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研究課題名（和文）Development and application of the flux approach for modelling of the long-term radiocesium cycling in Fukushima forests

研究課題名（英文）Development and application of the flux approach for modelling of the long-term radiocesium cycling in Fukushima forests

研究代表者

Ｙｏｓｃｈｅｎｋｏ　Ｖａｓｙｌ（Yoschenko, Vasyl）

福島大学・環境放射能研究所・特任教授

研究者番号：４０７４５５６９

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研究成果の概要（和文）：本研究の主な目的は、福島の森林における放射性セシウムの長期的動態を林業の観点から予測し評価することである。代表的な林業種が生育している実験区で調査を実施した。 避難指示解除地域でも、現在の樹木の放射性セシウム濃度は、日本の基準値を超えていることがわかった。 森林内の安定セシウムの循環に関する知見に基づき、私たちは樹木の各部分の放射性セシウム存在量が将来どのように変化するかを予測するモデルを開発した。 モデリングの結果は、主な林業種であるスギの場合、木材中の放射性セシウムの存在量の減少がかなり遅いことを示している。また、除染効率を分析し、放射線汚染地域における林業復興に向けた対策を提案した。

研究成果の概要（英文）：The main aim of our research was prediction of the long-term dynamics of radiocesium in the Fukushima forests for evaluation of the forestry perspectives. To achieve this purpose, we conducted monitoring observations at several experimental sites populated with the typical forestry species. We found that even in the areas were the evacuation orders have been lifted the radiocesium concentrations in wood currently may exceed the Japanese national standards. Using the knowledge on cycling of stable chemical elements in forests, we developed the model predicting how the radiocesium inventories in tree compartments will change in the future. Modelling results show that for the principal forestry species, Japanese cedar, decrease of radiocesium inventory in wood will be rather slow. Also, we analyzed efficiency of decontamination and suggested measures for revitalization of forestry at the radioactive contaminated territories.

研究分野：環境学

キーワード：Fukushima accident　radiocesium　stable cesium　Japanese cedar　forest ecosystems　radiocesium fluxes

１．研究開始当初の背景

(1) Till 2014, a large array of the experimental results describing dynamics of radiocesium in the Fukushima forests had been accumulated and reported by several research teams. Meta-analysis of these monitoring results[1] shows the dominant role of depuration processes (removal of radiocesium from the aboveground forest biomass with litterfall and with precipitation) at the early stage after the deposition. However, Chernobyl experience[2,3] shows that the early-stage regularities cannot be applied for the long-term predictions because of the changing roles of various processes (root uptake, internal translocations and return to soil) in redistribution of radionuclides at the later stages. The further dynamics of radiocesium in the Fukushima forests required elucidation.

(2) Perspectives of forestry in the evacuated areas in Fukushima prefecture depend on the radiocesium dynamics in trees. The major practical issues are: can forestry be restarted after lifting the evacuation orders or in the near future? Can radiation damage any forest tree species? Is decontamination an efficient measure for decreasing the dose rates in forests and radiocesium concentrations in wood, and how will its efficiency change with time? Are there any other measures for revitalization of forestry?

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２．研究の目的

(1) The principal research purpose was development of the model approach for prediction of the long-term dynamics of radiocesium in the Fukushima forests. Particularly, we focused on elaboration of the conceptual flux-based model approach and parameterization of the fluxes for the studied Japanese cedar forest at the experimental site in Yamakiya (Kawamata town, Fukushima prefecture) based on the monitoring results acquired since 2014.

(2) Other purpose of the study was evaluation of the forestry perspectives at the radioactive contaminated territories of Fukushima prefecture.

３．研究の方法

(1) In addition to monitoring at our principal experimental site in Yamakiya, during realization of the project we obtained access and started research at several other locations (Fig. 1), which enabled revealing general trends and inter-species differences in the ^{137}Cs behavior in the forest ecosystems.

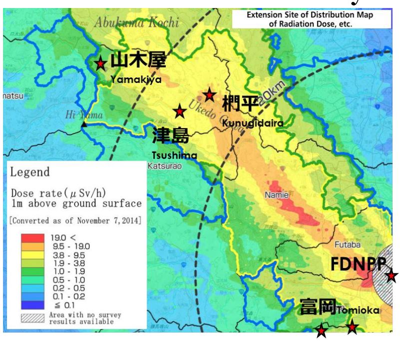

Fig. 1. Locations of experimental sites.

(2) For clarification of the ^{137}Cs future dynamics at the Yamakiya site, we also used stable cesium (^{133}Cs) distribution at this site and estimates of its fluxes obtained within the framework of JSPS grant 15H00968 (FY2015-2016).

(3) Annual fluxes of cesium isotopes in biomass were estimated based on its concentrations in biomass compartments and annual increments of biomass[4]. The annual return fluxes from the aboveground biomass to soil surface were calculated as the sums of the measured annual litterfall (LF), throughfall (TF) and stemflow (SF). ^{137}Cs leaching rate from litter was derived from its balance in the compartment during the observation period. For assessment of the geochemical migration flux, we utilized the annual infiltration rates obtained using the soil moisture monitoring equipment installed at the sites, and values of Kd.

(4) The aboveground biomass samples were collected every year in November-December from all major compartments of several model trees chosen in such manner that

their height and diameter distributions represent the whole studied forest stand. Soil and litter were sampled in several points at each site before the period of intensive litterfall. The biomass inventories in each compartment and their annual increments were derived from the literature data[5] with account to the actual height-diameter distribution, plantation densities and results of measurements of mass of each compartment in the model tree cut at the Yamakiya site.

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4．研究成果

Observations at several experimental sites resulted in acquiring a huge array of data that cannot be presented in a full volume in this report. In this reason, we will focus mainly on the results obtained at the Yamakiya site, where we have the longest and the most comprehensive observation series. We have already published the most important empirical data (Yamakiya) and are preparing for publication the modelling results.

(1) In our conceptual approach, cesium isotopes in the forest ecosystem are redistributed between its compartments by several major fluxes (Fig. 2). Our model considers all main interactions from ^{137}Cs interaction matrix suggested by the IAEA Biomass workgroup[6]. The current version of the model is aimed to predict the further dynamics of ^{137}Cs in the ecosystem based on its actual distribution measured at the beginning of the late stage (in 2016 in Yamakiya), and does not cover the initial stage. Attempt to apply the model to explain ^{137}Cs distribution measured in the pine forest in Chernobyl in 30 yr after its deposition demonstrated its satisfactory predictive ability for the late stage. The further development of the model should integrate early and late stage processes. The generic model based on meta-analysis of empirical data[1] successfully described the early-stage dynamics; however, the authors clearly state that their model is applicable only for that stage.

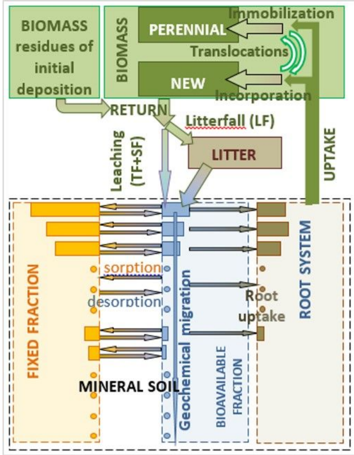

Fig. 2. Conceptual scheme of ^{137}Cs cycling in forest.

Rather realistic long-term predictions were obtained using the model approach that employed the knowledge on the carbon cycling along with radiocesium dynamics parameters[7]. For certain extent, our approach is similar; however, we use the data on the stable cesium cycling.

(2) ^{137}Cs concentration dynamics in biomass in 2014-2017 is shown at Fig. 3 (preliminary results for 2017). The general trend was a decrease of concentrations in the compartments that contained residues of initial deposition (outer bark, old foliage, branches), in litter and litterfall. Based on the dynamics in litter and litterfall, we estimate a period of ^{137}Cs half-leaching from litter as 1 yr.

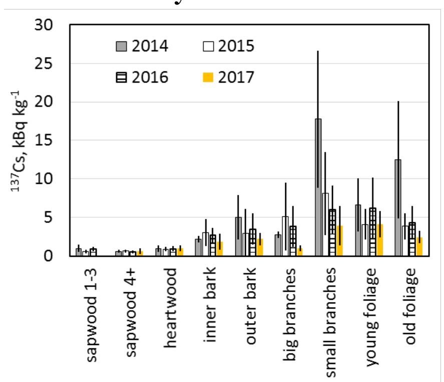

Fig. 3. ^{137}Cs concentrations in biomass of cedar (Yamakiya).

^{137}Cs distributions in soil profiles and their dynamics trends at the different sites were similar: major fractions of ^{137}Cs were localized in 5-cm topsoil, these fractions increased due to intake from litter and thoughfall, and there was no evidence of intensive downward migration of ^{137}Cs from topsoil (Fig. 4). ^{137}Cs fraction increased in soil from 74% of total deposition in 2014 to 92% in 2016, and decreased in litter from 19% to 4.5% (Fig. 5a).

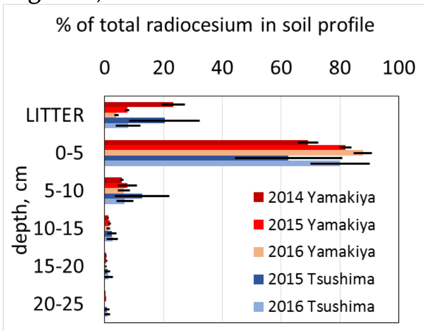

Fig. 4. ^{137}Cs distributions in soil profiles.

Fraction in biomass decreased from 6.1% in 2014 to 4.35% in 2015, and remained at the same level in 2016; these values are in good agreement with the results of other studies[8,9] (Fig. 5b).

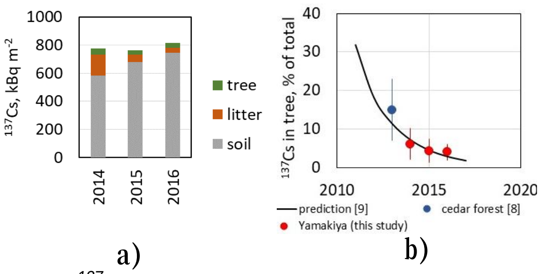

Fig. 5. ^{137}Cs distribution in cedar forest, Yamakiya (a) and dynamics of its biomass fraction (b).

Despite the apparent stabilization trend of ^{137}Cs inventory in aboveground biomass, its distribution between the biomass compartments, especially in the tree crown, significantly changed from year to year gradually approaching distribution of stable Cs (Fig. 6).

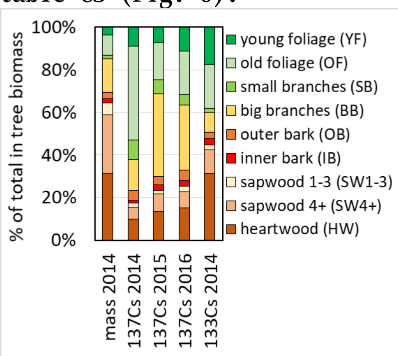

Fig. 6. Radioactive and stable cesium isotope distributions in tree biomass (cedar, Yamakiya).

In 2016, the strong correlation between ^{137}Cs and ^{133}Cs isotope concentrations occurred in most of compartments (Fig. 7) including even old foliage and outer bark. ^{137}Cs concentrations in these two compartments further decrease in 2017 (Fig. 3) allowing to infer that removal of residues of its initial deposition from the aboveground cedar biomass at the Yamakiya site might be completed by the end of 2017. Therefore, in the followed period ^{137}Cs should be recycled in the ecosystem in amounts proportional to those of ^{133}Cs, i.e. the flux ratios (partitions) of two cesium isotopes in biomass should be the same.

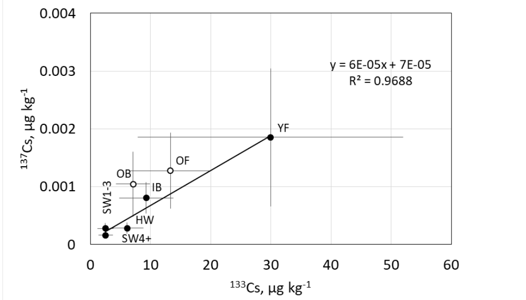

Fig. 7. Radioactive vs stable cesium isotope concentrations in cedar organs (Yamakiya).

(3) Main annual fluxes[4] of Cs isotopes in the cedar biomass at the Yamakiya site are presented in the table below.

	^{133}Cs, µg m^{-2}	^{137}Cs, % of total deposition
Incorporation	18.2	0.991
Uptake (Immobilization + Return)	12.4	0.672
Immobilization	1.4	0.074
Return (LF+TF+SF):	11.0	0.598
LF	4.47	0.243
TF	6.37	0.346
SF	0.15	0.008
Return 2 (LF2+TF2+SF2):		1.40
LF2		1.08
TF2		0.32
SF2		0.002
Translocation	5.9	0.319

Values of Incorporation, Immobilization and Translocation are the sums of the individual fluxes in the relevant compartments (not shown). ^{137}Cs fluxes for 2016 were derived from stable Cs fluxes using current ^{137}Cs/^{133}Cs ratio for Immobilization, i.e. assuming that Cs isotopes reached equilibrium and ^{137}Cs Immobilization is formed by its root uptake rather than translocation of residues of initial deposition. In the future, ^{137}Cs fluxes change according to growth of the biomass compartments and because of changes of its inventory in soil. We also assume that intensity of root uptake will remain stable at least in the near future due to the very slow redistribution of ^{137}Cs in soil profile. Our estimates show that moisture infiltration rate through the root-inhabited soil layer at the Yamakiya site may exceed 1000 mm yr^{-1}, but due to a high sorption ability the downward migration flux of ^{137}Cs from this layer is very low and radiocesium is still localized mainly in 5-cm topsoil (Fig. 4). Finally, Return of ^{137}Cs includes return of residues of initial deposition (Return 2 in 2017) with the partition of LF, TF and SF observed in 2016. Return 2 was obtained

as a difference between the total measured Return of ^{137}Cs in 2016 and its value expected from Return of ^{133}Cs.
Using the estimated flux values, for the Yamakiya site we predict increase of ^{137}Cs fraction in biomass (Fig. 8), however, due to radioactive decay ^{137}Cs inventory in biomass will not significantly change over the 30 yr period. Translocation from sapwood will result in accumulation of ^{137}Cs in heartwood, and concentration in this compartment between 2016 and 2046 will decrease only by a factor of 1.25.

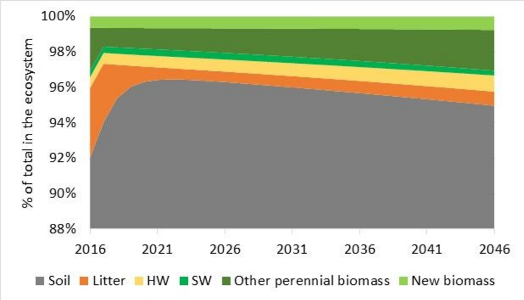

Fig. 8. Predicted long-term dynamics of ^{137}Cs in the cedar forest ecosystem (Yamakiya).

(4) Detail analysis of empirical data, their interpretation and assessment of impact of the Fukushima accident on forests and forestry are presented in our publications (section 5 of this report). Main conclusions of the study are:
- concentrations of ^{137}Cs in wood of the studied species at all our experimental sites exceed existing Japanese national standards (Fig. 9). Concentrations are higher in cedar and cypress than in pine;

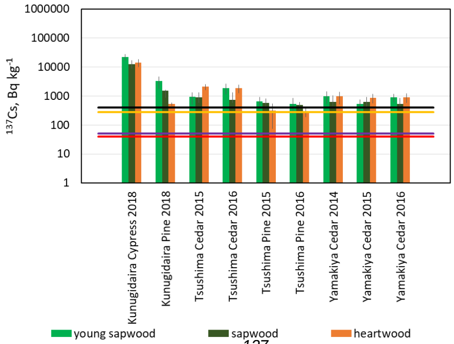

Fig. 9. Current levels of ^{137}Cs in wood vs Japanese national standards.

- for cedar and cypress forests, the forestry perspectives will strongly depend on ^{137}Cs concentrations and their dynamics in heartwood (Fig. 3, 8 and 9);
- removal of litter is not and will not be an efficient decontamination measure in cedar forests (Fig. 4, 5a and 8);
- current (Fig. 9) and predicted future ^{137}Cs levels in wood (Fig. 8) may conform the international standards applied to wood for industrial purposes. Establishing such standards in Japan, in case of public acceptance, may be suggested as a measure for forestry revitalization in Fukushima;
- irradiation forms morphological changes in young trees of Japanese red pine, which may endanger commercial value in case of establishing new pine plantations.

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〔図書〕（計　　件）

〔その他〕
ホームページ等

６．研究組織
(1)研究代表者
ヨシェンコ ヴァシル (Yoschenko Vasyl)
福島大学・環境放射能研究所・特任教授
研究者番号：40745569

(2)研究分担者
(　　　)
研究者番号：

(3)連携研究者
キーヴァ　セルギー (Kivva　Sergii)
福島大学・環境放射能研究所・特任教授
研究者番号：70745736

コノプリョフ　アレクセイ (Konoplev Aleksei)
福島大学・環境放射能研究所・教授
研究者番号：00745581

ジェレズニヤク　マーク (Zheleznyak Mark)
福島大学・環境放射能研究所・特任教授
研究者番号：90745712

難波　謙二 (Nanba Kenji)
福島大学・共生システム理工学類・教授
研究者番号：70242162

吉田　聡 (Yoshida Satoshi)
独立行政法人放射線医学総合研究所・福島復興支援本部・副本部長
研究者番号：20220642

高瀬つぎ子 (Takase Tsugiko)
福島大学・環境放射能研究所・特任准教授
研究者番号：10466641

(4)研究協力者
鶏徳浩司 (Keitoku Koji)
佐藤 なつみ (Sato Natsumi)
永田広子 (Nagata Hiroko)