand, when using private land, coordination between organizations owning the land and community organizations such as neighbourhood associations is required.

Third, micro-negotiation tactics, which are carried out by community organizations leaders, contribute to smooth progress of decontamination policies such as establishment of temporary storage yards. Previous studies have pointed out the importance of residents’ involvement in governance in the decontamination policy process (Moriguchi, 2015). The findings of this study suggest a role of community organization leaders as actors in community governance for decontamination policies. There should be more attention to power structures that serve in the relationship among community leaders in decontamination policies.

As shown in Figs. 4 and 6, there were differences in the decontamination policy processes between Miharu Town and Koriyama City. In Miharu Town, smooth communication between the town administration and residents was observed immediately after the accident. On the other hand, in Koriyama City, there were
miscommunications between the city administration and residents at the same time. It is presumed that the key factor determining the difference is experience in communication between the government and residents during the emergency phase.

Decontamination constitutes risk communication over land use in the local community. The findings of this study suggest that the relationship between community governance and land use deserves more attention, as it does with regard to other environment problems.

However, it cannot be said that among the ICSA, Miharu Town and Koriyama City had particularly high air dose rates. In terms of future tasks, it may be necessary to analyse cases by controlling non-social factors such as air dose rates and categorizing community governance in the ICSA.

Acknowledgment

This work was supported by National Institute for Environmental Studies Fukushima branch grant-in-aid for exploratory research from fiscal year 2017 to 2018.

References


Igarashi, Y. and Anshin Anzen no Kashiwa San Kashiwa Shou Round Table (2012) The form of 'Safety' we have decided: A year of Kashiwa searching for local production for local consumption post 3/11, Akishobo. Tokyo. (in Japanese)


Takashi Tsuji

Takashi Tsuji completed his Ph.D. in sociology at Nagoya University in 2019. Now, he is a researcher at the National Institute for Environmental Studies, Fukushima Branch. His research interests include disaster governance and community resilience, focusing on disaster/environmental policy processes with long-term community development.

Shogo Nakamura

Shogo Nakamura is a researcher in the Regional Environmental Renovation Section of the National Institute for Environmental Studies, Fukushima Branch. He holds a Ph.D. in agricultural science. He has played a central role in developing the monitoring systems in Minamisato as well as many other areas in Fukushima. Recently his interests have led him to participate in the Environment-Economy-Society Integration Research program.

Makoto Ooba

Dr. Ooba heads the Environmental Renovation Laboratory at the Fukushima Branch of the National Institute for Environmental Studies, Japan. From 2007 to 2012 and from 2014 to the present, he has participated in a study on spatial assessment of Japan’s regional forests using process-based models and remote sensing by NIES. Based on these studies, he has analyzed sustainability of forestry and harvested wood products. He has also worked at Osaka University, Nagoya University and the Tokyo University of Agriculture. He holds a Ph.D. in environmental science from Hokkaido University, 2002.

(Received 1 December 2020, Accepted 28 December 2020)
Overview of the Environmental Emergency Management Studies in National Institute for Environmental Studies (NIES)

Ryo TAJIMA* and Masahiro OSAKO

Centre for Material Cycles and Waste Management Research, National Institute for Environmental Studies
16-2 Onogawa, Tsukuba-shi, Ibaraki, 305-8506, Japan
*E-mail: tajima.ryo@nies.go.jp

Abstract

Despite its significance in achieving sustainability in an era of frequent disasters, environmental emergency management (EEM) is a field that has not attracted enough attention from policy makers. This article provides an overview of and outlook for EEM studies at the National Institute for Environmental Studies (NIES). For this, a framework is presented for EEM based on recent international literature, and representative works undertaken by NIES are presented in line with this framework to examine research gaps and outlook. Our analysis shows good coverage of research topics aimed at enhancing understanding of the impact of environmental emergencies and advancing both pre- and post-disaster actions for disaster waste management (DWM). Some research gaps are also identified: namely, research on post-disaster assessment of environmental impacts and decision making under emergency circumstances, research on responses and recovery actions against impacts from hazardous substances released in the course of natural hazard events, and research collaboration within the EEM discipline and between natural hazard experts (especially regarding physical countermeasures).

Key words: disaster waste, environmental emergency, management, toxic release, Natech

1. Introduction

Environmental emergencies are a serious concern for both developed and developing countries (Liao et al., 2012; Srinivas & Nakagawa, 2008). They are defined as sudden-onset disasters or accidents resulting from natural, technological or human-induced factors, or a combination of these, that cause or threaten to cause severe environmental damage as well as harm to human health and/or livelihoods (UNEP, 2002). They may occur in the form of a discharge of pollutants such as oil, hydrocarbons, hazardous chemicals or radioactive substances, or the generation of disaster waste that could result in public sanitation issues and environmental pollution (Srinivas & Nakagawa, 2008). Compared with general environmental pollution in normal times, environmental emergencies are characterized by sudden onset, typically a large volume of pollutant discharge in a short period of time, and the need for urgent decisions to be made under stressful circumstances (French & Geldermann, 2005; Liao et al., 2012). The aim of environmental emergency management (EEM) is to mitigate these environmental impacts by taking systematic pre- and post-disaster actions.

Despite its significance in achieving sustainability in an era of frequent disasters, EEM is a field that has not attracted enough attention from policy makers. The Joint UNEP/OCHA Environment Unit points out the policy gap and highlights the need for a new (or improved) preparedness framework that integrates environmental emergencies into disaster preparedness planning and emergency response (JEU, 2013a). In terms of research, a quick search in a scientific database (Web of Science Core Collection) shows an increasing trend in the number of studies related to EEM especially in the last ten years. Some focus on specific types of environmental emergencies, such as oil spills (e.g., Peterson et al., 2003; Kujawinski et al., 2011) or “Natechs,” i.e., natural-hazard triggered technological accidents (e.g., Young et al., 2004; Krausmann et al., 2011); and others focus on specific aspects of EEM such as decision making on initial responses (e.g., Hernandez & Serrano, 2001; Krausmann et al., 2011); and others focus on specific aspects of EEM such as decision making on initial responses (e.g., Hernandez & Serrano, 2001; Liao et al., 2012; Wang et al., 2020). There has been no attempt, however, to construct an integrated theory on EEM.

The aim of this article is to present an overview of recent EEM studies as a first step toward constructing a comprehensive EEM theory, with a special focus on the works undertaken at the National Institute for Environmental Studies (NIES), where EEM research has been conducted extensively and most comprehensively in Japan, mainly since the 2011 Tohoku Earthquake. The
Environmental impacts of disasters can be categorized by being triggered by natural hazard events (e.g., earthquakes, flooding, tsunamis) or technological hazards (e.g., chemical factory accidents). Another aspect is whether the impact is caused directly by the disaster or from response and recovery from the disaster. Based on these two aspects, at least four types of disaster-induced environmental impacts can be indicated (Table 1). The first is disturbances in the natural environment. An example is the damage caused by the 2004 Indian Ocean Tsunami to coral reefs, sea grass beds and other elements of coastal ecosystems (Srinivas & Nakagawa, 2008). This type of impact may have both negative and positive impacts on local sustainability.

The second is disaster waste generated through the destruction of the built environment. Disaster wastes are different from wastes disposed of in normal times as they include both household waste and industrial waste and are often mixed at source. They pose short-term sanitation risks (e.g., odor, pests) and public health risks (e.g., infection), and over the longer term, environmental risks from inappropriate treatment and disposal (Brown et al., 2011; JEU, 2013b). Serious environmental impacts may occur when disaster wastes are contaminated with hazardous substances such as asbestos.

The third is release of hazardous substances. The cause of such releases may be industrial accidents triggered by human/system errors, or Natechs triggered by natural hazard events, such as power plant explosions triggered by natural hazards (e.g., Young et al., 2004; Krausmann et al., 2011). Releases of hazardous substances may result in acute environmental and health impacts. In addition, recent studies highlight chronic environmental and health impacts. For example, the 1989 Exxon Valdez oil spill had delayed, chronic and indirect effects from petroleum contamination in the marine environment, including, e.g., decreased sea otter survival due to chronic exposure to residual petroleum hydrocarbons from sediment contact and ingestion of bivalve prey (Peterson et al., 2003).

The fourth is impacts caused by disaster recovery and reconstruction, from both natural and technological hazards. As disaster recovery is a resource intense project, environmental concerns from intensified resource depletion can have detrimental effects on the long-term sustainability of disaster-impacted countries (UNEP & SKAT, 2007; Chang et al., 2010). Reconstruction projects may also have direct and long-term environmental impacts, e.g., impacts on water quality caused by land-clearing projects to develop new housing sites (Spaling & Vroom, 2007).

Among the environmental impacts listed in Table 1, “(1) Disturbances in the natural environment” and “(4) Environmental impacts of disaster recovery” are different from “(2) Generation of disaster wastes” and “(3) Release of hazardous substances” in that the impact on human society does not appear in the immediate aftermath of the disasters, and thus their management does not share the common characteristics of EEM, i.e., urgent need and stressful circumstances of decision making (French & Geldermann, 2005). In this manuscript we focus on (2) and (3) in Table 1 as the target of EEM. However, this does not mean ecosystem disturbances and environmental impacts of reconstruction are less important. They can have a significant impact on sustainability of the stricken area after reconstruction and rehabilitation and should be managed under different management theories and tools.

2.2 Process of Environmental Emergency Management

Similar to the disaster management cycle (Collins, 2009), which embraces both pre-disaster activities (mitigation, preparedness, early warning) and post-disaster activities (relief, recovery, rehabilitation), EEM also has both pre- and post-disaster dimensions as illustrated in Fig. 1.

2.2.1 Post-disaster EEM Actions

The first two steps of post-disaster EEM are identification and assessment of potential environmental

Table 1 Environmental impacts of disasters and target of environmental emergency management (EEM).

<table>
<thead>
<tr>
<th>Triggered by natural hazard</th>
<th>Direct result of the hazard</th>
<th>Result of disaster response</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Disturbance on natural environment</td>
<td>(4) Environmental impact of disaster recovery</td>
<td></td>
</tr>
<tr>
<td>(2) Generation of disaster waste</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Triggered by technological hazard (including Natech)</th>
<th>(3) Release of hazardous substance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4) Environmental impact of disaster recovery</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1 Environmental emergency management framework.
impacts. This can be done at two different levels of concreteness. At a relatively abstract level, the type of environmental impact (disaster wastes, hazardous substances, etc.) and its urgency is identified, to guide common-sense response actions. Rapid Environmental Impact Assessment (REA) is a tool for this, in which potential environmental impacts in disaster situations can be defined and prioritized shortly after the disaster occurrence (Hauer & Kelly, 2018). At a more concrete level, actions to identify potential impacts differ according to the type of environmental impact. The impact of disaster wastes is identified by estimating the amount and composition of disaster wastes. Here, identification of impact (=estimation) is undertaken for different purposes at different phases of the disaster waste management (DWM) process. In the early response phase, a very rough estimation is made to decide the scale of DWM and necessary resources and external assistance. In later phases, after undertaking the initial response actions and initiating disaster waste treatment, more certain numbers can be acquired through measurement and calculation to facilitate decisions on the selection of treatment and disposal options (Tajima et al., 2018). To assess the potential impact of disaster wastes and the urgency and scale of DWM, the amount of disaster wastes is compared with the waste disposal capacity of the stricken area, the existence of putrefactive and hazardous wastes is ascertained, and the degree of separation (or mixture) of accumulated disaster wastes is evaluated (JEU, 2013b). In terms of hazardous substances, it is important to identify the released substances quickly through emergency monitoring and assess their impact in terms of toxicity, concentration and quantity (Young et al., 2004). Simulation of the transportation and dispersion of hazardous substances is typically undertaken. Identification and assessment of impacts may become problematic when the released substance is unknown, especially in the case of large-scale Natechs that involve multiple industrial accidents. In these cases, there are risks from released chemicals and their side products (e.g., from fires) that are not anticipated in normal times. The Flash Environmental Assessment Tool (FEAT) can help responders prioritize measures to reduce impacts from chemicals through decision trees and lookup tables (Posthuma et al., 2014).

The next two steps of post-disaster EEM are initial response to the impact (impact reduction) and treatment/disposal of the impact sources. For disaster wastes, collection and treatment of hazardous and putrefactive disaster wastes are the highest priority (JEU, 2013b). Following this is the collection of other non-hazardous disaster wastes (e.g., concrete from demolition) to reduce sanitation risks. Recycling and reuse of materials and appropriate treatment and disposal are then undertaken, considering the balance between the conflicting environmental (recycling rate, carbon footprint) and economic (direct cost) benefits and impacts (Amato et al., 2019). Mathematical models to support decisions on disaster waste processing systems under high uncertainty are being widely studied (e.g., Habib et al., 2019; Cheng et al., 2018). To implement collection, treatment and disposal, DWM requires specific management tasks including procurement, financing, and planning (Tajima, 2020). For hazardous substances, measures to reduce impact, including emission reduction (limiting the sources), dispersion (limiting the pathways) and evacuation (removal of impact receptors) are implemented (Posthuma et al., 2014). In some occasions, prophylactic drugs and antidote agents are used to reduce health impacts (Georgiadou et al., 2010). Such decisions are based on the characteristics of the site (e.g., location, surrounding environment) and the environmental and health standards to follow. Studies on methods and models to support decisions on initial response, based for instance on a case-based reasoning approach, have been widely studied (e.g., Hernandez & Serrano, 2001; Liao et al., 2012; Wang et al., 2020). After these response actions, the released substances and contaminated water/soils are collected using adsorbent materials or by physical removal to a reasonable extent and disposed of through the usual hazardous waste management stream.

Another important element of post-disaster EEM is overall management of the response and recovery process. The entire post-disaster EEM process needs to be monitored and evaluated because situations surrounding environmental emergencies become clear and new issues and needs arise over time. Overall management is also important because environmental impacts at the intersection of disaster wastes and hazardous substances can occur, such as contamination of disaster wastes by hazardous substances.

### 2.2.2 Pre-disaster EEM Actions

The aim of pre-disaster actions is to effectively reduce and respond to the impact of a foreseeable disaster. The lessons learnt through post-disaster EEM should guide pre-disaster EEM. Based on theoretical grounds in capacity development for disaster risk reduction (Hagelsteen & Becker, 2013), we considered four key elements of pre-disaster EEM actions: preparedness planning, training, institutional arrangements and physical countermeasures (Fig. 1). Pre-disaster EEM should be dynamic and continuous, and to enhance synergistic effects, these actions should not be undertaken in isolation (Karunasena & Amaratunga, 2016).

The first element is preparedness planning, the core of preparedness (USEPA, 2008; JEU, 2013b). Scholars in emergency management state that preparedness planning is a process of generating emergency response measures and protocols, and the written plan represents a snapshot of that process (Perry & Lindell, 2003). Another important implication of preparedness planning in EEM is that considering the large uncertainties of the
emergency context, the fundamental principles of response and priorities should be specified whereas the amount of operational details should be minimized (Perry & Lindell, 2003). For DWM this means identification of different waste management approaches and required resources including personnel, vehicles, staging and disposal sites, and recycling technology/facilities (Brown & Milke, 2016). The same principle applies to hazardous substances, but current research and practice seem more inclined to use detailed quantitative risk assessments for planning. One example is the procedure for Natech risk assessment which consists of (1) characterization of the natural event, (2) identification of target equipment, (3) identification of damage states and reference scenarios, (4) estimation of damage probability, (5) evaluation of consequences in reference scenarios, (6) identification of credible combinations of events, (7) frequency/probability calculations for each combination, (8) consequence calculations for each combination, and (10) calculation of risk indices (Antonioni et al., 2009). Mapping of those risks is also an effective practice (Girgin & Krausmann, 2013). Another important component of preparedness planning is to establish a coordination framework and personal relationships between organizations that will be required to coordinate in post-disaster EEM (Perry & Lindell, 2003). Unlike waste management and chemical accident management in normal times, EEM requires involvement of natural hazard experts and other disaster respondents such as military, civil engineers and social welfare staff.

The second element is training, which increases the effectiveness of preparedness plans. Preparedness plans are only effective when knowledge, skills and attitude (KSA) are transferred to emergency responders, and that KSA is applied effectively to real world performance (Ford & Schmidt, 2000). Typical training methods include lectures, workshops, drills, tabletop exercises and functional exercises, the latter being a more active type of learning. Training courses are also effective venues for developing inter-organizational coordination (Perry & Lindell, 2003).

The third element is institutional arrangements such as enactment and revision of laws and regulations. Legislation on waste management (e.g., mandatory recycling targets) can either enhance or compromise recycling of disaster wastes (Brown & Milke, 2016). Restricting industrial development in disaster-prone areas through land-use planning, building codes and safety regulations may reduce the risk of toxic releases after natural hazard events (Krausmann & Cruz, 2013). Regarding hazardous substances, standards for emergency exposure play a critical role because environmental standards developed for environmental management in normal times may not be applicable to acute and short-term exposures.

The final element, physical countermeasures, reduces the impact of natural hazard events and ensures the availability of resources and functions needed for response actions. Regarding disaster wastes, flood prevention facilities and anti-seismic reinforcement of housing can decrease the amount of disaster wastes, which in turn facilitates environmentally friendly disposal in terms of pollutant emissions (Hirayama et al., 2013; Wakabayashi et al., 2017). Reinforcement of installations and equipment in various ways such as by anchoring and using safe equipment design can also help reduce the impact of disasters (Krausmann et al., 2011).

Just as with post-disaster EEM, it is important to get an overview of the capacity development process and actions for preparedness. As environmental emergencies are dependent on local situations, analysis of the existing risks and capacity of the responding organizations is necessary for effective preparedness capacity development (Hagelsteen & Becker, 2013).

3. Environmental Emergency Management Studies at NIES

3.1 Understanding Impacts of Environmental Emergencies

NIES has conducted research aimed at elucidating the impact of environmental emergencies, focusing mainly on the 2011 Tohoku earthquake and tsunami, as little was known about the environmental impact of tsunamis and tsunami-induced industrial accidents. Regarding disaster wastes, the characteristics of disaster wastes from the 2011 Tohoku earthquake and their disposal process were summarized by Osako and Tajima (2014). A large concern regarding these disaster wastes, apart from those radioactively contaminated, was impact of tsunami sediments, amounting to ca. 10 million tons. Oguchi et al. (2013) summarized the state of chemical pollution and concluded that although some reports indicated levels in excess of environmental standards for lead, arsenic, fluorine and oil, the overall level of pollution was low. In terms of hazardous substances, Kanaya et al. (2016) investigated the ecological consequences of the fuel spills and subsequent conflagrations that resulted from the tsunamis following the 2011 Tohoku earthquake. The results indicated that although sediment in the bay still contained high levels of polycyclic aromatic hydrocarbons (PAHs) four years after the disaster, no negative impacts of the PAHs were detected in the dominant macrozoobenthos. A series of environmental emergency monitoring actions were also conducted to clarify the release and impact of some inorganic elements, persistent organic pollutants (POPs), microorganisms and pests, mainly near the evacuation centers and temporary storage/treatment sites for disaster wastes (Nakajima et al., 2019). Hashimoto et al. (2019) investigated the health and sanitation risks of debris stored at a temporary storage site on its surroundings and
found higher outdoor concentrations of certain microorganisms known to be respiratory allergens compared to in a normal environment. The effects of particulate matter (PM) derived from tsunami sediments on human health were studied and it was concluded that the overall concentration of PM was low but that vulnerable people may need special care (Suzuki et al., 2019). The impact of the 2011 Tohoku tsunami on the local ecology and population were also evaluated. It was found that a large-scale tsunami caused mass mortality of intertidal organisms over a broad spatial scale but did not significantly affect the genetic diversity of the local populations (Miura et al., 2017; Miura et al., 2019). Kanaya et al. (2019) reached a similar conclusion from studies in Fukushima and Ibaraki prefectures, but they also pointed out the detrimental impact of restoration work after 2016 on faunal diversity and mortalities of some marine taxa.

Comparing among the four types of environmental impacts of disasters indicated in Table 1, the research at NIES seemed to cover (1) ~ (4) relatively well, and some work has been done at the intersection of (2) and (3). Studies on other disasters could enhance generalization of their findings, as most of the work solely concerns the 2011 Tohoku earthquake.

### 3.2 Development of Post-disaster EEM Theory and Technology

Studies on post-disaster EEM at NIES are summarized in Table 2. Regarding identification of impacts, methods to estimate the amount of disaster wastes were developed, implemented and reviewed to enhance their accuracy (e.g., Hirayama et al., 2013; Tajima et al., 2018). A rapid screening method for asbestos was developed to help enhance disaster waste treatment while controlling health risks (Yamamoto et al., 2018). For hazardous substances, works related to developing and applying a technology that could quickly identify and quantify substances existing in post disaster environments, namely AIQS-GC (Automated Identification and Quantification System using gas chromatograph-mass spectrometry), were undertaken (e.g., Nakajima et al., 2019). On the other hand, there has been no particular research regarding assessment of the impact that could facilitate decision-making in the initial response.

Regarding the response and treatment/disposal step, research efforts have focused mainly on disaster wastes. For example, based on practical experience in providing technical assistance to management of temporary storage sites, management methods to prevent spontaneous fires, a potential risk during the initial response phase of DWM, were clarified (Endo & Yamada, 2012). Regarding disposal of disaster wastes, work has been done to confirm the risk of generating dioxins from incineration of wooden disaster wastes saturated with sea water, and ergonomic studies have been done on factors related to efficient hand separation. To enhance recycling of tsunami deposits, their properties were investigated and methods and standards for environmentally and physically safe recycling as geomaterials were clarified (e.g., Katsumi et al., 2017). These research activities contributed to production of guidelines for effective utilization of reconstruction materials recycled from disaster wastes (Japanese Geotechnical Society, 2014). Research on overall management was intensely undertaken regarding disaster wastes. Tasks and functions necessary for a DWM project were clarified from in depth research on various DWM cases in Japan, and differences related to the scale of the responding local government were analyzed (e.g., Tajima, 2020).

The first research gap indicated in Table 2 is research on assessing impacts, a missing link between results of impact identification and response actions. The research outputs mentioned above could contribute more to EEM by linking the results of impact identification to existing assessment tools such as REA, or by developing tools or systems to aid post-disaster EEM decision making. Another research gap in EEM worth noting is research on response methods and processes and their overall management, specifically for toxic releases under emergency circumstances. The current response methods and procedures summarized in the Japanese guidelines do not anticipate Natechs (Ministry of the Environment, 2009), which could hinder effective responses to toxic releases after large-scale natural hazard events and Natechs under stringent resource restrictions.

### 3.3 Development of Pre-disaster EEM Theory and Technology

Research on pre-disaster EEM at NIES is summarized in Table 3. With regard to preparedness planning, DWM planning principles have been summarized (e.g., Tajima et al., 2013a), extensively

| Table 2 Main research items of post-disaster EEM (environmental emergency management) research at NIES. |
|---------------------------------|---------------------------------|---------------------------------|
| Identification of impacts (debris, pollutants, etc.) | Estimation of disaster waste | Environmental monitoring system |
| Assessment of impacts | Rapid screening for asbestos | |
| Initial response to (reduction of) the impacts | Methods of managing temporary storage sites | No particular research output |
| Treatment and disposal of impact sources | Methods and strategies for recycling tsunami sediments | No particular research output |
| Overall management | Tasks and functions of DWM (disaster waste management) | No particular research output |
guided by principles of preparedness planning for emergency management (Perry & Lindell, 2003). Other works related to overall management in post disaster DWM also help inform the planning process by pointing out the necessary tasks, functions and resources. No particular work has been done to develop preparedness planning for hazardous substances, including research related to development of quantitative planning models and tools using linear programming and its applied methods, which have been rather well studied internationally (see 2.2.2 above). Training has gained special attention and works have been undertaken with regard to both disaster wastes and toxic releases. Notably, theories and methods for DWM training have been developed, including workshops (Tajima et al., 2015) and functional exercises for local government officers (Tajima et al., 2019), with workshops applied to enhance civic action among residents (Mori et al., 2020). These methods were developed based on understanding of the necessary KSAs for DWM personnel (Tajima et al., 2014). Research has been undertaken in collaboration with several prefectural governments and citizen groups in Japan, referring to the theory of action research (Stringer, 2014). Training to gain technical skills needed to use AIQS-GM has also been undertaken (Nakajima et al., 2019).

Another item that has received attention regarding both disaster wastes and hazardous substances is institutional arrangements. For disaster wastes, the effects of definitive and provisional institutional arrangements for DWM on actual management processes in the 2011 Tohoku earthquake have been analyzed, and suggestions have been made for future development (Tajima et al., 2013b). For hazardous substances, domestic and overseas efforts in response to accidents and disasters with release of chemical substances have been investigated, mainly from the viewpoint of exposure levels, and a list of substances deserving high-priority management has been developed (Koyama & Suzuki, 2019). In addition, NIES researchers have been extensively involved in the development of various EEM guidelines, including, e.g., the DWM guidelines of Japan’s Ministry of the Environment (Ministry of the Environment, 2018). No particular research has been conducted so far regarding physical countermeasures for disaster wastes and hazardous substances. For overall capacity management, online tools to evaluate the resilience of local waste management systems from various viewpoints have been developed (e.g., Tajima & Osako, 2017). They are intended to help local governments plan for capacity development, by recognizing the risks in their waste management system and their current capacity to respond, adapt to and cope with disaster wastes. This is associated with an online information platform for disaster waste management developed by NIES, in which technical and administrative guidance, reports on DWM experience, a database of local DWM plans and other materials for individual and organizational learning are consolidated.

One gap obvious from Table 3 is research on physical countermeasures. This is usually studied by structural dynamics experts. Collaboration with external natural hazard experts on physical countermeasures would have important implications in preparedness planning (e.g., the role of treatment facilities, post-disaster functionality of disposal facilities) and institutional arrangements (e.g., provision of incentives). Another issue regarding collaboration is inadequate interaction between disaster waste and hazardous substance researchers on preparedness planning, training and capacity management. For example, methods and theories on training for EEM could be developed and implemented more efficiently by integrating the findings from works undertaken for disaster wastes and toxic releases. A tool to evaluate the capacity to manage hazardous substance releases similar to the tool developed for disaster wastes could benefit from integration to enhance awareness of both issues by local governments.

4. Conclusions

Since 2011, research on EEM has been undertaken extensively by NIES, mainly driven by the needs and issues recognized in EEM practice. This article has attempted to clarify the overall framework of EEM, and give an overview of associated research conducted at NIES. Our analysis shows good coverage of research topics aimed at enhancing understanding of the impact of environmental emergencies and at advancing both pre- and post-disaster actions for DWM. Some research gaps have also been identified, namely, research on post-disaster assessment of environmental impacts and decision making under emergency circumstances, research on response and recovery actions against impacts from hazardous substances released by natural

Table 3 Main items studied in pre-disaster EEM (environmental emergency management) research at NIES.

<table>
<thead>
<tr>
<th>Disaster wastes</th>
<th>Hazardous substances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparedness planning</td>
<td>Principles of DWM (disaster waste management) planning</td>
</tr>
<tr>
<td>Training</td>
<td>Development of training methods and theories</td>
</tr>
<tr>
<td>Institutional arrangements</td>
<td>Impact of institutional arrangements on the DWM process</td>
</tr>
<tr>
<td>Physical countermeasures</td>
<td>No particular research output</td>
</tr>
<tr>
<td>Overall capacity management</td>
<td>Online tools to evaluate resilience of local waste management systems</td>
</tr>
</tbody>
</table>
hazard events, and research collaboration within the EEM discipline and among natural hazard experts (especially regarding physical countermeasures). Finally, we should note that to enhance EEM in an age of limited public resources (budgetary and staff), future research should focus on synergistic benefits for development in normal times and response in emergencies. Innovations in technologies and governance structures of normal-time environmental management are required in a way that mainstreams EEM.

References


Joint UNEP/OCHA Environment Unit (JEU) (2013a) Integration of environmental emergencies in preparedness and contingency planning. 35 pp.


genetic impact of the 2011 Tohoku Earthquake Tsunami on intertidal mud snails. Scientific Reports, 7, 44375.


Ryo Tajima

Ryo Tajima is a senior researcher at the Centre for Material Cycles and Waste Management Research, National Institute for Environmental Studies, Japan. His main research field is policy and planning for waste management under disaster and normal circumstances. He is involved in local and national efforts to draft guidelines and plans and to design training programs for disaster waste management.

Masahiro Osako

Masahiro Osako, who holds a doctorate of engineering, serves as director of the Material Cycles Division, National Institute for Environmental Studies (NIES). His specialty is environmental engineering, focusing on waste management. Since the Fukushima nuclear accident that resulted from the Great East Japan Earthquake in 2011, he has been dedicated not only to conducting various researches to properly manage radioactively contaminated wastes but also to playing an important role in the relevant policy-making by the national government. He also chairs the research committee on technological strategies for the final disposal out of Fukushima in the Society of Remediation of Radioactive Contamination in the Environment.
1. Introduction

Various harmful substances have been released into the environment during chemical accidents such as fires, explosions and spills. The number of accidents at facilities handling hazardous materials has been increasing since the 1990s (Fire and Disaster Management Agency, 2016). Quick and appropriate responses to accidental releases are essential for minimizing health and environmental risks. It is not easy to obtain information on risk assessment due to the difficulty of identifying substances and fluctuations in the amounts released and concentrations in the environment. Therefore, only a limited number of cases have been analyzed from the perspective of health and environmental risks to the general environment. In this study, we conducted questionnaire and interview surveys with site operators to collect information related to substance release processes and responses to them in past accidents. In addition, we extracted factors relevant to the emergency responses to the accidents and systematically analyzed the release processes.

2. Methods

2.1 Questionnaire Survey on Chemical Accidents

For the purpose of collecting information as a basis for categorizing chemical accidents, we conducted questionnaire surveys and interview surveys with site operators about accidents that had occurred in the past. To list up target accidents for these surveys, past accidents in Japan that may have involved releases of chemical substances were extracted from the Database of Disasters and Accidents (Accident and Disaster Information Center (ADIC)). These surveys were carried out twice. The first (Survey 1) was conducted in April 2019 and the second (Survey 2) was conducted in April 2020. Survey 1 covered accidents that had occurred in recent years (2017 to 2019) with no limit on the type of industry, and the Survey 2 covered accidents that had occurred after 1990 except for cases that would duplicate those in Survey 1. Survey 2 was intended to collect more information about the chemicals released. The number of questionnaires distributed in Survey 1 was 100, and in Survey 2, 51. In both surveys, the interviews were conducted after the questionnaire survey (Survey 1: 20 interviews, Survey 2: 18 interviews).

The questions asked in the questionnaire surveys were mainly concerned with the handling of substances at the time of the accident, the state of the released substances in the environment and the emergency response.
responses to the accident. Table 1 outlines the questions.

2.2 Considering Practical Information in Emergency Responses

Based on the results of the surveys in Section 2.1, information desirable to obtain for emergency responses was examined. Methods of identifying released chemicals, considered to be a particularly important factor in conducting environmental surveys, were compared. Here, the advantages and disadvantages of interviews with site operators and utilization of the Pollutant Release and Transfer Register (PRTR) notification data were compared. In addition, examples of other factors and criteria that could characterize chemical accidents were identified.

2.3 Classification of Release Processes and Responses

To manage the risks to the general environment from accidental releases of chemical substances from industrial sites, it is important to analyze systematically the behaviors of substances in the environment from the time of release of the chemical substances to the time of exposure. The concept of a migration process of released substances in environmental media had been brought up in several studies (International Atomic Energy Agency (IAEA), 2002; Moriguchi, 2013; World Health Organization, 2009), but there were differences in the settings of the environmental media. In this study, for the purpose of covering various possible situations, attempts were made to classify the migration processes of substances in the environment and the corresponding emergency responses. Possible emergency responses were listed in consideration of both possible general responses and replies to the questionnaire survey.

3. Results and Discussions

3.1 Analysis of Questionnaire Replies

Table 2 shows the number of replies to the questionnaire survey by industry. In Survey 1, as for classification of industry, “manufacturers of chemical and allied products” (7 respondents) accounted for the highest number of respondents. Next were “manufacturers of petroleum and coal products” (4 respondents), “manufacturers of transportation equipment” (4 respondents), and “waste disposal businesses” (4 respondents). They accounted for about 70% of the total respondents (19 of 29 respondents).

In Survey 1, accidental fires (including explosions) accounted for the majority of cases (27/29). On the other hand, in Survey 2, accidental fires comprised less than 30% (9/34 cases). In many of the cases investigated in this study, especially regarding accidental fires, the reports on the accidents were prepared by the operator or administrative authorities (obtained from Q2 in Survey 1). There were few cases, however, from which information on releases to the general environment could be obtained, because most of the reports were on investigations into causes and suggestions for improvement of facilities and operations.

Regarding whether chemical substances had been released into the general environment or not (Q11), in Survey 1, seven respondents replied “They were released to the general environment,” and about 30% (10 respondents) replied that it could not be ascertained (“Unknown” or no reply). In Survey 2, about 40% (13/34 respondents) replied “They were released to the general environment,” while all other respondents replied “The released substances remained within site boundaries.”

Regarding the handling substances related to the accident (Q12), relatively detailed information was
obtained for leakage accidents from “manufacturers of chemical and allied products,” but from the others, there were few cases in which details on those substances could be identified. This was because the causal substances in the accidents were often uncertain in the cases of fires or explosions.

Regarding release duration (Q10), in Survey 1, excluding “unknown” cases (9 cases), five cases were “instantaneous releases due to explosions” and 11 cases were “1 to 6 hours,” indicating the time it took to extinguish the accidental fires. In Survey 2 where many cases were leakage accidents, many (23 cases) replied “within an hour” (of which one was an instantaneous release), while in one case, it was estimated that leakage due to corrosion of buried piping had continued for several months.

Regarding unintentional reaction products (Q8), in both surveys, about half replied “There was no possibility of producing them.” In Survey 1, “Unknown” accounted for about 25% (7/29 cases), while in Survey 2, “Unknown” accounted for only two cases and more than 40% (14/34 cases) replied “There was a possibility of producing them” (due to combustion or unintended chemical reactions). Since Survey 2 covered accidents in chemical plants, it was thought they had knowledge of the substances being handled and reaction products in the accident. Generally, it is thought that unintentional reaction products are generated in accidental fires. In these surveys as well, many of the replies regarding accidental fires were “There was a possibility of producing them.” Therefore, understanding of unintentional reaction products in accidental fires is thought to be important.

Regarding measuring concentrations in the general environment (Q13), in both surveys, approximately 25% (Survey 1: 7/29 respondents, Survey 2: 8/23 respondents) replied that it had been conducted in some way after the accident. However, most of these were not conducted by the emergency response, but referred to data obtained by constant monitoring at site boundaries or periodic surveys of the surrounding environment. Estimations of environmental concentrations (model calculations, etc.) had been performed in only two cases in Survey 2.

The results of the questionnaire survey clarified that there were few cases of emergency response that involved environmental monitoring for the general environment. In the interview survey, some site operators said that the emergency responses at the time of the accident had been multiple and complicated, and environmental monitoring was not given very high priority.

### 3.2 Practical Information for Emergency Responses

The results of questionnaire survey in this study revealed that information on chemical substances released in the course of accidents was unavailable in many cases. Therefore, it is important to establish methods for identifying the chemical substances released into the general environment. The methods currently available to identify released substances are summarized below, along with their advantages and disadvantages.

As to methods of identifying released chemical substances, it is conceivable not only to ask the site operators, but also to use the related notification data on annual emissions or amounts handled.

Interviews with the site operators may provide a possible way to obtain information useful for risk assessment such as on substances handled during the accident, amounts released and so on. However, it is likely that they will not be able to reply immediately after the accident. In addition, even if it is possible, it will take some time to conduct. Therefore, this is not a realistic approach, especially in the case of emergencies.

PRTR notification data in Japan (Ministry of Economy, Trade and Industry, published annually) is...
readily available. PRTR data cover 462 substances with relatively high environmental risks and provide locations of business sites where they may be released or transferred at normal times. However, an analysis of Survey 1 (Koyama et al., 2019) revealed that only in a few cases were PRTR substances reported by the site operator related to the substances released during the accident. (In Survey 2, many cases had occurred before the start of the PRTR system, so a sufficient comparison could not be made.) Therefore, it can be said that PRTR data cannot always be used effectively regarding emergency responses.

None of the methods shown here is sufficient, so it is not easy to quickly identify a target substance using a single method. To carry out an appropriate environmental survey, the best way at present to estimate the substances that may have been released is by using a combination of these methods. Therefore, it is important to collect and analyze relevant information from before the accident so that the necessary information can be quickly obtained in future accidents or disasters.

There are thought to be some key factors defining the characteristics of chemical accidents, although not all relevant information could be obtained due to lack of information from the questionnaire surveys. These factors may be divided into those related to characteristics of chemicals (e.g., visibility, specific gravity, solubility, toxicity) and those related to characteristics of accidents (e.g., release destination, duration, quantity, types of surrounding areas).

It is important to set criteria for such factors to enable quick and appropriate responses. As an example of criteria for toxicity, there are five levels (A to E) of classification based on the toxicity categories of the GHS classification system (Osaka Prefectural Government, 2014). This classification is useful in that it can be applied to various chemical substances. For substances with high acute toxicity, it may be possible to use criteria for emergency responses such as Acute Exposure Guideline Levels (US Environmental Protection Agency).

As a next step, through a detailed study of these factors and criteria, it may be possible to classify chemical accidents with similar features. In the future, reviewing and classifying the responses actually taken or to be taken in similar cases will make these factors more useful in responses to future accidents.

3.3 Systematic Classification of Environmental Release Processes and Responses

To systematically classify the processes of release of chemical substances, the migration of chemical substances between media is expressed as a matrix in Fig. 1 referring to the migration matrix of radioactive materials (IAEA, 2002). In addition, the possible responses to this are summarized in Table 3 and Fig. 2.

Here, responses are classified into two categories, “Identification” and “Management.” In addition, the responses are separated into what is done for the media and what is done for transfers between the media. Regarding responses for the media, examples of “Identification” responses were “visible observation (smoke, crop damage, etc.),” “atmospheric monitoring” and “atmospheric concentration model calculation,” while an example of a “Management” response was...

<table>
<thead>
<tr>
<th>Accident site</th>
<th>Release</th>
<th>Release</th>
<th>Release</th>
<th>Release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>Dry and wet deposition</td>
<td>Dry and wet deposition</td>
<td>Dry and wet deposition</td>
<td>Dry and wet deposition</td>
</tr>
<tr>
<td>Volatilization</td>
<td>Rivers, lakes</td>
<td>Translocation</td>
<td>Translocation</td>
<td>Translocation</td>
</tr>
<tr>
<td>Re-suspension</td>
<td>Translocation</td>
<td>Forested land</td>
<td>Translocation</td>
<td>Ingestion (forest products)</td>
</tr>
<tr>
<td>Re-suspension</td>
<td>Translocation</td>
<td>Translocation</td>
<td>Farmland</td>
<td>Ingestion (agricultural products)</td>
</tr>
<tr>
<td>Re-suspension</td>
<td>Translocation</td>
<td></td>
<td>Residential areas</td>
<td></td>
</tr>
<tr>
<td>Volatilization</td>
<td></td>
<td></td>
<td>Sea</td>
<td>Ingestion (seafood)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The public</td>
</tr>
</tbody>
</table>

Fig. 1 An interaction matrix which describes the migration of released substances in the general environment. The diagonal elements are components of the system and the off-diagonal elements are the interactions between them. To identify the transfer processes the matrix should be read clockwise from the upper left.
“decontamination.” Regarding the responses to transfers between media, examples of “Identification” responses included “sensing odors (strange tastes)” and “personal exposure measurement,” while examples of “Management” responses included “spraying water in firefighting,” “oil fence installation,” “mask wearing,” “indoor evacuation” and “limiting water supplies.”

In “Management” responses, an action may have a new impact on substance migration between media. For example, fire extinguishing activities may reduce the amount transferred to the atmosphere, but they may increase the amount transferred to rivers or lakes or result in releases of other substances. Therefore, it is also important to sort out changes in the transfer process due to passage of time or response actions.

It should also be noted that the process from release to exposure varies depending on the accident type and the location of the release site. Emergency responses also vary depending on the accident type, chemical properties of the substances involved, available capacity to deal with accidents and so on. These classifications of media and migration processes are tentative, and some improvement may be needed. For example, scattering of chemical substances by explosions to forested land from industrial sites is classified as migration via atmosphere, but it may be more practical to classify such short-period migrations as direct migration. The blank cells in Figs. 1 and 2 do not necessarily indicate that a process does not exist or that a response is unnecessary, and it will be necessary to make corrections and additions in the future. To lead to appropriate responses to future accidents or disasters, it will be important to analyze release processes after chemical accidents as comprehensively as possible and examine responses that were (and were not) taken in past cases and the reasons for that.

**Table 3** Possible responses for the components of the environmental system in Fig.1.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accident site</td>
<td>On-site personnel interview Use of notification information (e.g., PRTR)</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>Visible plume, Air monitoring, Atmospheric dispersion model</td>
</tr>
<tr>
<td>Rivers, Lakes</td>
<td>Death of fish, Water quality monitoring Diffusion prevention (e.g., oil fence)</td>
</tr>
<tr>
<td>Forested land</td>
<td>Damage to forest Decontamination</td>
</tr>
<tr>
<td>Farmland</td>
<td>Damage to agricultural products Decontamination</td>
</tr>
<tr>
<td>Residential areas</td>
<td>Decontamination</td>
</tr>
<tr>
<td>Sea</td>
<td>Death of fish Diffusion prevention (e.g., oil fence)</td>
</tr>
<tr>
<td>The public</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 2** Possible responses to migration of chemicals. The top half of each square shows the identification responses and the bottom half shows the management responses.
4. Conclusion

We conducted questionnaire and interview surveys on chemical accidents and analyzed their characteristics. From these surveys, it became clear that few environmental surveys on the general environment have been conducted when accidents have occurred, and that the extent of information on released substances varies by industry and type of accident. We have revealed that information from existing notification systems such as PRTR has been insufficient for identifying target substances soon after accidents and it is important to collect information on amounts of chemical substances stored, including non-PRTR substances, for effective responses to accidents. We have also systematically analyzed release processes and the emergency responses to them. Expansion of this information will enable rapid and effective risk management of chemical substances released into the general environment in emergencies.

Acknowledgements

This research was performed under the auspices of the Environment Research and Technology Development Fund (JPMEEF18S11701) of the Environmental Restoration and Conservation Agency of Japan.

References


Yosuke KOYAMA

Dr. Yosuke Koyama is a researcher at the Center for Health and Environmental Risk Research, National Institute for Environmental Studies (NIES), Japan. He received his Ph.D. in Environmental Engineering from Kyoto University. He is interested in health and environmental risk management in emergencies such as the aftermaths of chemical incidents. His research interests include strategic approaches to comprehensive chemical risk management and control, and indoor-scale chemical dynamics.

Yoshitaka IMAIZUMI

Dr. Yoshitaka Imaizumi is a senior researcher at the Center for Health and Environmental Risk Research, National Institute for Environmental Studies (NIES), Japan. He is interested in environmental risk assessment and management, and relevant environmental fate models for chemical contaminants, including agricultural pesticides, radioactive substances, and industrial chemicals. He has investigated emission estimation methods and related fate models. He is also contributing to the public disclosure of risk-related information about regulations, amounts distributed, environmental monitoring results, and environmental measurement methods for chemicals, as part of his activities of the Risk Assessment Science Collaboration Office at NIES.

Noriyuki SUZUKI

Dr. Noriyuki Suzuki directs the Center for Health and Environmental Risk Research at the National Institute for Environmental Studies (NIES), Japan. His research fields are chemical contaminant risk assessment and relevant environmental fate analysis based on both fate models and monitoring approaches. He chairs the Working Group on PRTR at OECD and is also one of several working members engaged in OECD and UNEP projects on chemical risk management. He now is involved in a research project on integrating global mercury emissions, fate/transport, material flows and impacts, in addition to a project on chemical risk management in emergencies.

(Received 7 September 2020, Accepted 22 December 2020)
Strategy to Promote Residents’ Behaviors for Appropriate Disaster Waste Management

Tomoko MORI and Ryo TAJIMA

Centre for Material Cycles and Waste Management Research, National Institute for Environmental Studies
16-2 Onogawa, Tsukuba-shi, Ibaraki, 305-8506, Japan
*E-mail: moritomo517@gmail.com

Abstract

This paper aims to clarify appropriate disaster waste management behaviors by citizens based on an understanding of frequently experienced problems in past disaster waste management cases. We also discuss methods and strategies to promote citizens’ behaviors based on examples in disaster risk reduction fields. From our results, we have identified three problems that have often occurred in past disaster waste treatment: generation of large amounts of mixed disaster waste, creation of unauthorized temporary storage sites, and insufficient support for clean-up. In municipalities where large open spaces for temporary storage sites for disaster waste are difficult to find, residents also have to establish and operate the community’s storage sites in cooperation with other residents. To promote these behaviors among citizens, there are three key factors: preparedness by municipalities for disaster waste management, citizens’ understanding and motivation, and the existence of community networks. Based on examples of public involvement in the disaster risk reduction field, participatory training and planning involving citizens is effective at promoting their understanding and proper behaviors for disaster waste management. We propose three strategies to implement participatory methods and promote appropriate disaster waste management behavior by citizens. Firstly, seizing existing opportunities such as disaster drills would be a promising approach to communicating with residents and implementing participatory methods. Secondly, it would be important to identify citizen groups active in disaster risk reduction or waste management activities and collaborate with them. Thirdly, leveraging experience with disasters would be an effective way to promote disaster waste management because citizens’ awareness of disaster waste issues is enhanced after disasters.

Key words: collaborative behaviors, mutual help, participatory training and planning, public involvement

1. Introduction

Natural disasters have occurred frequently in Japan in recent years, and each time, a large amount of disaster waste, such as damaged household goods and demolished houses, has been generated. If we fail to implement disaster waste management (DWM), sanitary conditions in the damaged area become very poor and restoration is delayed. The national government of Japan has promoted policies for DWM especially since the Great East Japan Earthquake in 2011. Municipalities that have responsibility for DWM have also promoted measures for effective DWM such as preparedness planning and capacity building (Tajima et al., 2019).

In the field of Japanese disaster risk reduction, it is said that three aspects of preparedness are important: self-help, mutual-help and public help. “Self-help” refers to actions by individuals and families, “mutual help” to collaborative actions among citizens, and “public help” to countermeasures by government (Wada, 2018; Yamashita, 2010). So far Japanese policies for DWM have focused on public help. It is very difficult, however, to manage disaster wastes properly and promptly because devastated municipalities have to allocate their very limited resources to various disaster response activities in the confusing situation after a disaster. Therefore, self-help and mutual help become important.

What kinds of self-help and mutual help are expected for appropriate DWM? And how can we promote them? This paper clarifies citizens’ behaviors as self-help and mutual help for DWM based on experiences with DWM in past disasters. We also discuss methods and strategies to promote self-help and mutual help for DWM by reviewing examples of public involvement in activities for disaster risk reduction.

2. Frequent Problems in DWM

When a disaster strikes, DWM starts with the disposal of damaged household goods by the affected
people. These disaster wastes are typically transported by the affected people to temporary storage sites (TSS) or collected by the local government. Subsequently, damaged houses and buildings are repaired or demolished, generating additional disaster wastes. This paper focuses on the phases of disposal (clearing) from damaged houses and transportation to the TSS since these phases are closely related to citizens’ behaviors.

The problems that have typically occurred in the clearing and transportation phases of past disasters are shown in Fig. 1, along with their impacts, and their backgrounds. One of the most frequent problems is the generation of large amounts of mixed disaster wastes at the TSS. If the disaster waste is separated properly, more of it can be recycled or reused.

Perishable wastes should be separated and incinerated first. Once mixed disaster wastes are generated, the separation process takes more time, and waste treatment facilities will not accept them without separation. Increased processing results in higher costs and time requirements. The burden on the environment also increases since recycling rates decrease and the amount of waste going to landfills increases. Different types of disaster wastes get mixed when they are heavily commingled at source (e.g., in cases of tsunami disasters or when damaged household goods are collected with no consideration for separation), or when they are dropped off at the TSS without segregation.

A second frequent problem is the creation of unauthorized TSS, i.e., TSS set up by local residents but unknown to the municipality. In many cases at this kind of storage site, cleared wastes are mixed improperly, generating foul odors and vermin which may harm human health. It also costs money to collect and treat mixed waste. This has become an issue due to various factors including but not limited to: insufficient numbers of TSS established by the municipality, heavy traffic in the stricken area that hinders the ability to transport disaster waste to a TSS located at a distance, lack of vehicles (e.g., small trucks) available for transportation and failure to inform the people affected by the disaster about the location of the TSS.

A third frequent problem is insufficient support for cleaning up. Disaster volunteer activities have become popular in recent years and many volunteers enter disaster areas to help affected people clean up their houses after disasters. However, it is difficult to get enough support from volunteers if the disaster causes widespread damage and there are requests for help from many places, which was the case after the heavy rain disaster in western Japan in 2018. In addition, elderly and handicapped residents and those who have young children need generous support since it is difficult for them to clean up their damaged houses and transport large amounts of disaster wastes.

3. Citizens’ DWM Behaviors

What kind of citizens’ behaviors can mitigate the impacts of the frequent problems mentioned in Chapter 2. We discuss citizens’ DWM behaviors both before and after disasters.

3.1 Following Separation and Clearing Rules

Separation of disaster wastes at source and at TSS can only be achieved by appropriate waste disposal behavior by citizens. For this, information on separation and clearing rules should be provided to them. Collaborative action to share correct information about rules using bulletin boards or SNS in the community is important, too. However, getting to know the rules and following them are not as easy after disasters occur, because of the confusion in the disaster area with people who have been harmed physically or mentally by the disaster. Therefore, it is important to check rules predetermined by one’s municipality before disasters occur. It is also important to discuss information sharing schemes in the community before disaster strikes.
3.2 Storage at Community TSS

In some municipalities that have high-density population areas, it is difficult to find large open spaces for disaster wastes TSS. In such areas, the use of small open spaces such as local playgrounds as TSS may be a solution, provided that they are properly managed in collaboration with neighbors. Because it is quite difficult to decide on community TSS locations and management rules once disasters have happened, ideally discussions on where to establish community TSS and how to manage them in the community should be held before disasters occur.

3.3 Clean-up by Mutual Help

Cleaning up houses damaged by disasters is very tough work. The amount of waste is large and the weight of some household goods such as soaked carpets and tatami (traditional Japanese straw floor mats) is very heavy. Thus, the residents of disaster areas can help each other and collaborate with volunteers to clear and transport disaster wastes. Community meetings before disasters to discuss collaboration among residents and support systems for vulnerable neighbors could enhance mutual help after disasters. Such community meetings would be effective not only for DWM but also comprehensive disaster preparedness of the community overall because collaboration among residents is needed in various ways after disasters, such as for evacuation and management of the community’s shelters.

4. Key Factors for Promoting Citizens’ DWM Behaviors

4.1 Preparedness by Municipalities for DWM

When disaster strikes, some municipalities cannot decide on and announce rules for separation and clearing immediately because they lack advance preparation. As of 2019, about the half of Japan’s municipalities had not developed a DWM preparedness plan (Ministry of the Environment, 2020). The residents living in such areas will not be able to get information on rules immediately. Therefore, preparedness for DWM by municipalities is one of the most important key factors in promoting citizens’ DWM behaviors. Ideally, separation and clearing rules should be announced to the residents before disasters because it is difficult to distribute information to residents during times of disaster. Some municipalities have communicated with their residents by brochures or public relations magazines (Sakai City, 2017; Kawasaki City, 2019).

4.2 Gaining Citizens’ Understanding and Motivation for DWM

Obtaining citizens’ understanding and motivation for DWM is important in promoting citizens’ DWM behaviors because people do not always take action even if they know the rules. Hirose (2015) advocated a two-phase model for pro-environmental behaviors based on the theory of planned behaviors by Ajzen (1991) and proposed that risk perception of the problem, responsibility for dealing with the problem, and perceived effectiveness of the desired behavior influence people’s intention to contribute toward solving the problem. There are many existing studies using Hirose’s theory. Asato and Kimiya (2008) found that a sense of responsibility for dealing with problems has a strong positive influence on behavioral intentions toward cooperation with separation and collection of municipal wastes. Matsui et al. (2004) revealed that the perceived effectiveness of a behavior is one of the most important determinants of recyclable waste separation behavior. These studies indicate that having citizens understand the risks associated with poor DWM, i.e., health risks and hindrance of reconstruction, is an effective way to promote appropriate DWM behavior by the citizens. This may be further enhanced by recognizing that these risks can be reduced by following rules of separation, storage and transportation.

Educational materials on disaster wastes are a possible tool for promoting citizens’ understanding. Some municipalities provide their residents with brochures for disaster preparedness (Tokyo Metropolitan Government, 2015). Information about proper clearing and transportation of disaster waste is needed because existing brochures on disaster preparedness do not mention disaster wastes in many cases. It may be effective to include information about disaster wastes in the existing educational materials on disaster risk reduction because people tend to have considerable interest in information regarding disaster response in general. More study is needed to clarify effective ways to provide information about disaster wastes.

To promote citizens’ motivation not only for self-help such as checking pertinent rules before disasters but also for mutual help such as discussion at community meetings, the citizens have to know what mutual help for DWM is and how to perform it. Mori and Tasaki (2019) pointed out that a sense of responsibility for collaborative behaviors and perceived effectiveness of collaborative behaviors have strong positive influences on behavioral intentions toward collaborative behaviors. Therefore, it is important to provide them examples of mutual help before and after disasters and foster the cognition that mutual help is a meaningful action for citizens and an effective means of appropriate DWM. Ideally citizens’ recognition of their stake in mutual help for DWM should be fostered through dialogue or disaster drills in the community.

4.3 Community Networks

Community networks are important to have especially for promoting mutual help among residents.
Mutual trust among community members fostered through regular communication is the basis for helping each other in difficult times. It may also promote effective sharing of information on separation and clearing rules among residents after disasters. Common risk perceptions toward disasters in communities are also important because the residents will have higher motivation for DWM if many of them share a sense of crisis about disasters.

Matsumoto et al. (2012) revealed that making pro-environmental behaviors, such as waste reduction behaviors at schools, visible to other citizens, strongly influences social norms, i.e., cognition of other people’s behaviors and expectations for proper behaviors from family, friends and neighbors. Social norms affect people’s behavior strongly in communities in which the residents know each other. Therefore, social norms will have a positive influence on promoting residents’ appropriate clearing of disaster wastes in communities that have rich networking.

5. Methods for Developing Capacity in the Disaster Risk Reduction Field and their Applications in DWM

To promote citizens’ DWM behaviors, it is important to foster their understanding of DWM and develop community networks. How can we put that into practice? We refer to examples of public involvement in the field of disaster risk reduction and discuss their application to DWM.

5.1 Disaster Drills with Stakeholders

Disaster drills constitute pre-training in which disaster situations are simulated to promote proper behaviors in times of disaster. Disaster drills such as evacuation drills and emergency communication exercises are very popular in Japan. The residents can simulate their situation in a disaster and experience collaborative actions such as emergency food cooking and shelter operation through disaster drills. Some studies have pointed out that experiencing collaborative actions can enhance a sense of capability in collaborative action and promote greater collaborative efforts (Chawla & Cushing, 2007; Mori & Tasaki, 2019). Therefore, experiencing collaborative actions through disaster drills may be an effective way to promote mutual help after disasters.

Disaster drills for DWM are not yet common, but there are a few examples. One is a field exercise that involves setting up and managing a TSS using a real site and actual waste, conducted by Kakegawa City, Kikukawa City and the sanitation facility associations of both cities (National Institute for Environmental Studies, 2017). The residents who participate in this TSS exercise, gain an appreciation of how big an effort separating and transporting large amounts of disaster wastes can be and the importance of cooperation among residents. More study is needed to find effective methods of implementing disaster drills for DWM.

5.2 Imagination Games and Map Exercises

Disaster Imagination Games (DIG) are a popular type of simulation training in Japan. Participants break up into small groups and make notes of the high-risk places on their town’s map, then discuss with each other how to avoid or reduce the risks (Cabinet Office, Japan). The Meguro Method is another imagination tool for disaster simulation developed by Dr. Kimiro Meguro (Meguro, 2001). People imagine and write down their specific situation and behaviors in a disaster along a time axis. This method is useful for gaining an understanding of individual risk. It also has the effect of increasing the community’s or organization’s readiness for disasters if participants share their results and discuss them with each other (Abe & Meguro, 2005). Participatory disaster map making is another popular method. This method includes not only discussion at a table but also walking around the town to find disaster risks and consider measures. Toyoda and Kanegae (2012) studied the effect of participatory disaster map making and found it to be effective at enhancing participants’ disaster awareness and promoting action for disaster preparedness.

Studies and practices on these methods in the disaster risk reduction field indicate that to imagine individual concrete disaster situations and behaviors, on top of general knowledge about disaster situations, is an important way to enhance citizens’ disaster awareness. Therefore, imagination drills simulating clearing and transporting of disaster wastes may be effective. For example, participants examine the possible disaster wastes in their house on the assumption that they have flood damage with inundation above the floor level. Then, they imagine and discuss how they would clear and transport their disaster waste to the planned TSS. However, information and support by disaster experts is essential because it is difficult for residents without disaster experience to form a concrete image of a disaster situation.

5.3 Risk Communication in Workshops

There are some studies on workshop methods involving stakeholders. Nomura et al. (2013) conducted a workshop targeting municipal government staff and residents who had experienced the Noto Peninsula earthquake in 2007 and found that by promoting risk communication they could help residents gain an understanding the importance of self-help and mutual help. Ushiyama et al. (2009) developed a workshop method focusing on risk searches in the community and revealed that it was effective at promoting people’s disaster risk reduction actions. These examples focused
on risk communication. Workshop methods are effective not only at promoting communication among stakeholders but also at enhancing people’s understanding and actions. Therefore, workshops for residents that include discussion of local DWM risks and production of items such as maps and action lists in cooperation with other participants would also be effective in the field of DWM. If the residents can grasp concrete DWM risks and share this understanding with other community members through workshops, residents’ DWM actions can be promoted.

5.4 Preparedness Planning with Stakeholders

To enhance people’s sense of responsibility for disaster wastes, participatory planning provides a good reference. Tamura et al. (2004) developed a planning method for disaster risk reduction using workshops with stakeholders and revealed that their planning method could enhance the participants’ proactive attitude toward disaster management issues and foster a sense of ownership. Not only in the disaster risk reduction field but also in the city planning field, public involvement in planning is known as an effective way of enhancing residents’ sense of ownership in activities (Kinoshita et al., 2018).

Many municipalities face the risk that they will not be able to provide sufficient public services because of depopulation and staff shortages. Therefore, it becomes more important for the residents to realize that they have important roles in waste management, not leaving everything to their municipalities. Many DWM plans have been made without the residents’ involvement. It would be helpful for residents to get involved in development of DWM plans and discuss effective ways to clear disaster waste with their municipality. Additionally, residents can hold discussions in their community about preparing operation manuals for creating and managing a community TSS or support scheme for people needing special assistance in clearing and transporting disaster wastes. Such activities would be an effective way to enhance residents’ sense of ownership with DWM. Collaboration with the municipality and support by experts would be indispensable for the success of this kind of activities.

6. Strategies to Promote Residents’ DWM Behaviors

Figure 2 gives an overview of the discussion in the previous chapters. It depicts targets and residents’

![Fig. 2 Targets and related behaviors of residents and municipalities.](image-url)
behaviors and related actions by municipalities before and after disasters. Based on examples of public involvement in the disaster risk reduction field, participatory methods involving the residents such as workshops, DIG and creation of map and plans are helpful in developing networks among stakeholders and promoting residents’ understanding and behaviors. Therefore, implementation of participatory methods for the residents is desirable from the standpoint of promoting residents’ DWM behaviors. Below, we discuss three aspects of strategies to implement participatory methods for the residents: seizing existing opportunities, identifying and collaborating with the groups driving community’s DWM, and leveraging experience from disasters.

6.1 Seizing Existing Opportunities

One promising way to implement participatory DWM methods is to incorporate some exercises involving disaster wastes in existing disaster drill opportunities. For this, it is important to hold discussions with related stakeholders at an early stage.

It is also possible to use existing events for promoting public awareness to promote waste management as well. For example, Yokohama City has exhibited posters and created games involving disaster wastes at open days at the city’s incineration plant. These open days are held once a year, and many residents living around the incineration plant visit (National Institute for Environmental Studies, 2020). This example is not a participatory method. It is an effective way, however, to help the residents recognize disaster waste problems and serves as a first step toward implementation of a participatory method. If a festival or event related to environmental problems is held regularly, it is possible to use it as an opportunity for raising awareness about disaster waste problems.

6.2 Identifying and Collaborating with Citizen Groups Active in Disaster Risk Reduction or Environmental Activities

The citizens groups active in disaster risk reduction or waste management activities play an important role in implementing participatory methods and promoting residents’ DWM behaviors. Possible groups that could energize communities’ DWM include neighborhood associations and local NPOs working on environmental problems or disaster risk reduction. If there are such groups in the community, collaboration with the municipality and these groups would be an effective way to implement participatory DWM methods. Mori et al. (2020) tried a workshop on DWM for the residents of Kawasaki City in collaboration with a local NPO (Fig. 3). The participants of this workshop were residents engaged in local activities to resolve environmental problems or for disaster risk reduction. The aims of this workshop were not only to promote understanding of DWM but also to foster key persons for promoting the community’s DWM and developing a network. It was effective especially for developing a network of participants because most of the participants started planning original activities together after the workshop.

Municipalities should take the initiative to implement participatory methods and promote residents’ DWM behaviors if there are no groups active in disaster risk reduction or waste management activities. It may be difficult to implement participatory methods from the outset. Thus it would be helpful to start communicating with residents using existing opportunities such as disaster drills or public events. Such communication activities would be useful for finding future collaborators or partners to implement participatory methods.

6.3 Leveraging Experience of Disasters

Once a municipality suffers from a natural disaster, local politicians, governmental staff and residents have great interest after that in DWM. Experiencing a disaster is tough and unfortunate, but it is important not to miss the opportunity when everyone’s awareness of disaster waste problems is high. Kurashiki City was severely damaged by heavy rain in 2018 and many problems related to disaster wastes occurred. After this disaster, the Kurashiki City municipality conducted interview surveys on disaster waste treatment with the afflicted people to learn about problems they had had with DWM. Based on this survey, they made a handbook for residents about disaster waste disposal (Kurashiki City, 2020). Moreover, they plan to make a DWM instruction manual for early phases of disasters in collaboration with stakeholders. Their work is a good example of promoting DWM for residents by leveraging their experience in the disaster.

7. Conclusions

This paper has attempted to clarify appropriate DWM behavior by citizens based on an understanding of frequently experienced problems in past DWM cases. We have also discussed methods and strategies of promoting
these behaviors based on examples in the disaster risk reduction field.

From our results, we could identify three factors key to promoting citizens’ DWM behaviors for before and after disasters. Firstly, preparedness for DWM by municipalities is indispensable. Secondly, encouraging citizens’ understanding and motivation for DWM is crucial to promoting their DWM behaviors. Thirdly, community networks must be developed to promote mutual help before and after disasters.

Based on examples of public involvement in the disaster risk reduction field, it is thought that participatory training and planning involving citizens is effective at promoting their understanding and encouraging DWM behaviors. We have discussed three strategies for implementing participatory methods for citizens: seizing existing opportunities, identifying and collaborating with citizens groups active in disaster risk reduction or waste management activities, and leveraging experience in disasters.

DWM implementation using the proposed methods and strategies in real communities and evaluation of their effectiveness should be topics of future research.

References


Tomoko Mori is a Research Associate at the Centre for Material Cycles and Waste Management Research, National Institute for Environmental Studies, Japan. She received her Ph.D. in Environmentology from the University of Tokyo in 2018. Her research field is education for sustainable development to promote civic action for the environment. She also engages in research on capacity building among government officers and public involvement in disaster waste management.

Ryo Tajima is a senior researcher at the Centre for Material Cycles and Waste Management Research, National Institute for Environmental Studies, Japan. His main research field is policy and planning for waste management under disaster and normal circumstances. He is involved in local and national efforts on drafting guidelines and plans and designing training programs for disaster waste management.

(Received 25 September 2020, Accepted 21 December 2020)
Expanding the Scope of Environmental Emergency Research towards Disaster-resilience and Environmental Sustainability

Toshimasa OHARA\(^1\), Ryo TAJIMA\(^2\), Yujiro HIRANO\(^1\), Shigenori INO\(^1\) and Seiji HAYASHI\(^1\)

\(^1\) Fukushima Branch, National Institute for Environmental Studies
10-2 Fukasaku, Miharu Town, Tamura-gun, Fukushima 963-7700, Japan
\(^2\) Centre for Material Cycles and Waste Management Research, National Institute for Environmental Studies,
16-2 Onogawa, Tsukuba-shi, Ibaraki, 305-8506, Japan
*E-mail: tohara@nies.go.jp

Abstract
Climate change is already showing its influence in natural disasters and is likely to exacerbate natural disasters in the future. Given these circumstances, the results of and experience in research on disasters and the environment should facilitate the creation of a sustainable, disaster-resilient society. In this regard, systematic consideration of the knowledge gained from environmental emergency research conducted since the Great East Japan Earthquake would help establish a new research field based on disaster-related environmental research of the past. Here, we propose a conceptual framework for expanding the scope of environmental emergency research towards disaster-resilience and environmental sustainability.

Key words: disaster resilience, environmental emergency research, Great East Japan Earthquake, natural disasters, sustainability

1. Introduction
In recent years the sustainability of society has been impaired by environmental problems resulting from sudden-onset natural disasters. The Great East Japan Earthquake (GEJE) and the subsequent tsunami in 2011 that caused the Fukushima Daiichi nuclear power plant accident (hereinafter the “nuclear accident”) is one such example. The accident released radioactive substances that caused environmental pollution and necessitated the removal of large amounts of radioactive waste and contaminated soil. Since then, major natural disasters have occurred almost every year with great impacts on society and the environment. The existing academic discipline of environmental science is inadequate for addressing these circumstances. A new knowledge system for environmental issues from environmental emergency research conducted since the Great East Japan Earthquake would help establish a new research field based on disaster-related environmental research of the past. Here, we propose a conceptual framework for expanding the scope of environmental emergency research towards disaster-resilience and environmental sustainability.

2. Disaster-related Environmental Research in Japan
2.1 Summary of Disaster-related Environmental Research in Japan before the GEJE
Up to now in Japan, environmental issues and disasters have been addressed in research as separate issues in terms of environmental protection measures and disaster prevention/mitigation. There were two main impetuses that led to the launching of a movement in the early 2000s to address these issues simultaneously (National Institute for Environmental Studies, 2013). The first was the 2nd Science and Technology Basic Plan (Government of Japan, 2001), which stressed the importance of research on river basin management in harmony with nature. Based on this plan, technological development was conducted to link disaster prevention/mitigation measures with fundamental ecosystem services (such as hydrological cycle control) and regulatory services (such as natural disaster control) in river basin management. The second impetus, based on experiences of the 1995 Great Hanshin-Awaji earthquake, 2004 Niigata Chuetsu earthquake and 2004 Sumatra-Andaman earthquake, stemmed from the view that environmental infrastructure and disaster prevention/mitigation projects, both falling under the category of social infrastructure development, could be implemented more efficiently if carried out together and, furthermore, could contribute to...
local community development. For example, the Japan Society of Civil Engineers (2006) report titled Technology and System Coordination for Environmental and Disaster Prevention lays out the impacts of natural disaster prevention measures on the environment, and conversely, the impacts of environmental measures on disaster prevention. The report stresses the importance of coordination between the two.

2.2 Disaster-related Environmental Research after the GEJE

After the GEJE, a wide range of research on the disaster was carried out by newly-formed organizations including the Tohoku University International Research Center of Disaster Science, Fukushima University Institute of Environmental Radioactivity, Waseda Resilience Research Institute, and Fukushima Prefectural Centre for Environmental Creation, as well as existing organizations such as the Kyoto University Disaster Prevention Research Institute and Nagoya University Disaster Mitigation Center, which had been conducting disaster prevention and mitigation research prior to the GEJE. However, while much research has been conducted from the perspectives of disaster prevention and resilience, few studies have addressed post-disaster reconstruction and community development. Also, environmental perspectives have not always been adequately addressed.

As the papers included in this special issue show, many studies have addressed environmental emergency aspects including post-disaster environmental impacts of pollutants, environmental recovery and management of disaster wastes (e.g., Iijima et al., 2020). With regards to the nuclear accident caused by the GEJE, a wide range of research has been conducted and many results have already been reported on the environmental impacts of the large amounts of radioactive substances released into the environment (Science Council of Japan, 2020). These environmental emergency studies have made a major contribution to reconstruction efforts and environmental recovery in areas affected by the GEJE and nuclear accident. In addition, research on sustainable community development, including the establishment of sustainable regional environments, environmentally conscious reconstruction and the creation of disaster resilient regions is being carried out to some extent, as evident from the papers included in this special issue (e.g., Hirano et al., 2020; Otsuka et al., 2020; Gomi, 2020; Togawa et al., 2020). However, much less research is being conducted in these areas on the environmental impacts, environmental recovery and management of disaster wastes. Given the progress toward reconstruction of the disaster areas, further research is needed, especially in the nuclear disaster-affected areas of Fukushima Prefecture.

Furthermore, systematic research is needed to address the series of processes for increasing the resilience and sustainability of society during normal times, achieving the mitigation and appropriate management of environmental impacts during disasters, and accelerating the transition to sustainable society through environmental recovery.

3. Conceptual Framework of the New Research Field for Disaster-resilience and Environmental Sustainability

3.1 Necessity and Aim of the New Concept

In recent years, frequent large-scale natural disasters have occurred with substantial impacts on the environment. There is a high risk that the frequency of disasters will increase due to the accelerating impacts of climate change. The existing disciplines of environmental science and environmental engineering are inadequate for addressing these circumstances. A new body of knowledge on environmental issues is needed for integrating the knowledge gained on emergency response and disaster reconstruction through disaster science. However, as laid out in Chapter 2, while such research has been conducted to some extent, this research has not been organized within a theoretical framework. In particular, up to now, the conceptual framework and methodologies that seamlessly link different phases—from preparation for disaster resilience during normal times to systematic emergency response immediately following a disaster, rapid environmental recovery and development of a sustainable society in the medium to long-term—have not been explored either in Japan or abroad.

Given the frequent occurrence of various disasters, to have science contribute to the building of a sustainable, disaster-resilient society, a new research field needs to be established that can systematize the knowledge and experience accumulated through disaster response and contribute scientifically to the creation of a sustainable, disaster-resilient society. This research field would be defined as a body of knowledge with the objective of achieving sustainable societies in the long term by improving the sustainability and resilience of societies during normal times, achieving mitigation and appropriate management of environmental impacts during disasters, and using disaster reconstruction to improve sustainability further.

Tajima and Osako (2020) organized environmental impacts of disasters into four categories: (1) disturbances of the natural environment, (2) generation of disaster wastes, (3) release of toxic chemical substances and (4) environmental impacts associated with disaster recovery and reconstruction. The purpose of the disaster-resilience and environmental sustainability research field will be to systematize the knowledge related to the mitigation and management of the above environmental impacts associated with disasters.
3.2 Methodology

In addition to the aspects addressed by conventional environmental emergency management such as the mitigation and management of environmental impacts associated with disasters, it is important for the new research field to aim to improve the sustainability and disaster-resilience of societal systems during normal times, use disaster reconstruction to increase sustainability, and promote cycling and interrelationships between these three phases. Although there are various arguments regarding whether it is possible to achieve both sustainability and disaster resilience based on existing general principles proposed for accomplishing these two goals simultaneously (Redman, 2014; Elmqvist et al., 2019), the methodology for the disaster-resilience and environmental sustainability research field can be laid out by phase in a timeline from before to after disasters as shown in Fig. 1.

(1) Simultaneous improvement of sustainability and disaster resilience of social systems during normal times
Research to facilitate smooth implementation of environmental impact management during disasters, research on improving sustainability through disaster reconstruction, and research on environmental impact mitigation during disasters.

(2) Environmental impact management during disasters
Research on the overall management of the series of processes from the identification of pollution sources and assessment of impacts to emergency measures to mitigate impacts and treatment and disposal of pollution sources.

(3) Increasing sustainability by transforming social structures through reconstruction
Projects and community development utilizing local environmental resources to ensure sustainability in the recovery and reconstruction process and research to resolve environmental, social and economic issues existing in communities prior to disasters as part of regional disaster reconstruction.

It will be important to establish the new research field in collaboration with various stakeholders in disaster areas and to accumulate and systematize specialized knowledge and experience through the lateral transfer of research results to non-disaster areas.

4. Summary

There is a high risk of natural disasters increasing in the future due to the accelerating impacts of climate change. Given these circumstances, it is necessary to contribute scientifically to the building of a sustainable, disaster-resilient society based on the results from and experience gained through research on disasters and the environment. This report proposes a conceptual framework for expanding the scope of environmental emergency research towards disaster-resilience and environmental sustainability based on a review of domestic research trends. We plan to discuss and continuously revise our proposal with the input of many stakeholders. We hope that this paper will stimulate lively discussions towards the establishment of a new research field for disaster-resilience and environmental sustainability.

References

Elmqvist, T., Andersson, E., Frantzeskaki, N., McPhearson, T., Olsson, P., Gaffney, O., Takeuchi, K. and Folke, C. (2019) Sustainability and resilience for transformation in the urban...


---

**Toshimasa Ohara**

Toshimasa Ohara is a fellow at the National Institute for Environmental Studies. Immediately after the Fukushima accident, his group commenced atmospheric simulations of radionuclides and published the first results on temporal and spatial variations in deposition rates on a regional scale. Currently he leads the Environmental Emergency Research Program for contributing to environmental reconstruction and creation in Fukushima.

**Ryo Tajima**

Ryo Tajima is a senior researcher at the Centre for Material Cycles and Waste Management Research, National Institute for Environmental Studies, Japan. His main research field is policy and planning for waste management under disaster and normal circumstances. He is involved in local and national efforts to draft guidelines and plans and design training programs for disaster waste management.

**Yujiro Hirano**

Yujiro Hirano is a senior researcher at the Regional Environmental Renovation Section of the National Institute for Environmental Studies, Fukushima Branch. He holds a doctorate of engineering and has long been engaged in research on low-carbon lifestyles remote sensing of urban surfaces, urban heat island countermeasures and urban energy system. His recent research interests are in modeling and analysis of regional energy use for environmental renovation plans.

**Shigenori Iino**

Shigenori Iino is a researcher at the Radiological Contaminated Off-site waste Management Section of the National Institute for Environmental Studies, Fukushima branch. He holds a Doctor of Engineering degree, and his recent research interests lie in formation of a regional circular and ecological sphere centered on waste management in Fukushima.

**Seiji Hayashi**

Seiji Hayashi is a research group manager at the Fukushima branch of the National Institute for Environmental Studies. He is serving as project leader for research on the behavior of radioactive substances in multimedia environments. His energetic research activities are contributing to the environmental recovery of Fukushima Prefecture and its surrounding region.

(Received 20 December 2020, Accepted 28 December 2020)
Guidelines for Manuscripts

1. Qualifications for Contributions
   As a general rule, this publication accepts contributions from its membership. This rule may not apply, however, when the Editorial Committee requests contributions.

2. Categories of Contributions
   Reviews, original articles and commentary are welcomed.

3. Review of Manuscripts
   After the manuscript is received, it is read by several specialists in the related field. The decision to accept or reject the manuscript for publication is based upon their assessment.

4. English Revision
   Once the manuscript is accepted, it is sent to a native-English proofreader for revision.

5. Manuscript Style

   Cover:
   The cover sheet should include:
   (1) Full name, address, telephone number, fax number and e-mail address for sending galley proofs and editorial correspondence (in the case of several authors for one article, only information on the representative is needed),
   (2) A running title of 50 characters or less, and
   (3) The number of tables and/or figures.

   Title Page:
   The title page should include the names of all of the authors and their respective institutions with addresses.

   Abstract:
   The abstract should be a lucid digest of the paper, not exceeding 250 words for a full paper.

   Key Words:
   Select key words (not more than six words or phrases) which identify the most important subjects covered by the article and arrange them in alphabetical order.

   Main Text:
   Manuscripts should be no more than eight pages in length. In order to keep the length to within eight pages when published, please limit the main text, including the abstract, key words and references, to 5,000 words at a maximum. Meeting those conditions allows up to eight figures and tables to be included. When a manuscript exceeds eight pages in length, a charge of 20,000 yen will be assessed for each extra page. Chapter numbers are obligatory. Each chapter can have one or more sections. Footnotes should not be used. All explanations should appear in the main text.

   Tables:
   Tables should be submitted in a form suitable for publication as is. Tables should be type-written, one per page. No lines should be used to separate columns. In the text, ‘Table n’ should be used to refer to each table. This publication welcomes tables in color and adds them free of charge.

   Figures:
   Figures should be submitted in a form suitable for publication as they are. Since the printed pages will have two columns, figures should be made either one column (79 mm) or two columns (165 mm) wide. Do not reduce the size of figures by more than 50%. In the text, ‘Fig. n’ should be used to refer to each figure, except at the beginning of sentences, where ‘Figure n’ is used. This publication welcomes figures in color and adds them free of charge.

   Pictures:
   Pictures are counted as figures.

   Legends for Figures and Tables:
   In addition to the heading, a lucid legend should explain the meaning of the figure or table without requiring reference to the text. The legends of the figures and tables should be grouped on a separate sheet.

   References:
   All references mentioned or cited in the text should be listed in the reference list and vice versa.

   [Main text]
   Text references should be made by the authors’ names (for three or more authors use the first author’s name plus et al.) followed by the year of publication. Each reference should be given in the following form.
· In the case of a single author:
  Watanabe (2005), (Watanabe, 2005)
· In the case of two authors:
  Watanabe and Kachi (2008), (Watanabe & Kachi, 2008)
· In the case of three or more authors:
  Watanabe et al. (2010), (Watanabe et al., 2010)

Reference list
Names of journals and other publications should be spelled out, not abbreviated. Spell out all author’s names in the reference list. If there are references to publications by the same author(s) in the same year, a, b, c, etc. should be added after the year of publication. All references cited in the text should be arranged alphabetically according to the name of author(s) on separate sheets. Each reference should be given in the following form.

Citations from journals and periodicals
(In the case of electronic journals, include the DOI, URL and date of access.)
· Author, A. A. and Author, B. B. (Year of publication) Title of article. Title of Periodical, Volume number (Issue or part number), pp-pp. Retrieved from http://dx.doi.org/xxxx

Citations from books, pamphlets or similar publications
(In the case of electronic books etc., include the DOI, URL and date of access.)

Citations from chapters or portions of books, pamphlets or similar publications
(In the case of electronic books etc., include the DOI, URL and date of access.)
· Author, A. A. and Author B. B. (Year of publication) Title of chapter. In: Editor C. C. and Editor D. D. (eds.) Title of Publication, pp-pp. Publisher, Place of publication.

Citations from web pages
· Name of Department or Committee (Year of publication) Title of document, Publisher. Retrieved from http://xxxxx (Accessed d mm yyyy)

Submission of Manuscripts:
Manuscripts can be submitted to morimoto@airies.or.jp as an e-mail attachment.

Proofreading:
As a general rule, the authors perform proofreading for the first proof of the manuscript only, with proofreading becoming the responsibility of the editorial board for the second and subsequent proofs. Proofreading is performed to catch printing errors, but alterations in the text, figures and tables are not allowed. If errors are found that necessitate alterations, the authors may be requested to cover the costs of readjusting the proof.

Copyrights:
Copyrights shall belong to the Association of International Research Initiatives for Environmental Studies.

A manuscript preparation template is available at the AIRIES website, and everyone is invited to use it.

(Revised March 1, 2019)
<table>
<thead>
<tr>
<th>表 紙</th>
<th>刊号/発行年</th>
<th>タイトル</th>
<th>責任編集委員</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vol.1 No.1</td>
<td>1996年</td>
<td>地球環境</td>
<td>吉野 正敏</td>
</tr>
<tr>
<td>Vol.2 No.1</td>
<td>1997年</td>
<td>地球環境変化と健康</td>
<td>稲村 秀三/藤野 純一</td>
</tr>
<tr>
<td>Vol.2 No.2</td>
<td>1997年</td>
<td>IGAC特集</td>
<td>秋野 優</td>
</tr>
<tr>
<td>Vol.3 No.1</td>
<td>1998年</td>
<td>熱帯林の保全と修復に向けて</td>
<td>可知 直毅/高井 康雄</td>
</tr>
<tr>
<td>Vol.3 No.2</td>
<td>1998年</td>
<td>地球環境変化と健康</td>
<td>入來 正躬/安藤 満</td>
</tr>
<tr>
<td>Vol.4 No.1</td>
<td>1999年</td>
<td>責任編集委員</td>
<td>吉野 正敏</td>
</tr>
<tr>
<td>Vol.4 No.2</td>
<td>1999年</td>
<td>紙</td>
<td>今村 隆史</td>
</tr>
<tr>
<td>Vol.5 No.1</td>
<td>2000年</td>
<td>紙</td>
<td>今村 隆史</td>
</tr>
<tr>
<td>Vol.5 No.2</td>
<td>2000年</td>
<td>紙</td>
<td>今村 隆史</td>
</tr>
<tr>
<td>Vol.6 No.1</td>
<td>2001年</td>
<td>沿岸海洋環境</td>
<td>平 啓介</td>
</tr>
<tr>
<td>Vol.7 No.1</td>
<td>2002年</td>
<td>古代湖</td>
<td>今村 隆史</td>
</tr>
<tr>
<td>Vol.8 No.1</td>
<td>2003年</td>
<td>水と環境</td>
<td>小野寺 真一</td>
</tr>
<tr>
<td>Vol.8 No.2</td>
<td>2003年</td>
<td>水環境</td>
<td>小野寺 真一</td>
</tr>
<tr>
<td>Vol.9 No.1</td>
<td>2004年</td>
<td>森林と湿地-関の生物多様性</td>
<td>小野寺 真一</td>
</tr>
<tr>
<td>Vol.9 No.2</td>
<td>2004年</td>
<td>人間・文明</td>
<td>今村 隆史</td>
</tr>
<tr>
<td>Vol.10 No.1</td>
<td>2005年</td>
<td>水環境</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.10 No.2</td>
<td>2005年</td>
<td>水環境</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.11 No.1</td>
<td>2006年</td>
<td>水環境</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.11 No.2</td>
<td>2006年</td>
<td>水環境</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.12 No.1</td>
<td>2007年</td>
<td>種の生物多様性</td>
<td>吉野 正敏</td>
</tr>
<tr>
<td>Vol.12 No.2</td>
<td>2007年</td>
<td>人間・文明</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.13 No.1</td>
<td>2008年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.13 No.2</td>
<td>2008年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.14 No.1</td>
<td>2009年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.14 No.2</td>
<td>2009年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.15 No.1</td>
<td>2010年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.16 No.1</td>
<td>2011年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.16 No.2</td>
<td>2011年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.17 No.1</td>
<td>2012年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.17 No.2</td>
<td>2012年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.18 No.1</td>
<td>2013年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.18 No.2</td>
<td>2013年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.19 No.1</td>
<td>2014年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.19 No.2</td>
<td>2014年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.20 No.1</td>
<td>2015年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.20 No.2</td>
<td>2015年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.21 No.1</td>
<td>2016年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.21 No.2</td>
<td>2016年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.22 No.1</td>
<td>2017年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.22 No.2</td>
<td>2017年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.23 No.1 &amp; 2</td>
<td>2018年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.24 No.1</td>
<td>2019年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
<tr>
<td>Vol.24 No.2</td>
<td>2019年</td>
<td>日本の森林</td>
<td>五箇 公一</td>
</tr>
</tbody>
</table>

表紙：バックナンバー一覧
<table>
<thead>
<tr>
<th>Title</th>
<th>Volume &amp; Number / Year of Issue</th>
<th>Responsible Editor</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Back Issues</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Volume 11 No. 2 / 2007
**Principles and Practice of Ecological Restoration: the Case of Eurasian Wetlands**
Jumpei WASHITANI

### Volume 12 No. 2 / 2008
**Extinction and Global Change**
Masutoshi YOSHINO

### Volume 13 No. 1 / 2009
**New Horizons in Global Environmental Research: Bioclimatological Aspects**
Masami IRIKI

### Volume 14 No. 1 / 2010
**Desertification Control and Restoration of Ecosystem Services in Northeast Asia**
Toshiya OKURO

### Volume 15 No. 1 / 2011
**Renewal and Its Impacts on Earth’s Environment**
Haruo TSURUTA / Kenji PURUYAMA

### Volume 16 No. 1 / 2012
**Recent Advances in Environmental Research after the Fukushima Nuclear Disaster**
Reiko SODENO

### Volume 17 No. 1 / 2013
**Pathways towards Low-Carbon Societies in Asia**
Mikiko KAINUMA

### Volume 18 No. 2 / 2014
**Impacts of the Great East Japan Earthquake and Tsunami on Human Life and Ecosystems**
Hiroshi HIGUCHI

### Volume 19 No. 1 / 2015
**Sustainable Use of Phosphorus in Asia**
Hisa OHTake / Kanyo MATSUKA / Masaru YARME

### Volume 20 No. 1 & 2 / 2016
**Long-term Environmentally Sound Mercury Management after the Minamata Convention**
Takashi SODENO

### Volume 21 No. 1 & 2 / 2017
**Progress in Environmental Emergency Research after the Great East Japan Earthquake and Fukushima Nuclear Disaster**
Toshimasa OHARA / Katsuki YAMADA

### Volume 22 No. 1 / 2018
**PM2.5 Pollution in Asia**
Mari KOSAKA / Tanaka SATO

### Volume 23 No. 1 & 2 / 2019
**Sustainable Management of Marine Ecosystems Lessons from a Natural World Heritage Site, the Ogawara Islands**
Naoki Kachi

### Volume 24 No. 1 / 2020
**Recent Advances in Environmental Research after the Fukushima Nuclear Disaster**
Reiko SODENO

### Volume 25 No. 1 & 2 / 2021
**Recent Advances in Environmental Research after the Fukushima Nuclear Disaster**
Toshimasa OHARA / Katsuki YAMADA