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**論文 (Original article)**

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**Aggregated transfer factors ( $T_{ag}$ ) of cesium-137 in edible wild photosynthetic organisms**Yoshiyuki KIYONO<sup>1)\*</sup> and Akio AKAMA<sup>1)</sup>**Abstract**

Knowledge of the concentrations of radioactive materials in edible wild species is important to reduce the health risks associated with radiation exposure. Between 2015 and 2019, we collected 2094 parts of 380 edible wild photosynthetic species (plants, terrestrial cyanobacteria, and epilithic lichens), 72 parts of 27 non-edible wild photosynthetic species, and 22 parts of 15 edible cultivated plant species, for a total of 2187 parts of 422 species growing in areas affected by the 2011 Fukushima Daiichi Nuclear Power Station accident. Aggregated transfer factor ( $T_{ag}$ ) values of radioactive cesium-137 ( $^{137}\text{Cs}$ ) transferred to organisms from the habitat O-horizon and soil were investigated. Geometric mean values of  $^{137}\text{Cs}$   $T_{ag}$  of edible parts of wild species differed greatly among species in both vegetative organs and sexual reproductive organs (maximum/minimum ratio of species  $T_{ag}$  of ~2000 in vegetative organs and ~920 in sexual reproductive organs). Multiple regression analysis was performed to determine the factors that were associated with species geometric mean  $T_{ag}$  values in representative edible parts of vegetative organs and sexual reproductive organs of edible wild species. Forest species tended to have higher  $T_{ag}$  values than open-land-habitat species ( $P < 0.023$ ). Although data were obtained only for vegetative organs,  $T_{ag}$  values were higher for adherent species, such as those that adhere to tree trunks or stones (e.g., by adhering roots) ( $P < 0.010$ ). Species' ecological traits were significantly influenced species-level  $^{137}\text{Cs}$   $T_{ag}$ . Because  $^{137}\text{Cs}$   $T_{ag}$  values differ greatly depending on the species, it is important to use species as a unit in food-safety assessments of radioactivity in edible photosynthetic organisms.

**Key words :** edible wild plants, lichens,  $^{137}\text{Cs}$   $T_{ag}$ , cyanobacteria, food safety, Fukushima Daiichi Nuclear Power Station accident, symbiosis

**1. Introduction**

The 2011 Tokyo Electric Power Company Fukushima Daiichi Nuclear Power Station accident was the first serious radioactive-contamination accident to occur in a cultural sphere in which people often eat tree leaves as vegetables (Kiyono and Akama 2017a). Some radioactive cesium (Cs) released into the atmosphere was transferred to edible organisms. Knowledge of the concentrations of radioactive materials in edible wild species is important to reduce the health risks associated with radiation exposure. The transfer of radioactive cesium-137 ( $^{137}\text{Cs}$ ) from the environment to organisms is influenced by many physicochemical and biological factors (Burger and Lichtscheidl 2018), including the amount of exchangeable potassium in soil (Kobayashi 2013, Hirayama 2019).

There are many edible photosynthetic species in Japan, including terrestrial cyanobacteria and lichens, which have diverse life forms, growing environments, and abilities to absorb radioactive Cs through root and/or surface absorption. Contamination of various forest products is commonly quantified using the aggregated transfer factor ( $T_{ag}$ ,  $\text{m}^2 \text{kg}^{-1}$ ), which integrates various environmental parameters including soil and plant type, root distribution, and the nature and

vertical distribution of the contaminating deposits (IAEA 2009). However, previous studies on  $^{137}\text{Cs}$  transfer from the environment to edible wild photosynthetic species ( $^{137}\text{Cs}$   $T_{ag}$ ) have focused on berries (Calmon et al. 2009) and plant species that were obtained mostly at markets (Kiyono and Akama 2015b, Tagami and Uchida 2017, Uchida and Tagami 2018, IAEA 2020, Takada et al. 2022). Furthermore, few systematic studies have examined the factors leading to interspecies differences in  $^{137}\text{Cs}$   $T_{ag}$  values.

Therefore, to determine which species are most likely to absorb radioactive Cs in Japan, we targeted edible wild photosynthetic species that grow in areas that received relatively large amounts of radioactive fallout due to the 2011 Fukushima nuclear accident, and investigated  $T_{ag}$  values of  $^{137}\text{Cs}$  transferred to organisms from their habitat (O-horizon + soil to a depth of 0.05 m). Then, we investigated which factors were associated with species-level  $^{137}\text{Cs}$   $T_{ag}$  values. We also analyzed the effects of habitat microtopography, fertilization management, and season on  $^{137}\text{Cs}$   $T_{ag}$  values at the individual level. Some of the data obtained in this study were published in the Proceedings of the 21st Environmental Radioactivity Workshop (Kiyono and Akama 2021).

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## 2. Materials and Methods

### 2.1 Study area and sampling

Sampling was conducted in the Tohoku and Kanto regions of Japan; the main collection areas were Minamisoma, Okuma, Tomioka, Kawauchi, Iwaki, Otama, Koriyama, and Tadami in Fukushima Prefecture; and Hitachiomiya, Kasama, Ishioka, and Tsukuba in Ibaraki Prefecture. The study area has a temperate to cold climate (Peel et al. 2007), and the dominant tree species include *Quercus serrata*, *Cryptomeria japonica*, and *Pinus densiflora*. Between 2015 and 2019, we collected 2094 parts from 380 species of edible wild plants (including species that are commonly used as food wraps), terrestrial cyanobacteria, and epilithic lichens, as well as nearby or related species for comparison; 72 parts from 27 non-edible wild photosynthetic organisms; and 22 parts from 15 edible cultivated plants; for a total of 2187 parts from 422 species. When most samples were collected from wild individuals together with some samples from cultivated individuals, the species were treated as wild species (e.g., *Prunus persica* and *Eriobotrya japonica*). Sampling sites were selected to maximize the range of  $^{137}\text{Cs}$  deposition per land area (MEXT 2018) for each species. Cultivated individuals had been growing before the 2011 Fukushima nuclear accident, except for two species (*Carica papaya* and *Allium sativum*). Samples from edible species were collected in the appropriate period for edible parts to be consumed (e.g., sprouts, fruits, and tubers). For non-edible species, the harvesting period was in the sprout- or fruit-maturation stage, to correspond with the harvesting period of edible species. Most of the sampled parts were sprouts (current-year branches and leaves) for woody plants, aboveground parts or entire individuals for herbs, whole thalli for lichens, and colonies for terrestrial cyanobacteria. Sexual-reproductive-organ samples included inflorescences, fruits, seeds, and flower buds of Spermatophyta, and fertile leaves and stems of Polypodiopsida. Tuber samples often contained roots. After sample collection, the parts were divided as needed. Of the total 2187 samples, 47% were collected in spring (March–May), 28% in summer (June–August), 22% in autumn (September–November), and 3% in winter (December–February).

The arithmetic mean length and total fresh weight were recorded for most samples. The fresh weights of the samples ranged from 0.22–562 g. During sampling, the air-dose rate (ADR,  $\mu\text{Sv h}^{-1}$ ) of each individual was measured at 1 m above the ground using a scintillation survey meter (TCS 172B; Hitachi Aloka Medical, Ltd., Tokyo, Japan). Habitat topography, land use (forest, wet land, crop land, grassland currently or recently grazed and subsequently dominated by *Pteridium aquilinum* subsp. *japonicum*, or other grassland),

tree cover (open land, forest edge, or forest), ground-surface condition [covered with normal soil with sampled individuals growing on it, or covered with a hard material such as asphalt with sampled individuals growing in small gaps (Photo 1)], and the origin of the sampled individuals (wild or planted) were recorded. Organisms growing in small gaps were described as having “*dokonjōyasai*-like” growth (revised from Kiyono and Akama 2021). *Dokonjōyasai* is a Japanese term that refers to commonly cultivated vegetables that become semi-naturalized in small gaps in concrete or pavement.

In several cases, we combined two species to form a sample because they were closely related and difficult to distinguish: *Chenopodium album* and *C. album* var. *centrorubrum*, *Campanula punctata* and *C. punctata* var. *hondoensis*, *Elaeagnus multiflora* var. *multiflora* and *E. multiflora* var. *gigantea*, *Lonicera gracilipes* var. *gracilipes* and *L. gracilipes* var. *glabra*, *Sasa palmata* and *S. senanensis*, and *Rubus microphyllus* and *R. × medius*.

### 2.2 Sample preparation and analysis

The samples were rinsed with distilled or tap water to remove soil and debris, and dried for  $\geq 48$  h in a drying oven with air circulation at  $75^\circ\text{C}$  at the Forestry and Forest Products Research Institute (FFPRI). Next, the samples were weighed and placed in a U-8 or U-9 container (Umano Kagaku Youki Kabushiki Gaisya, Osaka, Japan) or a 0.7-L Marinelli vessel (Sekiya Rika Co., Ltd., Tokyo, Japan).  $^{137}\text{Cs}$  concentrations were measured using a germanium semiconductor detector (GEM40P4-76; SEIKO EG&G CO., LTD., Tokyo, Japan) at the FFPRI. The measured values were converted to  $^{137}\text{Cs}$  concentrations in a completely dry state ( $\text{Bq kg}^{-1}$  dry weight), assuming a moisture content of 4% at the time of oven-dried weight measurement. The water content was set at 4% because the loss on drying was approximately 4% [geometric mean = 4.00%, geometric standard deviation (SD) = 1.33,  $n$



Photo 1. *Dokonjōyasai*-like growth in *Valerianella locusta* (Tsukuba).

= 36; samples were leaves, branches, and stems of trees and perennials obtained separately in other studies; Kiyono et al., unpublished] when a plant sample dried at 75°C for ≥ 48 h or more was dried at 105°C by the sediment survey method (Ministry of the Environment, Water and Air Quality Bureau 2012). As a measurement condition, the <sup>137</sup>Cs counting error was set to ≤ 10%. Measurement times ranged from 0.5–24 h.

### 2.3 Estimation of <sup>137</sup>Cs inventory in the O-horizon and soil to a depth of 0.05 m

The <sup>137</sup>Cs inventory (kBq m<sup>-2</sup>) for the O-horizon and soil to a depth of 0.05 m in the habitats of the sampled individuals was estimated as previously described (Kiyono and Akama 2022), according to the following relationship, revised from Kiyono et al. (2019a):

$$\text{O-horizon + Soil } ^{137}\text{Cs inventory}_{\text{Forest habitat}} = 338.41 \text{ ADR}^{1.3741} \quad (R^2 = 0.9589) \dots\dots\dots (1)$$

For samples obtained from grassland dominated by *Pteridium aquilinum* subsp. *japonicum*, we revised the equation as follows:

$$\text{O-horizon + Soil } ^{137}\text{Cs inventory}_{\text{Paj habitat}} = 683.55 \text{ ADR}^{1.8196} \quad (R^2 = 0.8157) \dots\dots\dots (2)$$

According to the data of Kiyono et al. (2019a), the <sup>137</sup>Cs inventory of the O-horizon accounts for approximately 11% (0.5–94%) of the total <sup>137</sup>Cs inventory in the O-horizon and soil to a depth of 0.05 m in forests, and approximately 10% (0.3–36%) of that in *P. aquilinum* subsp. *japonicum* grasslands.

Because <sup>137</sup>Cs concentrations were decay-corrected using September 1, 2016, as the reference date in this study (described later), the ADR was also estimated as of September 1, 2016, using the following equation:

$$\text{ADR}_{2016/9/1} = \text{EXP} [-0.000206 (\text{Days since } 2016/9/1)] \text{ ADR}_{\text{measured date}} \dots\dots\dots (3)$$

where ADR<sub>2016/9/1</sub> (μSv h<sup>-1</sup>) is the ADR for September 1, 2016, and ADR<sub>measured date</sub> (μSv h<sup>-1</sup>) is the ADR for the sampling date. This is an empirical equation based on the fact that ADR decreased by slightly less than 10% annually from 2016 to 2018 (Kiyono et al. 2019a).

### 2.4 Calculation of T<sub>ag</sub> of <sup>137</sup>Cs from habitat to photosynthetic species

For each collected sample, <sup>137</sup>Cs T<sub>ag</sub> (m<sup>2</sup> kg<sup>-1</sup> dry weight) from the habitat to the organism was determined as follows:

$$^{137}\text{Cs T}_{\text{ag}} = (^{137}\text{Cs concentration in sample}) / (\text{O-horizon + Soil } ^{137}\text{Cs inventory in habitat}) \dots\dots\dots (4)$$

where <sup>137</sup>Cs concentrations are expressed in Bq kg<sup>-1</sup> dry weight.

Among the 14 species for which more than 10 samples were obtained, the relationship between harvest year and T<sub>ag</sub> values during the period 2015–2019 had a moderately strong negative relationship for *Kalopanax septemlobus* (*r* = -0.497, *n* = 13), a moderately strong positive relationship for *Osmunda japonica* (*r* = 0.502, *n* = 27), and weakly positive relationships for *Hydrangea petiolaris* (*r* = 0.273, *n* = 12) and *Osmundastrum cinnamomeum* var. *fokiense* (*r* = 0.278, *n* = 34). However, the other 10 species (*Aster microcephalus* var. *ovatus*, *Petasites japonicus*, *Artemisia indica* var. *maximowiczii*, *Aralia elata*, *Chengiopanax sciadophylloides*, *Hydrangea hydrangeoides*, *Pteridium aquilinum* subsp. *japonicum*, *Fallopia japonica* var. *japonica*, *Helwingia japonica*, and *Clethra barbinervis*) showed almost no relationship (*r* = -0.102 to 0.123, *n* = 13–88). Therefore, we ignored the influence of harvest year and calculated the geometric mean of <sup>137</sup>Cs T<sub>ag</sub> by species and by part where necessary. The geometric mean was used because the frequency distribution of concentrations can generally be approximated by a lognormal distribution, and the frequency distributions of <sup>137</sup>Cs T<sub>ag</sub> values in several species with large numbers of samples obtained separately in other studies [e.g., *Petasites japonicus* (*n* = 100) and *Osmunda japonica* (*n* = 131)] could also be approximated by a logarithmic normal distribution (Kiyono et al., unpublished). Thus, in this study, mean values indicate geometric mean values unless otherwise specified.

### 2.5 Comparison of <sup>137</sup>Cs T<sub>ag</sub> values between parts

The ratios of <sup>137</sup>Cs T<sub>ag</sub> values between parts were calculated for 181 individuals of 51 species, in which T<sub>ag</sub> values for different parts of the same individual were obtained. Reflecting interspecific differences in morphology and edible parts, the compared parts differed among species as follows. We compared sexual reproductive organs vs. vegetative organs in 60 individuals of 30 species, i.e., for Spermatophyta, fruits, inflorescences, or inflorescences vs. current-year branches and leaves, current-year leaves, or current-year vines; and for Polypodiopsida, fertile leaf petioles vs. sterile leaf petioles. We compared sexual reproductive organs vs. sexual reproductive organs (one individual of one species) in *Equisetum arvense* fertile-stem sheaths vs. others (cones, nodes, and internodes). We compared vegetative organs vs. vegetative organs (103 individuals of 12 species in total) between leaves vs. stems and branches, propagules vs. stems and leaves, leaf blades vs. petioles, or bamboo-shoot culms vs. culm sheaths. In addition,

aboveground parts vs. belowground parts were compared for 17 individuals of 8 species.

## 2.6 Statistical analysis of the relationship between species $^{137}\text{Cs}$ $T_{\text{ag}}$ values and ecological traits

One-way analysis of variance (ANOVA) was used to evaluate interspecific differences in species' mean  $T_{\text{ag}}$  values. This analysis was performed only for the edible parts of the wild species (Dataset A; Table S1, including appendages of edible parts such as fruit stalks and pericarp, which are not usually edible) and for all data including the non-edible parts of the edible wild photosynthetic species (e.g., raspberry current-year branches and leaves) + non-edible wild photosynthetic species + edible cultivated plant species (Dataset B; Table S1). In Datasets A and B, vegetative organs (Analysis 1; e.g., leaves, branches, stems, rhizomes, roots, and propagules) and sexual reproductive organs (Analysis 2; e.g., flowers, fruits, sporophylls) were separated because, in Japan, these are typically consumed as vegetables whereas most sexual reproductive organs (e.g., berries and nuts) are consumed as fruits; these vegetables and fruits generally have different nutritional components and are prepared differently (Gomi 2018, Katiboina 2022). Thus, four types of analyses were performed: edible vegetative organs (A1), edible sexual reproductive organs (A2), all vegetative organs (B1), and all sexual reproductive organs (B2). In addition, for species with samples of multiple parts, in principle, the part with the largest number of samples was used for analysis as a representative part of that species [as described later, differences in  $T_{\text{ag}}$  between parts were orders of magnitude smaller (Table 1) than those between species and are thought to have had negligible effects on analysis results]. However, for species from which samples were obtained from both vegetative and sexual reproductive organs, one representative part was selected for each organ type. For example, in *Petasites japonicus*, vegetative-organ  $T_{\text{ag}}$  values were analyzed using leaf data, and sexual-reproductive-organ  $T_{\text{ag}}$  values were analyzed using inflorescence data. In many cases, representative vegetative organs were the current-year branches and leaves for trees, young shoots for bamboos, and the aboveground parts for herbaceous plants. Lichens were not separated into vegetative and sexual reproductive organs, but treated as whole vegetative organs. Although  $T_{\text{ag}}$  values are likely to be affected by microtopography, fertilization management in the habitat, and collection season, we grouped the samples by species and parts (Table S1), and ignored any differences among habitats and seasons in this analysis. The results indicated significant interspecific differences in  $T_{\text{ag}}$  mean values (A1  $P < 0.001$ , A2  $P = 0.027$ , B1  $P < 0.001$ , B2  $P = 0.092$ ); therefore, multiple regression analysis was performed for A1, A2, B1, and B2 to

determine whether species' ecological traits were associated. The representative parts used for multiple regression analysis were the same as those used for one-way ANOVA. We selected five ecological traits of wild species in their normal habitat as candidates for explanatory variables, and dummy variables were assigned to each species as follows (Table S1): habitat tree-covering (HTc; 1, open land; 2, forest edge; 3, forest); habitat moisture environment (HM; 1, dry; 2, moderate; 3, wet); life span of the individual, as an indicator of the time required for total biomass replacement, or the reciprocal of the turnover rate (LiS; 1, annual plant; 2, biennial plant, perennial plant, terrestrial cyanobacterium, or shrub with a stem lifespan of ~2 years such as *Rubus* spp.; 3, other shrub or epilithic lichen; 4, tree); habitat temperature during leaf growth (HTLe; 1, spring ephemeral or non-evergreen winter green plant; 2, evergreen plant, summer green plant, mycoheterotrophic plant, terrestrial cyanobacterium, or epilithic lichen); species showing adherence to surfaces such as rock or tree bark, e.g., plants with adhering roots or epiphytes including lithophytes, the ground-creeping species *Lycopodium clavatum* var. *nipponicum*, epilithic lichens, and terrestrial cyanobacteria (AdTo; 1, without; 2, with). In this analysis, woody perennials that grow to > 5 m in height are referred to as trees, and vegetation dominated by trees is referred to as forest. *Oenothera stricta*, *O. laciniata*, *Picris hieracioides* subsp. *japonica*, *Chamaecrista nomame*, and *Astragalus sinicus* are plants that exhibit plasticity between annual and short-lived perennial strategies; therefore, these five species were assigned an LiS of 1.5. *Barnardia japonica* and *Allium schoenoprasum* var. *foliosum* have no leaves in summer and winter, respectively, and *Petasites japonicus* often has no leaves in summer in regions with warm temperate climates; therefore, they were assigned an HTLe of 1.5. Cultivated species such as *Prunus armeniaca* and *Allium sativum*, which were found only as cultivated individuals in the survey area, were assigned the appropriate tree-cover, moisture-environment, and temperature values for cultivated sites during the leaf-growth periods. Because the numbers of available samples differed among species (Table 2a, b), we changed the lower sample size limit, and performed multiple regression analysis for each change to evaluate sample-size effects. Thus, small samples may leave to greater errors in species-level  $T_{\text{ag}}$ . However, because many such species were included in this study, equations containing these species had large  $n$  values and the multiple regression equation had greater explanatory power. This trade-off allowed us to select the optimal case by calculating different thresholds for the number of samples. Dataset A1 contained 62 species with 6 or more samples per species ( $n \geq 6$ ), 105 species with  $n \geq 5$ , 181 species with  $n \geq 4$ , 262 species with  $n \geq 3$ , 311 species with  $n \geq 2$ , and 327 species with  $n \geq 1$ . Dataset B1 contained

64 species with  $n \geq 6$ , 109 species with  $n \geq 5$ , 193 species with  $n \geq 4$ , 278 species with  $n \geq 3$ , 340 species with  $n \geq 2$ , and 368 species with  $n \geq 1$ . For sexual reproductive organs, there were only three explanatory variables due to the lack of samples from spring ephemerals, winter green plants, plants with adhering roots, epiphytes, terrestrial cyanobacteria, and lichens. Dataset A2 contained 45 species with  $n \geq 3$ , 66 species with  $n \geq 2$ , and 68 species with  $n \geq 1$ . Dataset B2 contained 49 species with  $n \geq 3$ , 75 species with  $n \geq 2$ , and 86 species with  $n \geq 1$ . Positive and negative correlations (Pearson product-moment correlation coefficient  $|r| \geq 0.2$ ) were observed among candidate explanatory variables. In vegetative organs (Datasets A1 and B1), positive correlations with  $r \geq 0.2$  were detected between LiS and HTc (A1:  $n \geq 6$ ,  $r = 0.435$ ;  $n \geq 5$ , 0.417,  $n \geq 4$ ; 0.377;  $n \geq 3$ , 0.385;  $n \geq 2$ , 0.369;  $n \geq 1$ , 0.375. B1:  $n \geq 6$ , 0.416;  $n \geq 5$ , 0.396;  $n \geq 4$ , 0.339;  $n \geq 3$ , 0.355;  $n \geq 2$ , 0.345;  $n \geq 1$ , 0.329), between HTc and HTLe (A1:  $n \geq 4$ , 0.218;  $n \geq 3$ , 0.273;  $n \geq 2$ , 0.246;  $n \geq 1$ , 0.257. B1:  $n \geq 3$ , 0.254;  $n \geq 2$ , 0.235;  $n \geq 1$ , 0.236), between HTLe and LiS (A1:  $n \geq 6$ , 0.215;  $n \geq 5$ , 0.322;  $n \geq 4$ , 0.364;  $n \geq 3$ , 0.405;  $n \geq 2$ , 0.411;  $n \geq 1$ , 0.422. B1:  $n \geq 6$ , 0.211;  $n \geq 5$ , 0.319;  $n \geq 4$ , 0.352;  $n \geq 3$ , 0.394;  $n \geq 2$ , 0.399;  $n \geq 1$ , 0.410), and between LiS and AdTo (A1:  $n \geq 6$ , 0.220. B1:  $n \geq 6$ , 0.222). Negative correlations with  $r \leq -0.2$  were detected between LiS and HM (A1:  $n \geq 5$ , -0.217;  $n \geq 3$ , -0.204;  $n \geq 2$ , -0.206; B1:  $n \geq 5$ , -0.214). For sexual reproductive organs (Datasets A2 and B2), positive correlations with  $r \geq 0.2$  were detected between LiS and HTc (A2:  $n \geq 2$ , 0.211;  $n \geq 1$ , 0.213). However, most of these correlations were weak, with a maximum of  $r = 0.435$  in Dataset A, and  $r = 0.416$  in Dataset B. Therefore, multiple regression analysis was performed using the variable increase/decrease method (Fin = 2.0, Fout = 2.0), using all five factors as explanatory variables and  $^{137}\text{Cs}$   $T_{\text{ag}}$  values as objective variables. We also excluded data from wet sites in a multiple regression analysis, to understand the effects of HM in greater detail.

## 2.7 Analysis of habitat microtopography effects on $^{137}\text{Cs}$ $T_{\text{ag}}$

Individuals exhibiting *dokonjōyasai*-like growth (Photo 1) tend to have higher  $T_{\text{ag}}$  values (Kiyono and Akama 2021). Therefore, we compared the mean  $T_{\text{ag}}$  values of individuals showing *dokonjōyasai*-like and non-*dokonjōyasai*-like growth for each species.  $T_{\text{ag}}$  values for the same part were compared for each species. All samples including inedible wild species and edible cultivated plants were used for this comparison. Because fertilization management and collection season may also affect  $T_{\text{ag}}$  values, for this comparison, we selected samples subject to the same conditions except for those related to habitat microtopography.

## 2.8 Analysis of habitat fertilization management effects on $^{137}\text{Cs}$ $T_{\text{ag}}$

The amount of exchangeable potassium (K) in soil affects plant Cs concentrations (Kobayashi 2013, Hirayama 2019). Fertilized soil, such as agricultural land, contains large amounts of K, which may reduce Cs transfer to plants through root uptake (Nemoto 2014, Sakuma and Niitsuma 2016). Therefore, we examined samples collected from individuals on land that had been fertilized, including cultivated land, gardens, nurseries, pastures (all of which were considered agricultural land in this study), and land that had not been fertilized (control).  $T_{\text{ag}}$  values for the same part were compared for each species. All samples including inedible wild species and edible cultivated plants were used for this comparison. For this comparison, we selected samples subject to the same conditions except for those related to fertilization management.

## 2.9 Analysis of summer increase in $^{137}\text{Cs}$ $T_{\text{ag}}$ values

$T_{\text{ag}}$  values have been reported to increase in summer for *Osmunda japonica* in forests (Kiyono et al. 2018b) and *Petasites japonicus* under tree cover (Kiyono et al. 2018a). Therefore, we compared  $T_{\text{ag}}$  values in samples collected in summer (June–August) and in other months (control). All samples including non-edible wild species and edible cultivated plants were used for this comparison.  $T_{\text{ag}}$  values for the same part were compared for each species. For this comparison, we selected samples subject to the same conditions except for those related to collection season.

All  $^{137}\text{Cs}$  concentrations determined in this study were decay-corrected using September 1, 2016, as the reference date. Data were tested for normality using an online tool (<http://www.civilworks.jp/freetool/freetool.htm#normal>). Statistical analyses were performed using Ekuseru-Toukei 2012 (Social Survey Research Information Co., Ltd.). Multiple comparisons of three or more groups were evaluated using the Tukey-Kramer method at a significance level of  $P < 0.05$ . The nomenclature used in this study follows the YList (Yonekura and Kajita 2003–). Japanese names were transliterated using a version of the Hepburn Romanization system (Miuran Business Systems 2014).

## 3. Results

### 3.1 $T_{\text{ag}}$ of $^{137}\text{Cs}$ from habitat to photosynthetic species

#### 3.1.1 Habitat $^{137}\text{Cs}$ inventory and species-level $^{137}\text{Cs}$ $T_{\text{ag}}$ values

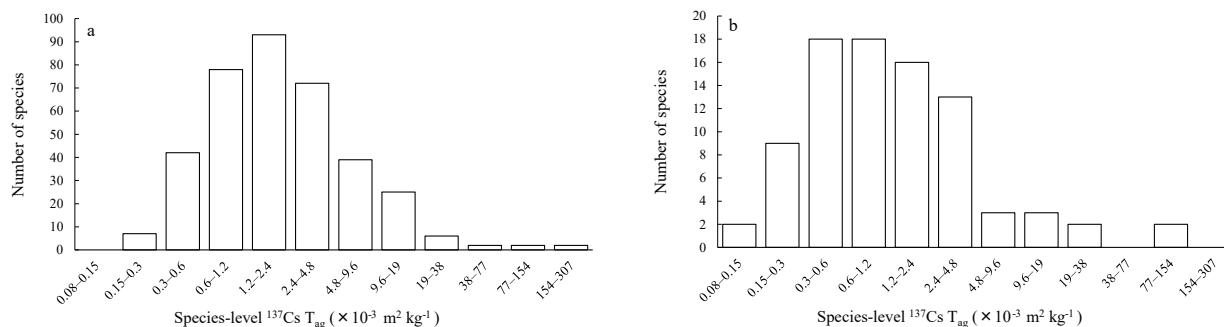
The habitat  $^{137}\text{Cs}$  inventory of the sampled individuals for the O-horizon and soil to a depth of 0.05 m was 0.77–30000 kBq  $\text{m}^{-2}$  (Table S1). The species mean  $T_{\text{ag}}$  values (Table S1) of vegetative organs were  $0.154\text{--}304 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$  (species  $n = 368$ , mean = 2.05; geometric SD = 3.24), with a maximum

interspecific difference of approximately 2000-fold (Fig. 1a). The  $T_{ag}$  value of the lowest-ranking 30% was 1.0, and that of the highest-ranking 30% was 3.2. For sexual reproductive organs, the species mean  $T_{ag}$  value was  $0.133\text{--}122 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$  (species  $n = 86$ ; mean = 1.25; geometric SD = 4.18), with a maximum interspecific difference of approximately 920-fold (Fig. 1b). The  $T_{ag}$  value of the lowest-ranking 30% was 0.47, and that of the highest-ranking 30% was 1.9. The distribution of  $T_{ag}$  values for sexual reproductive organs (Fig. 1b) was similar in shape, but the peak was shifted toward smaller  $T_{ag}$  values compared to that for vegetative organs (Fig. 1a). However, the two organ types showed wide, overlapping  $T_{ag}$  distributions. The species geometric SD (Fig. 2) obtained for species with sample  $n \geq 3$  showed no clear relationship with the species mean  $T_{ag}$  in either organ type, and most were  $< 10$ , with means of  $2.9 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$  ( $n = 276$ ) for vegetative organs and  $2.8 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$  ( $n = 52$ ) for sexual reproductive organs. Based on the  $T_{ag}$  distribution, and considering the difference in the  $T_{ag}$  distribution range between vegetative and sexual reproductive organs, among vegetative organs, species with  $T_{ag} < 1.0 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$  were classified as having low  $T_{ag}$  values, whereas those with  $T_{ag} > 3.2 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$  were classified as having high  $T_{ag}$  values, and intermediate species were classified

as having moderate  $T_{ag}$  values ( $1.0 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1} \leq T_{ag} \leq 3.2 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ). Among sexual reproductive organs, species with  $T_{ag} < 0.47 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$  were classified as having low  $T_{ag}$  values, species with  $T_{ag} > 1.9 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$  were classified as having high  $T_{ag}$  values, and intermediate species were classified as having moderate  $T_{ag}$  values ( $0.47 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1} \leq T_{ag} \leq 1.9 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ).

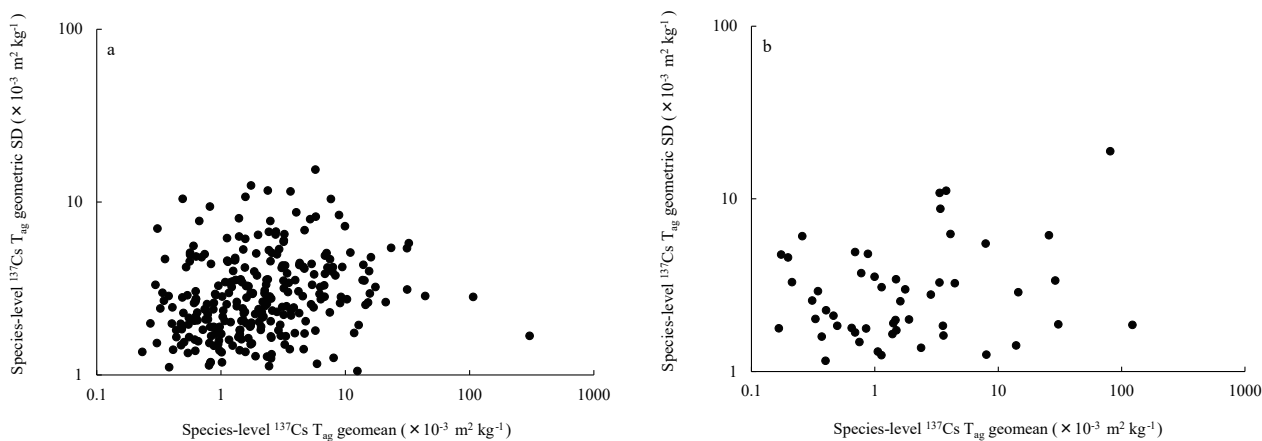
### 3.1.2 Phylogenetic group and species-level $^{137}\text{Cs } T_{ag}$ values

Some phylogenetic groups had relatively low  $^{137}\text{Cs } T_{ag}$  values at the species level, including Brassicaceae and gymnosperms, whereas others had high  $^{137}\text{Cs } T_{ag}$  values, including Ericaceae, Orchidaceae, Lycopphyta, Polypodiopsida, and lichens (Table S1). Urticaceae clades tended to have distinct species-level  $^{137}\text{Cs } T_{ag}$  values (Table S1). However, some phylogenetic groups showed no clear correspondence between group and species-level  $^{137}\text{Cs } T_{ag}$  values, including Asteraceae, bamboo, Asparagaceae, and Amaranthaceae (vegetative organs); *Rubus* (fruits), and Rosaceae (inflorescences) (Table S1). For example, among vegetative organs, seven of the 20 Brassicaceae species had low  $T_{ag}$  values ( $0.15\text{--}0.97 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), 13 had moderate  $T_{ag}$  values ( $1.0\text{--}2.5 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ); and



**Fig. 1. Distribution of species-level  $^{137}\text{Cs } T_{ag}$  values in the study area.**

a, vegetative organs (including all parts, aboveground parts, and belowground parts); b, sexual reproductive organs.



**Fig. 2. Geometric means and standard deviation of species-level  $^{137}\text{Cs } T_{ag}$  values.**

a, vegetative organs (including all parts, aboveground parts, and belowground parts); b, sexual reproductive organs. Species with sample  $n \geq 3$ .

none had high  $T_{\text{ag}}$  values. All three evergreen gymnosperms (*Cryptomeria japonica*, *Chamaecyparis obtusa*, and *Pinus densiflora*) had low  $T_{\text{ag}}$  values ( $0.31\text{--}0.94 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ). The terrestrial cyanobacteria *Nostoc commune* had a moderate  $T_{\text{ag}}$  value ( $2.6 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ). Two Ericaceae species (*Vaccinium japonicum*  $7.2 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$  and *V. hirtum*  $99 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) had high  $T_{\text{ag}}$  values. In Urticaceae, all four species of clade I (Boehmerieae) had low  $T_{\text{ag}}$  values ( $0.51\text{--}0.98 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) and all four species of clade II (Lecantheae) had high  $T_{\text{ag}}$  values ( $3.8\text{--}12 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), whereas one of the two clade III species had a moderate  $T_{\text{ag}}$  value ( $2.3 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) and the other had a high  $T_{\text{ag}}$  value ( $8.0 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), indicating that the  $T_{\text{ag}}$  distributions differed significantly among clades ( $P = 0.0237$ ). Among ferns, Lycophyta had one species with a moderate  $T_{\text{ag}}$  value ( $1.7 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) and three with high values ( $14\text{--}23 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), whereas Polypodiopsida had five species with moderate values ( $1.3\text{--}3.2 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) and 11 with high values ( $3.9\text{--}107 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), implying that ferns mainly had high  $T_{\text{ag}}$  values. The  $T_{\text{ag}}$  value of *Cryptomeria japonica* roots that invaded dead stems of *Osmundastrum cinnamomeum* var. *fokiense*, which had the highest  $T_{\text{ag}}$  among Tracheophyta species in this study ( $107 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), was  $126 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , which was significantly higher than that of *Cryptomeria japonica* ( $0.54 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ). All three lichen species (*Stereocaulon* sp., *Umbilicaria esculenta*, and *Parmotrema tinctorum*) had high  $T_{\text{ag}}$  values ( $72\text{--}304 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ). Among 59 Asteraceae species, 11 had low  $T_{\text{ag}}$  values ( $0.31\text{--}0.89 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), 30 had moderate values ( $1.0\text{--}3.19 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), and 18 had high values ( $3.20\text{--}32 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ). Among seven bamboo species, one had a low  $T_{\text{ag}}$  value ( $0.52 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), two had moderate values ( $1.6, 2.3 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), and four had high values ( $4.3\text{--}17 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ). Among 10 Asparagaceae species, three had low  $T_{\text{ag}}$  values ( $0.48\text{--}0.87 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), three had moderate values ( $1.5\text{--}2.0 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), and four had high values ( $4.7\text{--}8.3 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ). Among eight Amaranthaceae species, three had low  $T_{\text{ag}}$  values ( $0.49\text{--}0.56 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), three had moderate values ( $1.7\text{--}3.2 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), and two had high values ( $3.9$  and  $18 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ).

Among sexual reproductive organs, gymnosperms had low  $T_{\text{ag}}$  values (*Pinus densiflora*  $0.26 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$  and *Ginkgo biloba*  $0.53 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ). High  $T_{\text{ag}}$  values were found in five Ericaceae species (*Vaccinium japonicum*, *V. hirtum*, *V. oldhamii*, *Monotropa uniflora*, and *Monotropastrum humile*) ( $7.9\text{--}122 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) and in two Orchidaceae species (*Cyrtosia septentrionalis*  $3.4 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$  and *Cymbidium goeringii*  $29 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ). Among fruits from 11 *Rubus* species of the Rosaceae family, those of three species had low  $T_{\text{ag}}$  values ( $0.21\text{--}0.35 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), those of four species had moderate values ( $0.83\text{--}1.3 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), and those of four species had high values ( $3.6\text{--}4.4 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), indicating

a range of  $T_{\text{ag}}$  values from low to high. Among the fruits of 15 other Rosaceae species, those of eight species had low  $T_{\text{ag}}$  values ( $0.13\text{--}0.48 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), those of three species had moderate  $T_{\text{ag}}$  values ( $0.69\text{--}1.0 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), and those of four species had high  $T_{\text{ag}}$  values ( $2.0\text{--}4.1 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ), with large interspecific differences in  $T_{\text{ag}}$ .

### 3.1.3 Life form and species-level $^{137}\text{Cs}$ $T_{\text{ag}}$ values

From a life-form perspective, both plant species with adhering roots and most epiphytes without adhering roots had high  $^{137}\text{Cs}$   $T_{\text{ag}}$  values (Table S1).

The  $T_{\text{ag}}$  values of the vegetative organs of six adherent woody vine species that have adhering roots that can reach the tree layer (*Hydrangea petiolaris*, *H. hydrangeoides*, *Ficus sarmentosa* subsp. *nipponica*, *Parthenocissus tricuspidata*, *Trachelospermum asiaticum*, and *Hedera rhombea*) were high ( $6.9\text{--}31 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , mean  $14 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , geometric SD 1.64,  $n = 6$ ). Since the  $^{137}\text{Cs}$   $T_{\text{ag}}$  samples of *H. hydrangeoides* in Table S1 included samples collected in summer, when  $^{137}\text{Cs}$  concentrations may increase, the  $T_{\text{ag}}$  value shown above was calculated excluding the samples collected in summer. Similarly, since the  $^{137}\text{Cs}$   $T_{\text{ag}}$  samples of *Parthenocissus tricuspidata* in Table S1 included samples collected in agricultural land, where values may be low, the  $T_{\text{ag}}$  value shown above was calculated excluding the samples from agricultural land. Another four woody vine species (*Akebia quinata*, *A. trifoliata*, *Actinidia arguta* var. *arguta*, *Wisteria floribunda*) had comparable trunk sizes (diameter at breast height  $\geq 5$  cm) to the previous six species (diameter at breast height, 4–8 cm) and reached the tree layer, but did not have adhering roots. The vegetative organs of these four species without adhering roots had moderate  $T_{\text{ag}}$  values ( $1.4\text{--}1.8 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , mean  $1.55 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , geometric SD = 1.12,  $n = 4$ ) that were significantly lower than those of the six species with adhering roots ( $P = 0.011$ ). The vegetative organs of 22 tree species (*Pinus densiflora*, *Chamaecyparis obtusa*, *Cryptomeria japonica*, *Magnolia obovata*, *Robinia pseudoacacia*, *Cerasus speciosa*, *Pyrus pyrifolia*, *Morus australis*, *Fagus japonica*, *Quercus dentata*, *Q. serrata*, *Mallotus japonicus*, *Toxicodendron vernicifluum*, *Acer carpinifolium*, *Phellodendron amurense*, *Melia azedarach*, *Diospyros kaki*, *Chengiopanax sciadophylloides*, *Gamblea innovans*, *Kalopanax septemlobus*, *Alnus firma*, and *Acer maximowiczianum*) had  $T_{\text{ag}}$  values of  $0.27\text{--}44 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$  (mean  $1.80 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , geometric SD = 4.36,  $n = 22$ ) that were not significantly different from those of the four woody vine species without adhering roots ( $P = 0.457$ ).

The  $T_{\text{ag}}$  values of epiphyte species were moderate ( $2.7 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , vegetative organs) for *Phedimus aizoon* var. *floribundus* and high ( $6.3\text{--}20 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , vegetative

organs) for five species (*Selaginella tamariscina*, *Conandron ramondioides*, *Saxifraga fortunei*, *Sedum sarmentosum*, and *Lycopodium clavatum* var. *nipponicum*). Because the  $^{137}\text{Cs}$   $T_{\text{ag}}$  samples of *Phedimus aizoon* var. *floribundus*, *Selaginella tamariscina*, *Conandron ramondioides*, *Sedum sarmentosum*, and *Lycopodium clavatum* var. *nipponicum* in Table S1 included samples collected in summer, when  $^{137}\text{Cs}$  concentrations may increase, their  $T_{\text{ag}}$  values shown above were calculated excluding samples collected in summer.

### 3.1.4 Heterotrophy and species-level $^{137}\text{Cs}$ $T_{\text{ag}}$

The summer annual parasite *Orobanche minor*, which was hosted by *Trifolium pratense* ( $T_{\text{ag}}$   $1.3 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , vegetative organ), had a moderate  $T_{\text{ag}}$  value ( $2.5 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , inflorescence) (Table S1). The summer annual parasite vine of the Convolvulaceae family, *Cuscuta japonica* ( $0.49 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , vegetative organ), which was hosted by *Artemisia indica* var. *maximowiczii* ( $1.6 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , vegetative organ), had a low  $T_{\text{ag}}$  value that was similar to those of three other Convolvulaceae species (*Calystegia hederacea*, *C. pubescens*, and *C. soldanella*) ( $0.40\text{--}0.62 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , vegetative organs) (Table S1).

High  $T_{\text{ag}}$  values were observed in mycoheterotrophic plants [all sexual reproductive organs; *Gastrodia elata* ( $8.0 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) and *Cyrtosia septentrionalis* ( $3.4 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) of family Orchidaceae and *Monotropa uniflora* ( $81 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) and *Monotropastrum humile* ( $26 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) of family Ericaceae] and the partially mycoheterotrophic plants *Cymbidium goeringii* ( $29 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , inflorescences) of family Orchidaceae and *Vaccinium japonicum*, *V. hirtum*, and *V. oldhamii* ( $7.9\text{--}122 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , infructescences) of family Ericaceae (Table S1).

### 3.2 Differences in $^{137}\text{Cs}$ $T_{\text{ag}}$ values among parts

The  $T_{\text{ag}}$  ratios of sexual reproductive organs to vegetative organs (e.g., fruit to current-year branches and leaves) were 0.32–4.0 (mean = 0.96, geometric SD = 1.8, species  $n = 30$ ), with a maximum interspecific difference of approximately 13-fold (Table 1), whereas the  $T_{\text{ag}}$  ratio of leaves to stems and heads of *Equisetum arvense* fertile stems was 2.4 ( $n = 1$ ). The  $T_{\text{ag}}$  ratios of vegetative organs to vegetative organs (e.g., leaf blade to petiole) were 0.37–2.2 (mean = 0.83, geometric SD = 1.9,  $n = 12$ ), with a maximum interspecific difference of approximately 6.0-fold (Table 1). The  $T_{\text{ag}}$  ratios of aboveground to belowground parts were 0.32–1.4 (mean = 0.65, geometric SD = 1.7,  $n = 8$ ), with a 4.4-fold maximum interspecific difference (Table 1). There were no significant differences among the four  $T_{\text{ag}}$  ratios: sexual reproductive organ vs. vegetative organ, sexual reproductive organ vs. sexual reproductive organ, vegetative organ vs. vegetative organ, and

aboveground part vs. belowground part ( $P = 0.115$ ). The mean  $T_{\text{ag}}$  ratio between parts of all 51 pairs was 0.88 (geometric SD = 1.8,  $n = 51$ ) (Table 1).

### 3.3 Multiple regression analysis of species $^{137}\text{Cs}$ $T_{\text{ag}}$ values according to ecological traits

The results of multiple regression analyses of the edible parts of wild photosynthetic species (Dataset A, Table 2a) showed that for vegetative organs, HTc and AdTo were selected in all six cases ( $n \geq 1\text{--}6$  samples per species,  $P < 0.03$  for HTc and  $< 0.01$  for AdTo) and that HM and HTLe were selected in three cases ( $n \geq 1\text{--}3$ ,  $P < 0.11$  and  $< 0.03$ , respectively). For sexual reproductive organs, HTc and LiS were selected in all three cases ( $P < 0.002$  and  $< 0.084$ , respectively). The adjusted coefficients of determination (adjusted  $R^2$ ) of multiple regression analyses were 0.2572–0.3413 for vegetative organs and 0.2050–0.2247 for sexual reproductive organs. The absolute values of the partial correlation coefficients of the selected factors were relatively high for HTc (vegetative organs, 0.295–0.461,  $P < 0.023$ ; sexual reproductive organs, 0.473–0.489,  $P < 0.002$ ) and AdTo (vegetative organs, 0.331–0.407,  $P < 0.01$ ), followed by LiS (sexual reproductive organs, 0.196–0.264,  $P < 0.12$ ); those of all other factors were  $< 0.2$  ( $P < 0.11$ ).

The results for Dataset B (Table 2b) were similar to those for Dataset A. For vegetative organs, HTc and AdTo were selected in all six cases ( $n \geq 1\text{--}6$ ,  $P < 0.001$  and  $< 0.004$ , respectively). HTLe was selected in four cases ( $n \geq 1\text{--}4$ ,  $P < 0.093$ ), HM in three cases ( $n \geq 1\text{--}3$ ,  $P < 0.050$ ), and LiS in two cases ( $n \geq 4$  and  $n \geq 2$ ,  $P < 0.12$ ). In sexual reproductive organs, HTc and LiS were selected in all three cases ( $P < 0.001$  and  $< 0.15$ , respectively). The adjusted  $R^2$  values for multiple regression analysis were 0.2540–0.3562 for vegetative organs and 0.2421–0.2622 for sexual reproductive organs. The absolute values of the partial correlation coefficients of the selected factors were relatively high for HTc (vegetative organs, 0.417–0.487,  $P < 0.0007$ ; sexual reproductive organs, 0.510–0.516,  $P < 0.0003$ ) and AdTo (vegetative organs, 0.360–0.433,  $P < 0.004$ ), followed by LiS (sexual reproductive organs, 0.162–0.217,  $P < 0.16$ ); those of all other factors were  $< 0.2$  ( $P < 0.12$ ).

$^{137}\text{Cs}$   $T_{\text{ag}}$  values tended to be high in forest-habitat species; among vegetative organs,  $T_{\text{ag}}$  values were higher in adhering species. Their partial correlations were weak to moderate. Species with short individual lifespans (i.e., high biomass turnover rate), which experience high habitat temperatures during leaf-growth periods, or in water-rich habitats, tended to have higher  $T_{\text{ag}}$  values; however, their partial correlations were weak or almost negligible. When multiple regression analysis was performed excluding species in wet habitats (data



**Table 1.** <sup>137</sup>Cs T<sub>ag</sub> ratios between intraspecies parts.

Species	<sup>137</sup> Cs T <sub>ag</sub> ratio			n
	Parts for <sup>137</sup> Cs T <sub>ag</sub> ratio	Geometric mean	Geometric standard deviation (T <sub>ag</sub> ratios when n = 2)	
<i>Osmunda japonica</i>	Fertile-leaf stipe/sterile-leaf stipe	0.93	1.1, 0.78	2
<i>Pinus densiflora</i>	Infructescence/current-year shoot	0.84	1.2	3
<i>Zingiber mioga</i>	Inflorescence/shoot	4.0	4.1, 3.9	2
<i>Akebia quinata</i>	Fruit/current-year vine	0.48		1
<i>Akebia trifoliata</i>	Fruit/current-year vine	0.62		1
<i>Vitis flexuosa</i>	Fruit/current-year shoot	1.5		1
<i>Wisteria floribunda</i>	Seed/current-year shoot	0.84		1
<i>Cerasus speciosa</i>	Fruit/leaf	0.32	0.20, 0.51	2
<i>Chaenomeles japonica</i>	Fruit/current-year shoot	1.4	0.98, 1.9	2
<i>Malus toringo</i>	Fruit/current-year shoot	0.90	1.1, 0.94	2
<i>Pyrus pyrifolia</i>	Fruit/leaf	1.5		1
<i>Rubus hirsutus</i>	Fruit/current-year shoot	0.60	3.3	5
<i>Rubus mesogaeus</i> var. <i>mesogaeus</i>	Fruit/current-year shoot	0.60	0.40, 0.88	2
<i>Rubus phoenicolasius</i>	Fruit/current-year shoot	1.6		1
<i>Rubus trifidus</i>	Fruit/current-year shoot	0.85	5.0	3
<i>Ficus erecta</i> var. <i>erecta</i>	Fruit/current-year shoot	0.72	1.3, 0.39	2
<i>Corylus heterophylla</i> var. <i>thunbergii</i>	Fruit/current-year shoot	1.4	2.2, 0.88	2
<i>Trichosanthes cucumeroides</i>	Fruit/shoot	0.69		1
<i>Trichosanthes kirilowii</i> var. <i>japonica</i>	Fruit/current-year shoot	0.51	0.35, 0.75	2
<i>Zanthoxylum piperitum</i>	Fruit/current-year shoot	2.4	1.8, 3.1	2
<i>Diospyros kaki</i>	Fruit/current-year shoot	1.6		1
<i>Actinidia polygama</i>	Fruit gall/current-year shoot	0.62		1
<i>Vaccinium hirtum</i>	Fruit/current-year shoot	1.4	1.4, 1.4	2
<i>Vaccinium japonicum</i>	Fruit/current-year shoot	0.52	0.46, 0.59	2
<i>Alkekengi officinarum</i> var. <i>franchetii</i>	Fruit/current-year shoot	1.00		1
<i>Lycium chinense</i>	Fruit/current-year shoot	1.3	0.80, 2.2	2
<i>Physalistrum echinatum</i>	Fruit/current-year shoot	0.47		1
<i>Petasites japonicus</i>	Inflorescence/leaf	0.60	2.1	7
<i>Chengiopanax sciadophylloides</i>	Infructescence/current-year shoot	1.6	1.3	4
<i>Gamblea innovans</i>	Infructescence/current-year shoot	2.0		1
Subtotal		0.96	1.8	60
<i>Equisetum arvense</i>	Fertile stem leaf/fertile stem without leaf	2.4		1
<i>Osmunda japonica</i>	Lamina/petiole	2.0	1.5	15
<i>Osmundastrum cinnamomeum</i> var. <i>fokiense</i>	Lamina/petiole	1.2	1.5	3
<i>Dioscorea japonica</i>	Propagule/stem and leaf	0.37	0.32, 0.44	2
<i>Phyllostachys edulis</i>	Culm sheath/culm	0.63	1.2, 0.33	2
<i>Phyllostachys nigra</i> var. <i>henonis</i>	Culm sheath/culm	0.58	2.0	3
<i>Phyllostachys reticulata</i>	Culm sheath/culm	0.42	1.2	3
<i>Sasa borealis</i>	Culm sheath/culm	0.79	1.2	3
<i>Sasa kurilensis</i>	Culm sheath/culm	2.2	4.1, 1.2	2
<i>Sasa</i> sp.	Culm sheath/culm	0.40		1
<i>Elatostema involucreatum</i>	Leaf/stem and branch	0.58	1.7	3
<i>Farfugium japonicum</i>	Lamina/petiole	1.3		1
<i>Petasites japonicus</i>	Lamina/petiole	1.4	1.5	65
Subtotal		0.83	1.9	103
<i>Dioscorea japonica</i>	Belowground part/aboveground part	1.4	1.9	4
<i>Dioscorea tokoro</i>	Belowground part/aboveground part	1.4		1
<i>Polygonatum lasianthum</i>	Belowground part/aboveground part	0.47		1
<i>Polygonatum macranthum</i>	Belowground part/aboveground part	0.33		1
<i>Polygonatum odoratum</i> var. <i>pluriflorum</i>	Belowground part/aboveground part	0.42	0.40, 0.45	2
<i>Apios fortunei</i>	Belowground part/aboveground part	0.59	1.5	3
<i>Codonopsis lanceolata</i>	Belowground part/aboveground part	0.57		2
<i>Helianthus tuberosus</i>	Belowground part/aboveground part	0.71	2.3	3
Subtotal		0.65	1.7	17
Total		0.88	1.8	181

not shown), HM was selected in all three cases for sexual reproductive organs in Dataset A. In Dataset B, two cases for vegetative organs ( $n \geq 1-2$ ) and all three cases for sexual reproductive organs were selected. All partial regression coefficients were negative, and species sampled at dry sites tended to have higher  $T_{ag}$  values than those at sites with moderate moisture levels. The partial correlation coefficients varied from 0.106 to 0.263 ( $P < 0.15$ ).

The adjusted  $R^2$  values were maximized at a lower sample number threshold of 1 (Datasets B1 and B2) and 2 (Dataset A1 and A2) (Table 2). The multiple regression equations that maximized the adjusted  $R^2$  values for Dataset A are as follows. Note that sample  $n \geq 2$  for both vegetative and sexual reproductive organs.

$$\ln(^{137}\text{Cs } T_{ag \text{ veg}}) = -10.8 + 0.651 \text{ HTc} + 0.405 \text{ HM} + 0.319 \text{ HTLe} + 1.94 \text{ AdTo} \dots\dots\dots (5)$$

where  $^{137}\text{Cs } T_{ag \text{ veg}}$  indicates the  $T_{ag}$  value for vegetative organs. For Eq. (5),  $P < 0.0001$ ,  $n = 311$ , and adjusted  $R^2 = 0.3413$ .

$$\ln(^{137}\text{Cs } T_{ag \text{ sex}}) = -7.65 + 1.08 \text{ HTc} - 0.348 \text{ LiS} \dots\dots\dots (6)$$

where  $^{137}\text{Cs } T_{ag \text{ sex}}$  indicates the  $T_{ag}$  value for sexual reproductive organs. For Eq. (6),  $P = 0.0001$ ,  $n = 66$ , and adjusted  $R^2 = 0.2247$ .

Eqs. (5, 6) were used to predict species-level  $^{137}\text{Cs } T_{ag}$  values. Some species deviated greatly from the regression line of predicted values for both vegetative organs (Fig. 3a) and sexual reproductive organs (Fig. 3b). For vegetative organs, the observed values of four species—*Umbilicaria esculenta*, *Chengiopanax sciadophylloides*, *Osmundastrum cinnamomeum* var. *fokiense*, and *Gamblea innovans*—were 15- to 40-fold higher than the predicted values. For sexual reproductive organs, the measured values of three species—*Vaccinium hirtum*, *Monotropa uniflora*, and *Buckleya lanceolata*—were 10- to 85-fold higher than the predicted values.

### 3.4 Effect of habitat microtopography on $^{137}\text{Cs } T_{ag}$ values

Among all 28 (herbaceous) species examined, individuals exhibiting *dokonjōyasai*-like growth had greater  $T_{ag}$  values than controls (Fig. 4), with ratios of 1.5–107 and a mean of 14.9 (geometric SD = 3.01). The  $T_{ag}$  values of controls were  $< 5.2$ . Among the 28 species, 19 were open-land species, 6 were forest-edge species, and 3 were forest species.

**Table 2. Factors associated with species-level  $^{137}\text{Cs } T_{ag}$  values and partial correlation coefficients determined through multiple regression analysis.**

<b>a Edible parts of wild<sup>a)</sup> photosynthetic species, Dataset A.</b>									
	Vegetative organs <sup>b)</sup>						Sexual reproductive organs		
Number of samples per sp.	$\geq 6$	$\geq 5$	$\geq 4$	$\geq 3$	$\geq 2$	$\geq 1$	$\geq 3$	$\geq 2$	$\geq 1$
Number of spp.	62	105	181	262	311	327	45	66	68
Partial correlation coefficient									
HTc <sup>c)</sup>	0.295	0.445	0.455	0.429	0.461	0.450	0.478	0.489	0.473
HM <sup>d)</sup>				0.133	0.163	0.143			
LiS <sup>e)</sup>							-0.264	-0.239	-0.196
HTLe <sup>f)</sup>				0.102	0.122	0.119	-	-	-
AdTo <sup>g)</sup>	0.331	0.403	0.374	0.407	0.370	0.400	-	-	-
Multiple regression equation									
$p$	0.000145	5.25E-09	4.85E-14	2.15E-22	1.37E-27	5.13E-29	0.00244	0.000123	0.000216
Adjusted $R^2$	0.2572	0.2984	0.2834	0.3237	0.3413	0.3412	0.2133	0.2247	0.2050
<b>b Edible and non-edible parts of wild<sup>a)</sup> photosynthetic species + non-edible wild<sup>a)</sup> photosynthetic species + edible cultivated plant species, Dataset B.</b>									
	Vegetative organs <sup>b)</sup>						Sexual reproductive organs		
Number of samples per sp.	$\geq 6$	$\geq 5$	$\geq 4$	$\geq 3$	$\geq 2$	$\geq 1$	$\geq 3$	$\geq 2$	$\geq 1$
Number of spp.	64	109	192	278	340	368	49	75	86
Partial correlation coefficient									
HTc <sup>c)</sup>	0.417	0.457	0.474	0.469	0.487	0.468	0.511	0.510	0.516
HM <sup>d)</sup>				0.136	0.107	0.111			
LiS <sup>e)</sup>			-0.114		-0.092		-0.211	-0.217	-0.162
HTLe <sup>f)</sup>			0.135	0.102	0.144	0.109	-	-	-
AdTo <sup>g)</sup>	0.360	0.399	0.375	0.402	0.382	0.433	-	-	-
Multiple regression equation									
$p$	4.92E-05	1.78E-09	2.42E-15	2.99E-25	7.25E-31	1.80E-34	0.000639	1.12E-05	1.23E-06
Adjusted $R^2$	0.2540	0.3033	0.3132	0.3480	0.3534	0.3562	0.2421	0.2513	0.2622

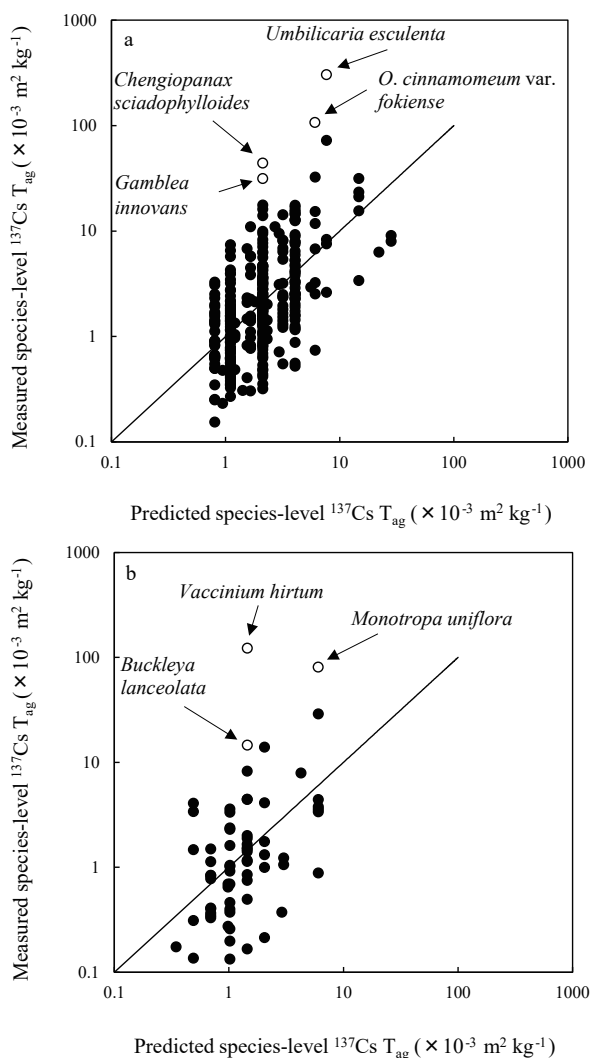
a) When most samples were collected from wild individuals together with some samples from cultivated individuals, the species were treated as wild species; b) Including all parts, aboveground parts, and belowground parts; c) Habitat tree-covering; d) Habitat moisture environment; e) Life span of the individual; f) Habitat temperature during leaf growth; g) Species showing adherence to surfaces such as rock or tree bark.

### 3.5 Effect of habitat fertilization management on <sup>137</sup>Cs T<sub>ag</sub> values

Among all 17 species examined, those growing on agricultural land had lower T<sub>ag</sub> values than controls (Fig. 5), with ratios of 0.039–0.94 and a mean of 0.23 (geometric SD = 2.31). <sup>137</sup>Cs migration was suppressed to approximately 25% on average.

### 3.6 Summer increase or decrease in <sup>137</sup>Cs T<sub>ag</sub> values

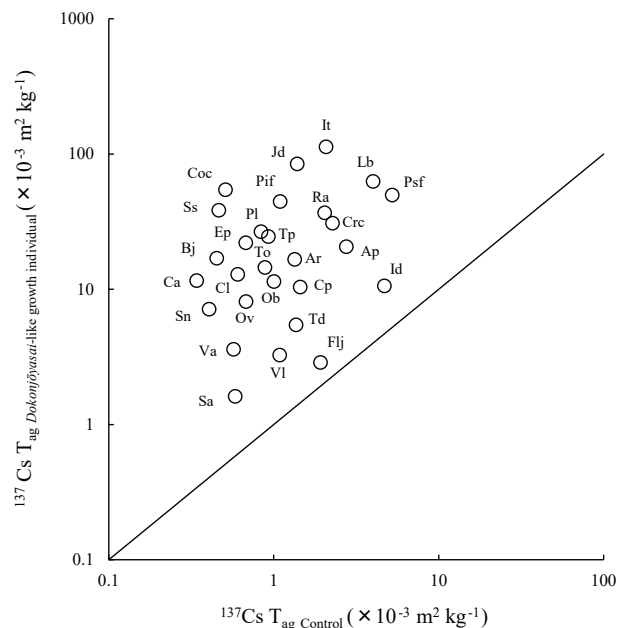
The tendency of T<sub>ag</sub> to increase or decrease in summer varied among species (summer T<sub>ag</sub>/non-summer T<sub>ag</sub> ratio = 0.037–108, mean = 1.08, geometric SD = 3.83; Fig. 6). Overall, there was no bias toward an increase or decrease. Species with small sample sizes (*n* < 3 in either or both of summer and non-summer samples) showed greater variation in T<sub>ag</sub> values.



**Fig. 3. Predicted and measured <sup>137</sup>Cs T<sub>ag</sub> values in edible parts of wild photosynthetic species.**

a, vegetative organs (including all parts, aboveground parts, and belowground parts); b, sexual reproductive organs. The solid lines indicate the cases where predicted and measured <sup>137</sup>Cs T<sub>ag</sub> values are the same.

The ratio of summer T<sub>ag</sub> to non-summer T<sub>ag</sub> values was 1.3 for *Petasites japonicus* leaves and 2.7 for *Osmunda japonica* leaves, in which T<sub>ag</sub> values increased in summer, whereas for *Pteridium aquilinum* subsp. *japonicum* leaves, the ratio was 0.48, in which T<sub>ag</sub> values decreased in summer.



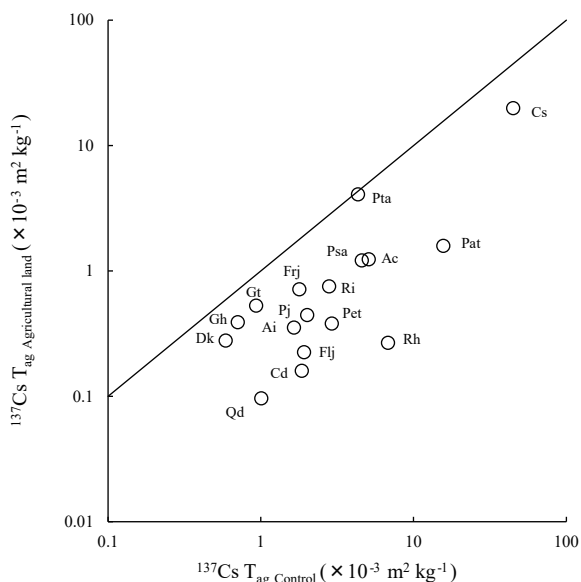
**Fig. 4. <sup>137</sup>Cs T<sub>ag</sub> values of dokonjōyasai-like growth individuals and control individuals.**

Aboveground parts or all parts of *Amaranthus retroflexus* (Ar, dokonjōyasai-like growth individual, *n* = 1; control, *n* = 2), *Chenopodium album*/*C. album* var. *centrorubrum* (Ca, *n* = 1; *n* = 5), *Perilla frutescens* var. *crispa* f. *viridis* (Pif, *n* = 1; *n* = 2), *Stellaria aquatica* (Sa, *n* = 1; *n* = 2), *Stellaria neglecta* (Sn, *n* = 1; *n* = 1), *Brassica juncea* (Bj, *n* = 1; *n* = 3), *Orychophragmus violaceus* (Ov, *n* = 1; *n* = 2), *Cardamine leucantha* (Cl, *n* = 1; *n* = 3), *Oenothera biennis* (Ob, *n* = 4; *n* = 1), *Epilobium pyrricholophum* (Ep, *n* = 1; *n* = 1), *Laportea bulbifera* (Lb, *n* = 1; *n* = 3), *Saxifraga stolonifera* (Ss, *n* = 1; *n* = 1), *Taraxacum denudatum* (Td, *n* = 1; *n* = 2), *Taraxacum platycarpum* var. *platycarpum* (Tp, *n* = 1; *n* = 2), *Taraxacum officinale* (To, *n* = 1; *n* = 6), *Ixeridium dentatum* subsp. *dentatum* (Id, *n* = 1; *n* = 3), *Japonicalia delphiniifolia* (Jd, *n* = 1; *n* = 6), *Crassocephalum crepidioides* (Crc, *n* = 1; *n* = 4), *Angelica pubescens* (Ap, *n* = 1; *n* = 3), *Veronica anagallis-aquatica* (Va, *n* = 1; *n* = 1), *Persicaria longiseta* (Pl, *n* = 2; *n* = 4), *Persicaria filiformis* (Psf, *n* = 1; *n* = 3), *Fallopia japonica* var. *japonica* (Fj, *n* = 3; *n* = 10), *Rumex acetosa* (Ra, *n* = 1; *n* = 6), *Impatiens textorii* (It, *n* = 1; *n* = 1), *Campanula punctata*/*C. punctata* var. *hondoensis* (Cp, *n* = 2; *n* = 7), *Valerianella locusta* (Vl, *n* = 1; *n* = 3), and *Commelina communis* (Coc, *n* = 2; *n* = 3). The solid line indicates the case where <sup>137</sup>Cs T<sub>ag</sub> values of dokonjōyasai-like growth individual and the control are the same.

#### 4. Discussion

##### 4.1 Species growing in forests had high $^{137}\text{Cs}$ $T_{\text{ag}}$ values

Multiple regression analysis showed that  $^{137}\text{Cs}$   $T_{\text{ag}}$  values tended to be low in open-land-habitat species and high in forest-habitat species (Table 2a, b). Fallen leaves tend to accumulate under trees. In forests, biological circulation of  $^{137}\text{Cs}$  occurs (Yamaguchi et al. 2012), such that sedimentary organic matter derived from sources such as tree leaf litter is decomposed by soil microbes,  $^{137}\text{Cs}$  in the O-horizon and soil-surface layer is absorbed by roots and transferred to plants, and this  $^{137}\text{Cs}$  returns to the soil through plant death processes such as defoliation. Fungi that decompose organic matter incorporate radioactive Cs into their bodies along with the K that they require for survival (Kaneko 2018). These mechanisms result in an abundance of  $^{137}\text{Cs}$  in forest-soil organic matter (Toriyama et al. 2018, Manaka et al. 2020) and the long-term presence of  $^{137}\text{Cs}$  in the O-horizon and soil



**Fig. 5**  $^{137}\text{Cs}$   $T_{\text{ag}}$  values of individuals grown on agricultural and unfertilized (control) land.

Current-year shoots of *Rubus hirsutus* (Rh, agricultural land,  $n = 1$ ; control,  $n = 5$ ), *Parthenocissus tricuspidata* (Pat,  $n = 2$ ;  $n = 1$ ), *Diospyros kaki* (Dk,  $n = 1$ ;  $n = 2$ ), and *Chengiopanax sciadophylloides* (Cs,  $n = 1$ ;  $n = 65$ ); leaves of *Quercus dentata* (Qd,  $n = 1$ ;  $n = 3$ ); aboveground parts or all parts of *Pteridium aquilinum* subsp. *japonicum* (Pta,  $n = 9$ ;  $n = 16$ ), *Persicaria thunbergii* (Pet,  $n = 1$ ;  $n = 2$ ), *Fallopia japonica* var. *japonica* (Flj,  $n = 1$ ;  $n = 10$ ), *Glechoma hederacea* subsp. *grandis* (Gh,  $n = 1$ ;  $n = 4$ ), *Geranium thunbergii* (Gt,  $n = 1$ ;  $n = 1$ ), *Cardamine dentipetala* (Cd,  $n = 1$ ;  $n = 4$ ), *Rorippa indica* (Ri,  $n = 3$ ;  $n = 1$ ), *Petasites japonicus* (Pj,  $n = 2$ ;  $n = 43$ ), *Pseudognaphalium affine* (Psa,  $n = 1$ ;  $n = 4$ ), *Artemisia indica* var. *maximowiczii* (Ai,  $n = 1$ ;  $n = 16$ ), *Farfugium japonicum* (Frj,  $n = 1$ ;  $n = 3$ ), and *Aralia cordata* (Ac,  $n = 2$ ;  $n = 6$ ). The solid line indicates the case where  $^{137}\text{Cs}$   $T_{\text{ag}}$  values of individuals grown on agricultural and unfertilized (control) land are the same.

surface. In *Petasites japonicus* communities surveyed in 2014, three years after the 2011 Fukushima nuclear accident (Kiyono and Akama 2015a), organic-matter weight and  $^{137}\text{Cs}$  inventory were approximately three-fold higher in the O-horizon under trees than in that of open land. The five Ericaceae species examined in this study were sampled in forests or forest edges (open land  $n = 0$ , forest edge  $n = 2$ , and forest  $n = 3$ ; Table S1), and therefore considered to have high  $T_{\text{ag}}$  values. Many of the 20 Brassicaceae species examined in this study grew on open land (12, 7, and 1; Table S1), which probably contributed to their low  $T_{\text{ag}}$  values. Among the Urticaceae species investigated in this study, clade I species (2, 2, and 0; Table S1) that grew on open land and at forest edges had low  $T_{\text{ag}}$  values, whereas clade II species (0, 1, and 3; Table S1) that grew at forest edges and in forests had high  $T_{\text{ag}}$  values, and two clade III species (0, 0, and 2; Table S1) that grew in forests had moderate to high  $T_{\text{ag}}$  values. Among these Urticaceae species, the gradient of habitats (open land to forest edge to forest) appeared to correspond roughly to  $T_{\text{ag}}$  levels among phylogenetic groups. Forest plants and their symbiotic fungi absorb nutrients by extending their roots and hyphae into the O-horizon and surface soil. Thus, plants in forests with developed O-horizons may absorb more  $^{137}\text{Cs}$  compared to those growing on open land.

##### 4.2 $^{137}\text{Cs}$ $T_{\text{ag}}$ values were high in adhering photosynthetic species

Multiple regression analysis showed that adhering species tended to have high  $^{137}\text{Cs}$   $T_{\text{ag}}$  values (Table 2a, b). The terrestrial cyanobacterium *Nostoc commune* grows through colony-forming thalli that are weakly attached to open-land soil and rocks. This species retains Cs inside and outside the cell (Sasaki et al. 2016). Because the thallus shrinks as it dries and swells as it absorbs water, it is thought to take up deposits on its surface as well as substances contained in surface water. The three lichen species examined in this study are all epilithic species that grow mainly on rocks in open land. *Stereocaulon* sp. is a symbiote of fungi, green algae, and cyanobacteria (Kashiwadani 1998) that clings to rocks using sympodium and forms fruticose. *Umbilicaria esculenta* has a thallus and sticks to rocks using an umbilicus. *Parmotrema tinctorum* has thalli and clings to rocks using rhizines. Because these epilithic fruticose and foliose lichens do not invade rock crevices with their hyphae (Kawasaki 2010), they are thought to take up nutrients mainly from the body surface (Harada 2019). Thus, *Nostoc commune* and these three lichens are expected to have taken up  $^{137}\text{Cs}$  directly attached to the organisms after the Fukushima nuclear accident together with nutrients. In this study,  $T_{\text{ag}}$  values were moderate ( $2.6 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) for *Nostoc commune* and markedly high for lichens ( $72\text{--}304 \times 10^{-3} \text{ m}^2$

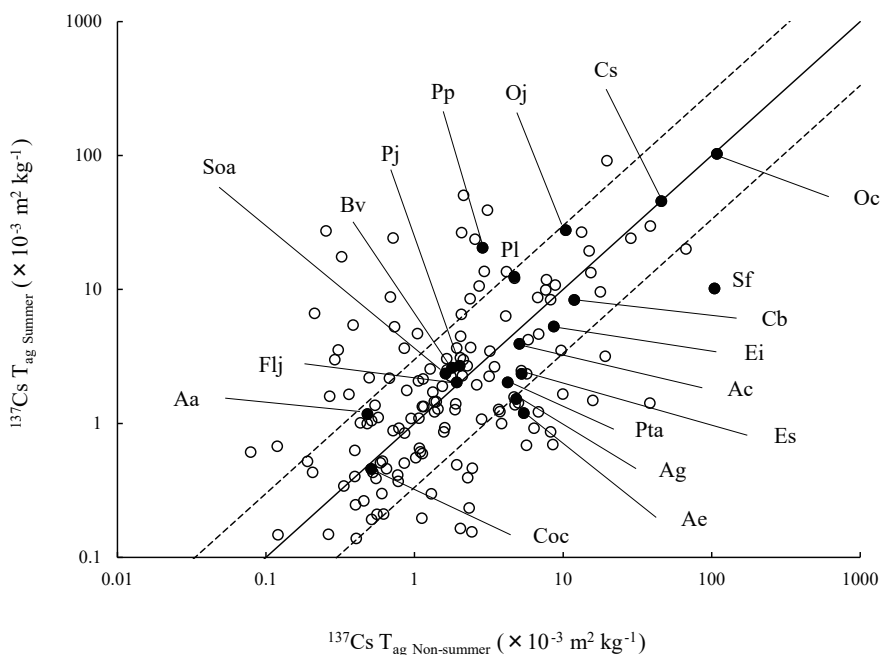


Fig. 6. <sup>137</sup>Cs T<sub>ag</sub> values of individuals collected in summer and other seasons.

● Species with  $n \geq 3$  for both summer and non-summer samples. **Summer T<sub>ag</sub>/non-summer T<sub>ag</sub> ratio > 3:** aboveground parts of *Pilea pumila* (Pp, summer,  $n = 3$ ; non-summer,  $n = 3$ ). **3 ≥ summer T<sub>ag</sub>/non-summer T<sub>ag</sub> ratio ≥ 1/3:** aboveground parts of *Petasites japonicus* (Pj,  $n = 43$ ;  $n = 24$ ), *Osmunda japonicum* (Oj,  $n = 12$ ;  $n = 15$ ), *Pteridium aquilinum* subsp. *japonicum* (Pta,  $n = 3$ ;  $n = 25$ ), *Elatostema involucreatum* (Ei,  $n = 3$ ;  $n = 3$ ), *Solidago altissima* (Soa,  $n = 3$ ;  $n = 3$ ), *Ambrosia artemisiifolia* (Aa,  $n = 3$ ;  $n = 3$ ), *Aralia cordata* (Ac,  $n = 3$ ;  $n = 6$ ), *Botrychium virginianum* (Bv,  $n = 3$ ;  $n = 6$ ), *Osmundastrum cinnamomeum* var. *fokiense* (Oc,  $n = 9$ ;  $n = 25$ ), *Persicaria longisetata* (P1,  $n = 4$ ;  $n = 4$ ), *Fallopia japonica* var. *japonica* (Fj,  $n = 5$ ;  $n = 10$ ), and *Commelina communis* (Coc,  $n = 3$ ;  $n = 3$ ); current-year shoots of *Eleutherococcus spinosus* (Es,  $n = 3$ ;  $n = 3$ ), *Chengiopanax sciadophyloides* (Cs,  $n = 22$ ;  $n = 65$ ), and *Clethra barbinervis* (Cb,  $n = 5$ ;  $n = 18$ ). **1/3 > summer T<sub>ag</sub>/non-summer T<sub>ag</sub> ratio:** aboveground parts of *Saxifraga fortunei* (Sf,  $n = 3$ ;  $n = 4$ ) and *Aster glehnii* (Ag,  $n = 3$ ;  $n = 4$ ), and current-year shoots of *Aralia elata* (Ae,  $n = 4$ ;  $n = 22$ ).

○ Species with  $n < 3$  in either or both of summer and non-summer samples. **Summer T<sub>ag</sub>/non-summer T<sub>ag</sub> ratio > 3:** infructescences of *Orobancha minor* ( $n = 1$ ;  $n = 1$ ); infructescences of *Morus australis* ( $n = 4$ ;  $n = 1$ ), *Zanthoxylum schinifolium* ( $n = 7$ ;  $n = 2$ ), *Lonicera gracilipes* var. *gracilipes*/L. *gracilipes* var. *glabra* ( $n = 4$ ;  $n = 2$ ), and *Actinidia arguta* var. *arguta* ( $n = 2$ ;  $n = 1$ ); current-year shoots of *Malus toringo* ( $n = 1$ ;  $n = 2$ ), *Staphylea japonica* ( $n = 1$ ;  $n = 2$ ), *Pinus densiflora* ( $n = 2$ ;  $n = 1$ ), and *Cryptomeria japonica* ( $n = 1$ ;  $n = 7$ ); aboveground parts of *Mentha canadensis* ( $n = 1$ ;  $n = 1$ ), *Polygonatum involucreatum* ( $n = 1$ ;  $n = 3$ ), *Cirsium comosum* ( $n = 3$ ;  $n = 1$ ), *Ligularia dentata* ( $n = 2$ ;  $n = 2$ ), *Humulus scandens* ( $n = 4$ ;  $n = 2$ ), *Cryptotaenia canadensis* subsp. *japonica* ( $n = 1$ ;  $n = 5$ ), *Ostericum sieboldii* ( $n = 2$ ;  $n = 3$ ), *Vicia villosa* subsp. *varia* ( $n = 1$ ;  $n = 2$ ), *Vicia unijuga* ( $n = 2$ ;  $n = 3$ ), *Persicaria lapathifolia* var. *lapathifolia* ( $n = 2$ ;  $n = 3$ ), *Persicaria hydropiper* ( $n = 2$ ;  $n = 1$ ), *Phedimus aizoon* var. *floribundus* ( $n = 3$ ;  $n = 1$ ), *Codonopsis lanceolata* ( $n = 1$ ;  $n = 1$ ), and *Allium tuberosum* ( $n = 2$ ;  $n = 1$ ); aboveground parts or whole plants of *Epilobium pyrricholophum* ( $n = 1$ ;  $n = 1$ ); whole plants of *Lycopodium mackianus* ( $n = 1$ ;  $n = 1$ ) and *Spuriopimpinella calycina* ( $n = 2$ ;  $n = 2$ ); post-3.11 aboveground parts of *Lycopodium clavatum*

var. *nipponicum* ( $n = 1$ ;  $n = 8$ ). **3 ≥ summer T<sub>ag</sub>/non-summer T<sub>ag</sub> ratio ≥ 1/3:** infructescences of *Elaeagnus multiflora* var. *multiflora*/E. *multiflora* var. *gigantea* ( $n = 4$ ;  $n = 1$ ), *Vaccinium oldhamii* ( $n = 1$ ;  $n = 4$ ), *Pyrus pyrifolia* (2, 1), *Cerasus speciosa* ( $n = 1$ ;  $n = 1$ ), *Vitis ficifolia* ( $n = 1$ ;  $n = 3$ ), *Zanthoxylum piperitum* ( $n = 3$ ;  $n = 2$ ), and *Cornus kousa* subsp. *kousa* ( $n = 1$ ;  $n = 1$ ); fruit galls of *Actinidia polygama* ( $n = 1$ ;  $n = 2$ ); seeds of *Firmiana simplex* ( $n = 1$ ;  $n = 2$ ); inflorescences of *Monotropastrum humile* ( $n = 3$ ;  $n = 2$ ), *Gastrodia elata* ( $n = 2$ ;  $n = 1$ ), and *Zingiber mioga* ( $n = 2$ ;  $n = 2$ ); leaves of *Athyrium crenuloserrulatum* ( $n = 2$ ;  $n = 4$ ) and *Conandron ramondioides* ( $n = 2$ ;  $n = 1$ ); post-3.11 leaves of *Selaginella tamariscina* ( $n = 2$ ;  $n = 1$ ); aboveground parts of *Causonis japonica* ( $n = 1$ ;  $n = 3$ ), *Trichosanthes kirilowii* var. *japonica* ( $n = 2$ ;  $n = 3$ ), *Amaranthus retroflexus* ( $n = 2$ ;  $n = 1$ ), *Amaranthus blitum* ( $n = 1$ ;  $n = 1$ ), *Chenopodium album*/C. *album* var. *centrorubrum* ( $n = 5$ ;  $n = 1$ ), *Achyranthes bidentata* var. *japonica* ( $n = 2$ ;  $n = 2$ ), *Lamium album* var. *barbatum* ( $n = 1$ ;  $n = 5$ ), *Elatostema laetevirens* ( $n = 2$ ;  $n = 1$ ), *Boehmeria gracilis* ( $n = 2$ ;  $n = 1$ ), *Boehmeria nivea* var. *concolor* f. *nipponivea* ( $n = 4$ ;  $n = 1$ ), *Laportea cuspidata* ( $n = 1$ ;  $n = 3$ ), *Polygonatum odoratum* var. *pluriflorum* ( $n = 1$ ;  $n = 4$ ), *Polygonatum macranthum* ( $n = 2$ ;  $n = 3$ ), *Polygonatum falcatum* ( $n = 1$ ;  $n = 2$ ), *Taraxacum officinale* ( $n = 2$ ;  $n = 6$ ), *Erigeron annuus* ( $n = 2$ ;  $n = 1$ ), *Aster yomena* var. *dentatus* ( $n = 1$ ;  $n = 1$ ), *Aster iinuma* ( $n = 2$ ;  $n = 3$ ), *Aster microcephalus* var. *ovatus* ( $n = 2$ ;  $n = 13$ ), *Parasenecio aidzuensis* ( $n = 1$ ;  $n = 2$ ), *Ligularia stenocephala* ( $n = 2$ ;  $n = 3$ ), *Ixeridium dentatum* subsp. *nipponicum* var. *albiflorum* f. *amplifolium* ( $n = 1$ ;  $n = 1$ ), *Crepidiastrum denticulatum* ( $n = 1$ ;  $n = 6$ ), *Senecio cannabifolius* ( $n = 1$ ;  $n = 8$ ), *Atractylodes ovata* ( $n = 3$ ;  $n = 1$ ), *Carpesium abrotanoides* ( $n = 2$ ;  $n = 1$ ), *Syneilesis palmata* ( $n = 2$ ;  $n = 6$ ), *Crassocephalum crepidioides* ( $n = 4$ ;  $n = 1$ ), *Xanthium occidentale* ( $n = 1$ ;  $n = 1$ ), *Artemisia indica* var. *maximowiczii* ( $n = 1$ ;  $n = 15$ ), *Angelica keiskei* ( $n = 1$ ;  $n = 3$ ), *Angelica japonica* ( $n = 3$ ;  $n = 1$ ), *Hydrocotyle ramiflora* ( $n = 2$ ;  $n = 1$ ), *Saururus chinensis* ( $n = 1$ ;  $n = 1$ ), *Persicaria neofiliformis* ( $n = 2$ ;  $n = 2$ ), *Persicaria filiformis* ( $n = 1$ ;  $n = 3$ ), *Fallopia japonica* var. *japonica* ( $n = 1$ ;  $n = 3$ ), *Rumex acetosa* ( $n = 1$ ;  $n = 6$ ), *Metaplexis japonica* ( $n = 4$ ;  $n = 1$ ), *Sambucus chinensis* ( $n = 2$ ;  $n = 1$ ), *Comfrey Symphytum* × *uplandicum* ( $n = 3$ ;  $n = 2$ ), *Epimedium grandiflorum* var. *thunbergianum*

( $n = 3$ ;  $n = 1$ ), *Adenophora remotiflora* ( $n = 1$ ;  $n = 4$ ), *Imperata cylindrica* var. *koenigii* ( $n = 2$ ;  $n = 2$ ), *Phyllostachys reticulata* ( $n = 2$ ;  $n = 1$ ), *Calystegia pubescens* ( $n = 2$ ;  $n = 3$ ), and *Pollia japonica* ( $n = 2$ ;  $n = 1$ ); post-3.11 aboveground parts of *Selaginella remotifolia* ( $n = 1$ ;  $n = 4$ ); aboveground parts or all parts of *Perilla frutescens* var. *crispa* f. *viridis* ( $n = 2$ ;  $n = 1$ ), *Geranium thunbergii* ( $n = 1$ ;  $n = 6$ ), *Nasturtium officinale* ( $n = 1$ ;  $n = 5$ ), *Polygonatum lasianthum* ( $n = 1$ ;  $n = 1$ ), *Parasenecio maximowiczianus* ( $n = 4$ ;  $n = 1$ ), *Synurus pungens* ( $n = 2$ ;  $n = 4$ ), and *Nemosenecio nikoensis* ( $n = 2$ ;  $n = 1$ ); all parts of *Viola rossii* ( $n = 2$ ;  $n = 1$ ), *Aster scaber* ( $n = 1$ ;  $n = 4$ ), and *Monochoria vaginalis* ( $n = 2$ ;  $n = 1$ ); belowground parts of *Helianthus tuberosus* ( $n = 2$ ;  $n = 1$ ), *Apios fortunei* ( $n = 1$ ;  $n = 2$ ), *Dioscorea tokoro* ( $n = 2$ ;  $n = 1$ ), and *Dioscorea japonica* ( $n = 4$ ;  $n = 2$ ); current-year shoots of *Vitis flexuosa* ( $n = 1$ ;  $n = 3$ ), *Phellodendron amurense* ( $n = 2$ ;  $n = 6$ ), *Diospyros kaki* ( $n = 2$ ;  $n = 2$ ), *Mentha suaveolens* ( $n = 1$ ;  $n = 1$ ), *Hydrangea hydrangeoides* ( $n = 2$ ;  $n = 11$ ), *Hydrangea hirta* ( $n = 3$ ;  $n = 1$ ), *Hydrangea paniculata* ( $n = 1$ ;  $n = 3$ ), *Myriophyllum aquaticum* ( $n = 1$ ;  $n = 1$ ), *Carica papaya* ( $n = 1$ ;  $n = 1$ ), and *Sedum sarmentosum* ( $n = 3$ ;  $n = 2$ ). **1/3 > summer T<sub>ag</sub>/non-summer T<sub>ag</sub> ratio:** Fruits of *Rubus palmatus* var. *coptophyllus* ( $n = 1$ ;  $n = 2$ ); infructescences of *Rosa rugosa* ( $n = 1$ ;  $n = 1$ ); current-year shoots of *Rubus hirsutus* ( $n = 1$ ;  $n = 5$ ), *Vaccinium japonicum* ( $n = 1$ ;  $n = 2$ ), and *Gamblea innovans* ( $n = 2$ ;  $n = 6$ ); aboveground parts or all parts of *Physaliastrum echinatum* ( $n = 3$ ;  $n = 1$ ), *Trichosanthes cucumeroides* ( $n = 2$ ;  $n = 1$ ), *Prunella vulgaris* subsp. *asiatica* ( $n = 2$ ;  $n = 3$ ), *Lycopus lucidus* ( $n = 2$ ;  $n = 1$ ), *Saxifraga stolonifera* ( $n = 1$ ;  $n = 4$ ), *Polygonatum humile* ( $n = 1$ ;  $n = 1$ ), *Solidago virgaurea* subsp. *asiatica* ( $n = 1$ ;  $n = 6$ ), *Chamaecrista nomame* ( $n = 1$ ;  $n = 2$ ), *Trifolium pratense* ( $n = 1$ ;  $n = 3$ ), *Zizania latifolia* ( $n = 1$ ;  $n = 4$ ), *Matteuccia struthiopteris* ( $n = 1$ ;  $n = 5$ ), *Lysichiton camtschatcensis* ( $n = 1$ ;  $n = 1$ ), *Smilax riparia* ( $n = 2$ ;  $n = 2$ ), *S. nipponica* ( $n = 1$ ;  $n = 4$ ), *Platycodon grandiflorus* ( $n = 2$ ;  $n = 1$ ), and *Heremacallis citrina* var. *vespertina* ( $n = 1$ ;  $n = 3$ ); and all parts of *Allium sativum* ( $n = 1$ ;  $n = 1$ ). The solid line indicates the case where <sup>137</sup>Cs T<sub>ag</sub> values of individuals collected in summer and other seasons are the same; the dashed lines show the cases where the summer T<sub>ag</sub> values are 3 times (top) and 1/3 (bottom) of the non-summer T<sub>ag</sub> values.

kg<sup>-1</sup>). The lifespan of *Nostoc commune* colonies under natural conditions is unclear (Sand-Jensen 2014). Lichens are reported to be long-lived and to retain Cs for long periods (Calmon et al. 2009, Suno et al. 2021).

*Hydrangea petiolaris* and *H. hydrangeoides*, which have adhering roots and climb trunks and rock walls, have been reported to have high <sup>137</sup>Cs concentrations (Kiyono and Akama 2013). In this study, we also found that their <sup>137</sup>Cs T<sub>ag</sub> values were high. The T<sub>ag</sub> values of the other four species with adhering roots (*Ficus sarmentosa* subsp. *nipponica*, *Parthenocissus tricuspidata*, *Trachelospermum asiaticum*, and *Hedera rhombea*) were also generally high. Such species attach their adhering roots to bark, humus, lichens, and mosses, which were directly affected by radioactive material released by the Fukushima nuclear accident, and they may therefore have taken up more <sup>137</sup>Cs than plants without adhering roots through the ready absorption of water-soluble components dissolved in water flowing down bark and rocks. Six epiphyte species (*Saxifraga fortunei*, *Selaginella tamariscina*, *Conandron ramondoides*, *Sedum sarmentosum*, *Phedimus aizoon* var. *floribundus*, and *Lycopodium clavatum* var. *nipponicum*) mostly had high T<sub>ag</sub> values. Epiphytes spread their roots on rocks and ground surfaces where humus is scarce, and absorb nutrients from small amounts of humus, rainwater, condensed water, and splashes of river water. Thus, epiphytes are likely to have absorbed water-soluble <sup>137</sup>Cs that migrated with water over rocks and ground, similar to plants with adhering roots.

#### 4.3 Time required for biomass replacement, habitat moisture environment, and habitat temperature during leaf growth may not greatly affect <sup>137</sup>Cs T<sub>ag</sub> values

Multiple regression analysis showed that species with low biomass turnover rates tended to have low T<sub>ag</sub> values (Table 2a, b). T<sub>ag</sub> values tended to be high in species that grew in water-rich habitats (Table 2a, b); when only species from habitats with low and moderate moisture levels were analyzed, the former tended to have higher T<sub>ag</sub> values. Although only vegetative organ data were available for this analysis, species from habitats with high temperatures during leaf growth tended to have high T<sub>ag</sub> values (Table 2a, b). However, the maximum partial correlation coefficients were 0.264 for LiS and < 0.2 for HM and the HTLe, indicating weak relationships with T<sub>ag</sub>.

We concluded that T<sub>ag</sub> values were low in species with low biomass turnover rates for the following reason. The time required for all the biomass to be replaced (turnover rate<sup>-1</sup>) is 0.5–0.6 years for *Petasites japonicus* (Kiyono et al. 2018a), approximately 0.5 years for *Pteridium aquilinum* subsp. *japonicum* (Kiyono et al. 2021b), and 1.4 and 5.7 years for *Osmunda japonica* (Kiyono et al. 2018b). For trees, the reciprocal of the biomass turnover rate can be estimated as

$[(\text{biomass } T_0 + \text{biomass } T_1)/2]/[(\text{biomass gain } T_{0-1} + \text{biomass loss } T_{0-1})/2]$ . Thus, using aboveground biomass data for natural broadleaf forests in Cambodia (Kiyono et al. 2017) as an example, the mean lifespan was calculated to be 45 years (range = 8–305 years, stand  $n = 63$ ). Trees replace biomass more slowly than do perennial herbs. <sup>137</sup>Cs values would tend to balance between an organism and its surrounding environment rapidly in species with high biomass turnover rates and slowly in species with low biomass turnover rates. Therefore, we reasoned that at the time of this study, which was conducted several years after the Fukushima accident, trees would not have reached a balanced <sup>137</sup>Cs distribution, which explains their low T<sub>ag</sub> values.

Regarding the high T<sub>ag</sub> values of water-rich habitat species, radiocesium concentrations in edible wild plants were high at 1–2 years after the Fukushima nuclear accident in areas where surface water and groundwater tended to collect, such as depressions and valley-shaped terrain; however, this trend was obscured at 4–6 years after the accident (Kiyono et al. 2021a). In this study, data obtained at 4–8 years after the accident for comparisons between species from dry, moderate, and wet sites showed little relationship and, in some cases, relatively wet sites had higher T<sub>ag</sub> values (partial correlation coefficient = 0.107–0.163, Table 2). However, when species from dry and moderate sites were compared, T<sub>ag</sub> values were sometimes higher in species from dry sites (partial correlation coefficient = 0.104–0.240); this trend is consistent with the higher <sup>137</sup>Cs T<sub>ag</sub> values obtained in samples from upper slopes than in those from lower slopes in 1-year-old *Quercus serrata* trees planted in 2017, six years after the accident (Saito 2020). Because O-horizons develop well on dry sites (upper slopes), we conclude that <sup>137</sup>Cs often remains in the O-horizon and the soil surface immediately below it, and migrates to plants through roots and symbiotic organisms. We also hypothesize that, as time passed after the accident, the movement of water-soluble <sup>137</sup>Cs, which migrates easily to plants, stopped, and <sup>137</sup>Cs effects became noticeable in sedimentary organic matter.

The correlation between the amount of water absorbed by *Cryptomeria japonica* seedlings and the amount of <sup>137</sup>Cs transferred through roots (Ohashi 2017) provides a possible explanation for the effects of temperature during leaf growth on <sup>137</sup>Cs T<sub>ag</sub>. At high temperatures, evapotranspiration from organism surfaces becomes active, and more water is taken up through roots and other mechanisms. Depending on the amount of water absorbed, a corresponding amount of <sup>137</sup>Cs would remain in the organism after the water evaporates. However, even in woody vines with 2–4-fold greater sap flux than trees (Ichihashi et al. 2017), there were no significant differences in T<sub>ag</sub> values between those without adhering roots and tree species; thus, differences in evapotranspiration may not have

had a large effect on  $T_{\text{ag}}$  values in the species targeted in this study.

#### 4.4 $^{137}\text{Cs}$ $T_{\text{ag}}$ values appear to reflect $^{137}\text{Cs}$ uptake by symbiotic species in parasitic and mycoheterotrophic plants

Parasitic plants absorb nutrients from the living tissues of their host. The  $T_{\text{ag}}$  values (Table S1) of the parasitic Convolvulaceae plant, *Cuscuta japonica* ( $0.49 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , vegetative organ), were not significantly different from those of its host, *Artemisia indica* var. *maximowiczii* ( $1.6 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , vegetative organ); and the  $T_{\text{ag}}$  values of the parasitic plant *Orobanche minor* ( $2.5 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , sexual reproductive organ) were not significantly different from those of its host, *Trifolium pratense* ( $1.3 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , vegetative organs).

The  $T_{\text{ag}}$  values of mycoheterotrophic plants in this study were high [all sexual reproductive organs; *Gastrodia elata* ( $8.0 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) and *Cyrtosia septentrionalis* ( $3.4 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) of the family Orchidaceae and *Monotropa uniflora* ( $81 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) and *Monotropastrum humile* ( $26 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) of the family Ericaceae] (Table S1). *Gastrodia elata* and *Cyrtosia septentrionalis* live in symbiosis with wood-decay fungi (*Armillaria* spp.) and other species (Yamato and Yagame 2009, Umata et al. 2013, Xu and Mu 1990). Two Ericaceae species, *Monotropa uniflora* and *Monotropastrum humile*, live in symbiosis with Russulaceae fungi and other fungi such as ectomycorrhizae (Bidartondo 2005, Yokoyama et al. 2013). Wood-decay fungi obtain carbon mainly from dead wood, whereas ectomycorrhizal fungi obtain carbon from living plants (Suetsugu et al. 2020). Although the  $^{137}\text{Cs}$   $T_{\text{ag}}$  values of symbiotic fungi are unknown,  $^{137}\text{Cs}$  concentrations tend to be greater in ectomycorrhizal fungi than in wood-rotting fungi (Komatsu et al. 2019), which agrees with the relative  $^{137}\text{Cs}$   $T_{\text{ag}}$  values of mycoheterotrophic fungi in Orchidaceae and Ericaceae. In mycoheterotrophic plants,  $^{137}\text{Cs}$  is thought to migrate from the O-horizon and surface soil (for wood-rotting fungi, also from dead and live wood) to symbiotic fungi and then to mycoheterotrophic plants. When  $^{137}\text{Cs}$  is abundant in organic matter near the ground surface (Toriyama et al. 2018, Manaka et al. 2020), it is likely that large amounts of  $^{137}\text{Cs}$  are retained by fungal cells in the O-horizon and surface soil and subsequently taken up by mycoheterotrophic plants from host fungi. However, because *Cyrtosia septentrionalis* and *Gastrodia elata* have distinct roots that contact the soil, some  $^{137}\text{Cs}$  may be absorbed directly from these roots. High  $T_{\text{ag}}$  values (Table S1) were also obtained for the partially mycoheterotrophic plant *Cymbidium goeringii* ( $29 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , inflorescences) of the family Orchidaceae, which lives in symbiosis with Russula ectomycorrhizal fungi (Motomura et al. 2010) and for *Vaccinium japonicum*, *V. hirtum*, and *V.*

*oldhamii* ( $7.9\text{--}122 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , inflorescences) of family Ericaceae, which live in symbiosis with Ericoid mycorrhizas (Akema 2022). Three *Vaccinium* species (Ericaceae) in parts of the former Union of Soviet Socialist Republics affected by the Chernobyl accident had high  $T_{\text{ag}}$  values ( $30\text{--}120 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ , fruits) (Beresford et al. 2001). *Calluna vulgaris* (Ericaceae) contributes to high  $^{137}\text{Cs}$  concentrations in honey (Molzahn and Assmann-Werthmüller 1993) and had rather high  $T_{\text{ag}}$  values ( $25\text{--}241 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}$ ) in twigs at 12 years after the Chernobyl accident (Moberg et al. 1999). These values were comparable to those of the Ericaceae species examined in this study. Thus, high  $^{137}\text{Cs}$   $T_{\text{ag}}$  values may be characteristic of some Ericaceae species. The high  $T_{\text{ag}}$  values detected in mycoheterotrophic plants may be the result of  $^{137}\text{Cs}$  uptake together with nutrients from symbiotic mycorrhizae with high  $^{137}\text{Cs}$  absorption ability.

The adjusted coefficients of determination of Eqs. (5, 6) in the model used to predict species-level  $^{137}\text{Cs}$   $T_{\text{ag}}$  values were 0.2247 and 0.3413 (Table 2), which are insufficient for accurate prediction. One reason for these low  $R^2$  values is the presence of species that deviated greatly from the regression line (Fig. 3). The  $T_{\text{ag}}$  values of *Monotropa uniflora* and *Vaccinium hirtum* are likely to have increased due to the effect of symbiotic mycorrhizal fungi. However, in our multiple regression analysis, information on symbiotic mycorrhizal fungi was scarce and their effects were not considered, which reduced the prediction accuracy of the equations. It has been suggested that endophytic bacteria in roots facilitate absorption of  $^{137}\text{Cs}$  by *Chengiopanax sciadophylloides* (Yamaji et al. 2016). *Buckleya lanceolata* is a semi-parasitic plant in the family Santalaceae that has a high  $T_{\text{ag}}$  value, which is likely to be due to the influence of its hosts (e.g., *Abies firma*, *Pieris japonica* subsp. *japonica*, *Acer rufinerve*). It remains unknown why the  $T_{\text{ag}}$  values of *Umbilicaria esculenta*, *Osmundastrum cinnamomeum* var. *fokiense*, and *Gamblea innovans* were significantly higher than expected. Species with  $T_{\text{ag}}$  values that deviate markedly from predictions imply the involvement of factors that are not yet considered in the prediction model. Future studies should evaluate the effects of adding nutrient-dependence information for symbiotic species.

#### 4.5 Summer $^{137}\text{Cs}$ $T_{\text{ag}}$ fluctuations may depend on species phenology

Our comparisons of individuals collected in summer and in other seasons indicated that some species had high summer  $T_{\text{ag}}$  values and others had low summer  $T_{\text{ag}}$  values; however, we identified no clear trend across all species. In *Osmunda japonica* (Kiyono et al. 2018b) and *Petasites japonicus* (Kiyono et al. 2018a), which had higher leaf  $^{137}\text{Cs}$  concentrations in summer,  $T_{\text{ag}}$  values were higher in summer (Fig. 6). In *Pteridium aquilinum* subsp. *japonicum* (Kiyono et al. 2021b),

which had lower leaf  $^{137}\text{Cs}$  concentrations in summer,  $T_{\text{ag}}$  values were lower in summer (Fig. 6). These trends were consistent with those of the  $^{137}\text{Cs}$  concentrations reported in previous studies on *Osmunda japonica*, *Petasites japonicus*, and *Pteridium aquilinum* subsp. *japonicum*; therefore, we conclude that these diverse changes in summer  $T_{\text{ag}}$  values (Fig. 6) may reflect trait diversity among species. In *Petasites japonicus* and *Osmunda japonica*, decomposition of forest soil organic matter may be accelerated in summer due to higher temperatures and root absorption of increased exchangeable  $^{137}\text{Cs}$  (Kobayashi 2013, Burger and Lichtscheidl 2018). By contrast, seasonal increases in biomass and delayed  $^{137}\text{Cs}$  uptake may reduce  $^{137}\text{Cs}$  concentrations in the plant body (Bunzl and Kracke 1989), which may explain the summer declines in  $T_{\text{ag}}$  values. However, the number of species in which growth seasonality has been observed is extremely limited. To investigate the causes of interspecies  $T_{\text{ag}}$  diversity sufficiently, the phenology of each species must be elucidated.

#### 4.6 Individuals exhibiting *dokonjōyasai*-like growth had high $^{137}\text{Cs}$ $T_{\text{ag}}$ values and those growing on fertilized land had low $^{137}\text{Cs}$ $T_{\text{ag}}$ values

Even within species,  $^{137}\text{Cs}$   $T_{\text{ag}}$  values tended to be higher in individuals exhibiting *dokonjōyasai*-like growth and lower in those growing in fertilized soil such as agricultural land (Figs. 4, 5). Plants exhibiting *dokonjōyasai*-like growth utilize water and soluble components that flow downward to collect on hard, low-permeability soil surfaces that can flood after heavy rain, causing soil and humus to drift and accumulate around these individuals. However, such soil and humus are unstable and can be carried away by heavy rainfall or by human actions. Because there is little soil in such cases, only small amounts of water-soluble  $^{137}\text{Cs}$  separated from organic matter will be fixed in clay minerals. Therefore, in  $^{137}\text{Cs}$  inventory estimates based on the air-dose rate, the  $^{137}\text{Cs}$  values for individuals exhibiting *dokonjōyasai*-like growth are likely to tend toward high proportions of  $^{137}\text{Cs}$  easily absorbed by plants. Individuals showing *dokonjōyasai*-like growth appear to absorb more  $^{137}\text{Cs}$  than do normal plants, resulting in higher  $T_{\text{ag}}$  values.

Because Cs and K compete for root uptake, Cs transfer to plants is suppressed in farmland with high K content due to fertilization (Kobayashi 2013). Even under natural conditions,  $^{133}\text{Cs}$  concentrations in *Chengiopanax sciadophylloides* shoots decrease in soils rich in exchangeable K (Kiyono et al. 2019b). One reason for the low  $T_{\text{ag}}$  values in individual plants grown on farmland among all 17 plant species investigated in this study (Fig. 5) was the large inventory of exchangeable K in the soil. Another possible reason is that farmland soils typically contain less organic carbon than forest soils, and therefore, less easily absorbed Cs (Hashimoto et al. 2021). The habitat

$^{137}\text{Cs}$  inventory used to calculate  $T_{\text{ag}}$  at multiple points in this study was estimated from ADR. This method was suitable for our purpose; however, the resulting  $^{137}\text{Cs}$  inventory does not distinguish between forms that are easily absorbed by plants (e.g., exchange forms) and those that are difficult to absorb (e.g., those fixed in clay). Changes in these forms in response to the environment should be examined in a future study.

#### 4.7 In mixed-species communities, individual $^{137}\text{Cs}$ concentrations can be influenced by species composition

Cs is not an essential element for plants (Marschner 1995) and is not actively recovered from leaves when they abscise (Akama and Kiyono 2016, Kiyono et al. 2021b). For this reason, most of the  $^{137}\text{Cs}$  contained in dead plant parts, such as fallen leaves, is released outside the plant body. This  $^{137}\text{Cs}$  is absorbed by roots in the O-horizon and soil-surface layers during litter decomposition, and is transferred to plants. Fine roots of *Cryptomeria japonica* that invade the dead stems of *Osmundastrum cinnamomeum* var. *fokiense* have shown very high  $T_{\text{ag}}$  values. Even *C. japonica*, which has a low  $^{137}\text{Cs}$  absorptive ability (Table S1), was shown to absorb large amounts of  $^{137}\text{Cs}$  by growing roots into dead *O. cinnamomeum* var. *fokiense*, which has a high Cs absorptive ability. In a heterogeneous community, individual  $^{137}\text{Cs}$  concentrations can change due to the influence of neighboring species. A 5-year follow-up survey of  $^{137}\text{Cs}$  concentrations in 19 edible wild-plant species in a heterogeneous community, from the spring of 2012 (Kiyono and Akama 2018, Komatsu and Kiyono 2021), revealed that two species with increased  $^{137}\text{Cs}$  concentrations (*Chengiopanax sciadophylloides* and *Osmundastrum cinnamomeum* var. *fokiense*) had a high ability to absorb  $^{137}\text{Cs}$ , whereas 13 species with decreased concentrations (*Matteuccia struthiopteris*, *Aralia cordata*, *A. elata*, *Sambucus racemosa* subsp. *sieboldiana*, *Akebia trifoliata*, *Clethra barbinervis*, *Petasites japonicus*, *Erythronium japonicum*, *Artemisia indica* var. *maximowiczii*, *Pteridium aquilinum* subsp. *japonicum*, *Fallopia japonica* var. *japonica*, *Aster microcephalus* var. *ovatus*, and *Syneilesis palmata*) showed a lower ability to absorb  $^{137}\text{Cs}$ , and four other species that showed no clear concentration change (*Hydrangea petiolaris*, *H. hydrangeoides*, *Osmunda japonica*, and *Helwingia japonica*) exhibited an intermediate ability. This finding implies the following process: plant species with low  $^{137}\text{Cs}$  absorption ability absorb less  $^{137}\text{Cs}$  as they excrete through shedding dead plant parts; as a result,  $^{137}\text{Cs}$  concentration in the plant body decrease. By contrast, species with high  $^{137}\text{Cs}$  uptake ability absorb not only the  $^{137}\text{Cs}$  excluded through shedding dead parts but also that not absorbed by other species with low absorption ability. As a result,  $^{137}\text{Cs}$  concentrations in the plant body increase. Because Cs contained in fallen dead plants is easily absorbed,



$^{137}\text{Cs}$  distribution in a heterogeneous community may be biased toward species with relatively high Cs absorption ability. This process can contribute to inhomogeneity in soil  $^{137}\text{Cs}$  density.

### 5. Conclusion

We measured the  $^{137}\text{Cs}$   $T_{\text{ag}}$  values of many edible wild photosynthetic species and clarified that they differed among species. As factors of species-level  $^{137}\text{Cs}$   $T_{\text{ag}}$  values, species' ecological traits (e.g., solar-radiation or moisture requirements, life form, adherence to others, and phenology) were significant factors. As a factor of  $^{137}\text{Cs}$   $T_{\text{ag}}$  values among individuals within species, the physical and chemical properties of the soil within the habitat, including those in *dokonjōyasai*-like growth, were important. Because  $^{137}\text{Cs}$   $T_{\text{ag}}$  values vary greatly according to species, it is important to use species as a unit in food-safety assessments of the radioactivity of edible photosynthetic organisms. Increasing our knowledge of nutrient exchange among organisms, including symbiotic relationships, would greatly improve predictions of  $^{137}\text{Cs}$   $T_{\text{ag}}$  values.

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### Literature

Akama, A. and Kiyono, Y. (2016) Radioactive cesium contamination of *Eleutherococcus sciadophylloides*—Comparisons between the regions of different contamination level and the seasons—. *Kanto Shinrin Kenkyu*, 66-2, 225–228, (in Japanese with English summary).

Akema, T. (2022) "Erikoido kinkon (Ericoid mycorrhiza)". <http://cse.ffpri.affrc.go.jp/akema/public/mycorrhiza/mycorrhiza.html#ericoid>, (in Japanese) (accessed 2022-

12-17).

Andersen, K. (2021) "*Oenothera stricta*: A Future Addition to Bedding Flowers". Plant Science Major, University of Minnesota, <https://conservancy.umn.edu/bitstream/handle/11299/225169/Oenothera%20stricta%20by%20Kayla%20Andersen.pdf?sequence=1>, (accessed 2022-12-17).

Beresford, N. A., Voigt, G., Wright, S. M., Howard, B. J., Barnett, C. L., Prister, B., Balonov, M., Ratnikov, A., Travnikova, I., Gillett, A. G., Mehli, H., Skuterud, L., Lepicard, S., Semiochkina, N., Perepeliantnikova, L., Goncharova, N. and Arkhipov, A. N. (2001) Self-help countermeasure strategies for populations living within contaminated areas of Belarus, Russia and Ukraine. *Journal of Environmental Radioactivity*, 56, Issues 1–2, 215–239.

Bhattarai, H. D., Kim, T., Oh, H. and Yim, J. H. (2013) A new pseudodepsidone from the Antarctic lichen *Stereocaulon alpinum* and its antioxidant, antibacterial activity. *The Journal of Antibiotics*, 66, 559–561.

Bidartondo, M. I. (2005) The evolutionary ecology of myco-heterotrophy. *New Phytologist*, 167, 335–352.

Bunzl, K. and Kracke, W. (1989) Seasonal variation of soil-to-plant transfer of K and fallout  $^{134,137}\text{Cs}$  in peatland vegetation. *Health Physics*, 57 (4), 593–600.

Burger, A. and Lichtscheidl, I. (2018) Stable and radioactive cesium: A review about distribution in the environment, uptake and translocation in plants, plant reactions and plants' potential for bioremediation. *Science of the Total Environment*, 618, 1459–1485.

Calmon, P., Thiry, Y., Zibold, G., Rantavaara, A., Fesenko, S. and Orlov, O. (2009) Radionuclide transfer in forest ecosystems. In "*Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments*". IAEA-TECDOC-1616, International Atomic Energy Agency, Vienna, 333–396.

Choi, N. -S. (2021) Comparison on Volatile Flavor Compounds in *Ligularia stenocephala* and *Ligularia fischeri* Leaves. *The Korean Journal of Food and Nutrition*, 34 (4), 340–346.

Crawford, S. D. (2015) Lichens used in traditional medicine. In Ranković, B. (ed.) "*Lichen secondary metabolites*". Springer, Cham, 31–97.

Fern, K. (2022a) "Temperate Plants Database", <http://temperate.theferns.info/>, (accessed 2022-12-17).

Fern, K. (2022b) "Tropical Plants Database", <http://tropical.theferns.info/>, (accessed 2022-12-17).

Gomi, I. (2018) "Kudamono (Fruits)", Ministry of Health, Labour and Welfare, <https://www.e-healthnet.mhlw.go.jp/information/food/e-01-003.html>, (in Japanese) (accessed

- 2023-3-19).
- Harada, H. (2019) "Chiirui tte naani? (What is lichen?)", [https://www.chiba-muse.or.jp/NATURAL/special/chii\\_cbm/doc/chii-naani-190227a.pdf](https://www.chiba-muse.or.jp/NATURAL/special/chii_cbm/doc/chii-naani-190227a.pdf), (in Japanese) (accessed 2022-12-17).
- Hashimoto, I. (2007) Wild Food Lexicon, Japan: A Unique Photographic Guide to Finding Cooking and Eating Wild Plants Ferns and Lichen. Kashiwashobo, Tokyo, 496pp, (in Japanese).
- Hashimoto, S., Komatsu, M. and Miura, S. (2021) Shinrin no hōshasen seitaigaku (Radiation Ecology of Forests). Maruzen, Tokyo, 219pp, (in Japanese).
- Hattori, Y. (2011-) "Sabaibaru setsuyakujutsu (Survival Savings)", <http://www43.tok2.com/home/hatlee/index.html>, (in Japanese) (accessed 2022-12-17).
- Heibonsha (2007) HEIBONSHA'S WORLD ENCYCLOPEDIA. Heibonsha, Tokyo, (in Japanese).
- Henmi, K. (1967) Taberareru yasō (Edible Wild Herbs). Colour Books, 134, Hoikusha, Osaka, 153pp, (in Japanese).
- International Atomic Energy Agency (2020) Environmental transfer of radionuclides in Japan following the Accident at the Fukushima Daiichi Nuclear Power Plant. IAEA-TECDOC-1927, International Atomic Energy Agency, Vienna.
- Japan Herb Federation (2022) "Yakuyō shokubutsu ichiranhyō (List of Medicinal Plants)", <http://www.e-yakusou.com/sou/index.html>, (in Japanese) (accessed 2022-12-17).
- Julia's Edible Weeds (2022) "Julia's edible weeds turn your weeds into delicious, nutritious food!", <https://www.juliasedibleweeds.com/>, (accessed 2022-12-17).
- Kaneko, N. (2018) Decontamination of radioactive cesium in forests using mycelium. *Suirikagaku*, 360, 119–133, (in Japanese).
- Kashiwadani, H. (1998) Chiirui—Kin to sō no kyōseitai (Lichen—A Symbiosis of Fungi and Algae). *Kagakutoseibutsu*, 36 (9), 597–602, (in Japanese).
- Katiboina, V. (2022) "What Is the Difference Between Fruits and Vegetables?", *MedicineNet*, [https://www.medicinenet.com/what\\_is\\_the\\_difference\\_between\\_fruits\\_and\\_vegetables/article.htm](https://www.medicinenet.com/what_is_the_difference_between_fruits_and_vegetables/article.htm), (accessed 2023-3-19).
- Kawasaki, E. (2010) "Research on Stone Cultural Heritage Epiphytic Lichens from the Conservation Sciences Perspective", 2013 PhD Thesis, The University of Tsukuba, 197pp, <https://core.ac.uk/download/pdf/56657608.pdf> (in Japanese) (accessed 2022-12-17).
- Kiyono, Y. and Akama, A. (2013) Radioactive cesium contamination of edible wild plants after the accident at the Fukushima Daiichi Nuclear Power Plant. *Japanese Journal of Forest Environment*, 55 (2), 113–118.
- Kiyono, Y. and Akama, A. (2015a) Seasonal variations of radioactive cesium contamination in cultivated *Petasites japonicus*. *Journal of Japanese Forestry Society*, 97 (3), 158–164, (in Japanese with English summary).
- Kiyono, Y. and Akama, A. (2015b) The amount of <sup>137</sup>Cs deposition and transfer ratio of <sup>137</sup>Cs to wild edible-wild-plants after the accident at TEPCO's Fukushima Daiichi Nuclear Power Station. Proceeding of the International Symposium on Radiological Issues for Fukushima's Revitalized Future, Paruse Iizaka, Fukushima City, Japan, May 30–31 (Sat.–Sun.), 2015, 57–61.
- Kiyono, Y. and Akama, A. (2017a) Sansai to hōshasei busshitsu (Wild vegetables and radioactive materials). *Suirikagaku*, 355 (61-2), 36–50, (in Japanese).
- Kiyono, Y. and Akama, A. (2017b) Seasonal changes in biomass and the amounts of biomass <sup>40</sup>K and <sup>137</sup>Cs in *Petasites japonicus* communities with radioactive contamination. *Kanto Shinrin Kenkyu*, 68-1, 71–72, (in Japanese).
- Kiyono, Y. and Akama, A. (2018) Radiocesium concentration of edible wild plants: Annual trends since the FDNPS accident. *Kanto Shinrin Kenkyu*, 69 (1), 109–110, (in Japanese).
- Kiyono, Y. and Akama, A. (2021) Aggregated transfer factors of cesium-137 from the environment to 318 edible wild plant species: an interim report. In Bessho, K., Matsumura, H., Miura, T. and Yoshida, G. (eds.) "Proceedings of the 21st workshop on environmental radioactivity, KEK, Tsukuba, Japan, March 12–13, 2020 (Canceled)". KEK Proceedings 2020-4 November 2020 R, High Energy Accelerator Research Organization, Tsukuba, 89–91, (in Japanese with English summary).
- Kiyono, Y. and Akama, A. (2022) Fine-root depth influences differences in soil-to-plant transfer of <sup>137</sup>Cs and <sup>133</sup>Cs. *Bulletin of FFPRI*, 21-1 (No.461), 39–47, (in Japanese with English summary).
- Kiyono, Y., Akama, A. and Iwaya, M. (2019a) Challenges in estimating the radiocesium deposition in the habitats of edible wild plants with the air dose rate. *Kanto Shinrin Kenkyu*, 70 (1), 115–116, (in Japanese).
- Kiyono, Y., Akama, A., Iwaya, M. and Yoshida, Y. (2018a) The transfer of radiocesium released in the 2011 Fukushima Daiichi Nuclear Power Station accident to petioles of wild butterbur (*Petasites japonicus*). *Bulletin of FFPRI*, 17 (3) (No.447), 249–257, (in Japanese with English summary).
- Kiyono, Y., Akama, A., Iwaya, M. and Yoshida, Y. (2019b) Transfer of radiocesium released in the 2011 Fukushima Daiichi Nuclear Power Station accident to *Eleutherococcus sciadophylloides*, a wild tree that produces edible sprouts. *Bulletin of FFPRI*, 18 (2) (No.450), 195–211, (in Japanese with English summary).

- Kiyono, Y., Akama, A., Iwaya, M., Yoshida, Y. and Shima, T. (2021b) Growth of bracken (*Pteridium aquilinum* subsp. *japonicum*) and dynamics in bracken of radiocesium released in the 2011 Fukushima Daiichi Nuclear Power Station accident. *Bulletin of FFPRI*, 20 (2) (No.458), 83–100, (in Japanese with English summary).
- Kiyono, Y., Akama, A., Matsuura, T., Iwaya, M., Yoshida, Y. and Shima, T. (2021a) The transfer of radiocesium released in the 2011 Fukushima Daiichi Nuclear Power Station accident to bracken (*Pteridium aquilinum* subsp. *japonicum*). *Bulletin of FFPRI*, 20 (2) (No.458), 69–82, (in Japanese with English summary).
- Kiyono, Y., Ito, E., Monda, Y., Toriyama, J., Saito, H., Furuya, N., Sum, T., Tith, B., Keth, N., Keth, S., Chandararity, L., Phallaphearaoth, O., Chann, S. and Sokh H. (2017) A feasibility study for determining the mean annual aboveground biomass gain of tropical seasonal forests in Cambodia. *TROPICS*, 25 (4), 127–138.
- Kiyono, Y., Komatsu, M., Akama, A., Matsuura T., Hiroi, M., Iwaya, M. and Futamoto, T. (2018b) The transfer of radiocesium released in the 2011 Fukushima Daiichi Nuclear Power Station accident to leaves of wild *Osmunda japonica*, an edible fern. *Bulletin of FFPRI*, 17 (3) (No.447), 217–232, (in Japanese with English summary).
- Kobayashi, N. (2013) "Hōshasei seshiumu wo herasu! naze kariumu de? —shokubutsu kenkyūsha no shikōkairo— (Reduce Radioactive Cesium! Why Potassium? —Plant Researcher's Train of Thought—)", *The 4th Science Café "Let's ask about radioactive substances and farm products ~Reduce radioactive cesium! Why potassium?~"*, Research Center for Food Safety, Graduate School of Agricultural and Life Sciences, The University of Tokyo, [http://www.frc.a.u-tokyo.ac.jp/wp-content/uploads/130727\\_shiryō.pdf](http://www.frc.a.u-tokyo.ac.jp/wp-content/uploads/130727_shiryō.pdf), (in Japanese) (accessed 2022-12-17).
- Komatsu, M. and Kiyono, Y. (2021) Kinoko to sansai no hōshanō osen ni tsuite wakattakoto · kongo no mitōshi (What We Learned About Radioactive Contamination of Mushrooms and Edible Wild Plants and Its Future Prospects). *Shinrin Kagaku*, 91, 6–9, (in Japanese).
- Komatsu, M., Nishina, K. and Hashimoto, S. (2019) Extensive analysis of radiocesium concentrations in wild mushrooms in eastern Japan affected by the Fukushima nuclear accident: Use of open accessible monitoring data. *Environmental Pollution*, 255, Part 2, 113236.
- Konoshima, M., Shibata, S., Shimomura, T. and Higashi, J. (1987) *Hirokawa yakuyō shokubutsu daijiten* (Hirokawa's Dictionary of Medicinal Plants). HIROKAWA, Tokyo, 468pp, (in Japanese).
- Li, Z. and Guo, M. (2018) Healthy efficacy of *Nostoc commune* Vaucher. *Oncotarget*, 9 (18), 14669–14679.
- Łuczaj, Ł., Končić, M. Z., Miličević, T., Dolina, K. and Pandža, M. (2013) Wild vegetable mixes sold in the markets of Dalmatia (southern Croatia). *Journal of Ethnobiology and Ethnomedicine*, 9, 2.
- Manaka, T., Ono, K., Furusawa, H., Ogo, S. and Miura, S. (2020) Chemical sequential extraction of O horizon samples from Fukushima forests: Assessment for degradability and radiocesium retention capacity of organic matters. *Journal of Environmental Radioactivity*, 220–221, 106306.
- Marschner, H. (1995) "*Mineral Nutrition of Higher Plants*". 2nd ed. Academic Press, London, 889pp.
- Matsumura, S. (2022) "Niwaki zukan uekipedia (Field Guide to Garden Trees, Uekipedia)", <https://www.uekipedia.jp/>, (in Japanese) (accessed 2022-12-17).
- Ministry of Agriculture, Forestry and Fisheries (2022) "Omona take no shurui (Major Species of Bamboo)", <https://www.rinya.maff.go.jp/j/tokuyou/take/syurui.html>, (in Japanese) (accessed 2022-12-17).
- Ministry of Health, Labour and Welfare (2004) "Shinfuitsumu (iwayuru konfuri) oyobi kore wo fukumu shokuhin no toriatsukai ni tsuite (sono 2) [Handling of *Symphytum* spp. (So-Called Comfrey) and Foods Containing It (Part 2)]", <https://www.mhlw.go.jp/topics/2004/06/tp0618-2.html>, (in Japanese) (accessed 2022-12-17).
- Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and Japan Wildlife Research Center (2022) "Amami guntō seibutsu shigen uebu dētābēsu (Amami Islands Biological Resources Web Database)", [http://www.amami.or.jp/seibutsusigen/plant\\_wamei\\_list\\_aa.html](http://www.amami.or.jp/seibutsusigen/plant_wamei_list_aa.html), (in Japanese) (accessed 2022-12-17).
- Miuran Business Systems (2014) "Rōmaji henkan (Romaji Converter)", instant tools, [https://tools.m-bsys.com/original\\_tooles/romaji.php](https://tools.m-bsys.com/original_tooles/romaji.php), (in Japanese) (accessed 2022-12-17).
- Moberg, L., Hubbard, L., Avila, R., Wallberg, L., Feoli, E., Scimone, M., Milesi, C., Mayes, B., Iason, G., Rantavaara, A., Vetikko, V., Bergman, R., Nylén, T., Palo, T., White, N., Raitio, H., Aro, L., Kaunisto, S. and Guillitte, O. (1999) An integrated approach to radionuclide flow in semi-natural ecosystems underlying exposure pathways to man. Final report of the LANDSCAPE project, Swedish Radiation Protection Institute, Stockholm (Sweden), 108pp.
- Moge, S. (2021) "An Investigation into the Endophytic Medicinal and Biological Properties of *Solidago sempervirens*", Salem State University, <http://hdl.handle.net/20.500.13013/1504>, (accessed 2022-12-17).

- Molzahn, D. and Assmann-Werthmüller, U. (1993) Caesium radioactivity in several selected species of honey. *Science of The Total Environment*, 130–131, 95–108.
- Motomura, H., Selosse, M. -A., Martos, F., Kagawa, A. and Yukawa, T. (2010) Mycoheterotrophy evolved from mixotrophic ancestors: evidence in *Cymbidium* (Orchidaceae). *Annals of Botany*, 53, 573–581.
- Nagano Prefecture (2021) "Nagano ken yakuzaisaikai Yakuso no mori Rindō ~Sugadaira yakusō saibai shikenchi~ (Nagano Pharmaceutical Association Medicinal Herb Park "Rindou" ~Sugadaira Medicinal Herb Cultivation Testing Site~)", <https://www.pref.nagano.lg.jp/yakuji/kenko/iryo/shoyaku/shikenchi/index.html>, (in Japanese) (accessed 2022-12-17).
- Nakaike, T. and Kawasaki, S. (2007) An annotated inventory of plants found on the campus of Toyo Eiwa University (Yokohama): Plants used for human consumption. *Toyo Eiwa journal of the humanities and social sciences*, 25, 155–206, (in Japanese with English summary).
- National Agriculture and Food Research Organization (NARO) (2022) "Ōnamomi (*Xanthium orientale* subsp. *orientale*)", NARO, <https://www.naro.affrc.go.jp/org/nkk/m/56/05.pdf>, (in Japanese) (accessed 2022-12-17).
- Nemoto, K. (2014) "Soba no kari seyō niyoru hōshasei seshiumu no kyūshū yokusei kōka ni tsuite (Inhibition Effect of Potassium Application on Radioactive Cesium Absorption in Buckwheat)", 2013 Information on radiation-related support techniques, Fukushima Agricultural Technology Center, <https://www.pref.fukushima.lg.jp/uploaded/attachment/306745.pdf>, (in Japanese) (accessed 2022-12-17).
- Ohashi, S. (2017) "Understanding of a factor that increases radiocesium concentration in stem wood of Japanese cedar: the effect of water uptake", <https://kaken.nii.ac.jp/ja/file/KAKENHI-PROJECT-15H06847/15H06847seika.pdf>, (in Japanese with English summary) (accessed 2021-12-17).
- Okada, M., Mitsuhashi, H., Wada, H., Terabayashi, S., Kondo, K. Murata, J. and Kikuchi, G. (2002) Newly Revised Illustrated Medicinal Plants of the World. HOKURYUKAN, Tokyo, 822pp, (in Japanese).
- Oyedjeji, O., Oziegbe, M. and Taiwo, F. O. (2011) Antibacterial, antifungal and phytochemical analysis of crude extracts from the leaves of *Ludwigia abyssinica* A. Rich. and *Ludwigia decurrens* Walter. *Journal of Medicinal Plant Research*, 5 (7), 1192–1199.
- Peel, M. C., Finlayson, B. L. and McMahon, T. A. (2007) Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11, 1633–1644.
- Plants For A Future (2010–2022) "Plants For A Future, earth·plants·people", <https://pfaf.org/user/>, (accessed 2022-12-17).
- Saito, N. (2020) "Shamen ichi ni okeru konara shokusaiboku no hōshasei seshiumu ikōkeisū no chigai (Differences in Radiocesium Transfer Factors in *Quercus serrata* Planted Along Slope Positions)", 2019 Information on radiation-related support techniques, Fukushima Prefectural Forestry Research Centre, <https://www.pref.fukushima.lg.jp/uploaded/attachment/378254.pdf>, (in Japanese) (accessed 2022-12-17).
- Sakuma, Y. and Niitsuma, K. (2016) "Suitō ni okeru inawara seyō no hōshasei seshiumu kyūshū yokusei kōka (Inhibition Effect of Rice Straw Application on Radioactive Cesium Absorption in Paddy Rice)", 2016 Information on radiation-related support techniques, Fukushima Agricultural Technology Center, <https://www.pref.fukushima.lg.jp/uploaded/attachment/457922.pdf>, (in Japanese) (accessed 2022-12-17).
- Sand-Jensen, K. (2014) Ecophysiology of gelatinous *Nostoc* colonies: unprecedented slow growth and survival in resource-poor and harsh environments. *Annals of Botany*, 114, 17–33.
- Sasaki, H., Tamaoki, H., Nakata, Y., Sato, K., Yamaguchi, Y. and Takenaka, H. (2016) Localization of cesium and strontium in terrestrial cyanobacteria *Nostoc commune*. *Algal Resources*, 9, 87–92.
- Shimada, H. (2006–) "Atomigunpofu (Atomi Spectrum)", <http://www.atomigunpofu.jp/index.htm>, (in Japanese) (accessed 2022-12-17).
- Shimatani, M. (2016) *Nihonryōri kazarikiri kyōhon* (Japanese Food Decorative Cutting Textbook). SEIBUNDO SHINKOSHA, Tokyo, 176pp, (in Japanese).
- Shogakukan (1994) *Encyclopedia Nipponica* 2001. 1, 19, 21, and 23, Shogakukan, Tokyo, (in Japanese).
- Shuto, A. and Shimizu, H. (2020) The consideration of effective use of fruits and leaves of *Phellodendron amurense* (1st Report). Report of Nara Prefectural Institute of Industrial Development, 46, 33–36, (in Japanese).
- Suetsugu, K., Matsubayashi, J. and Tayasu, I. (2020) Some mycoheterotrophic orchids depend on carbon from dead wood: Novel evidence from a radiocarbon approach. *New Phytologist*, 227, 1519–1529.
- Suno, H., Machida, M., Dohi, T., Ohmura, Y. (2021) Quantum chemical calculation studies toward microscopic understanding of retention mechanism of Cs radioisotopes and other alkali metals in lichens. *Scientific Reports*, 11, 8228.
- T. K (2022) "Herbs and Flowers Journey", <https://yakusoutohana.shop-pro.jp/>, (in Japanese) (accessed

- 2022-12-17).
- Tagami, K. and Uchida, S. (2017) Changes of effective half-lives of  $^{137}\text{Cs}$  in three herbaceous plants and bioavailable  $^{137}\text{Cs}$  fraction in soil after the Fukushima nuclear accident, *Applied Geochemistry*, 85, B, 162–168.
- Takada, M., Yasutaka, T., Hayashi, S., Takagi, M. and Tagami, K. (2022) Aggregated transfer factor of  $^{137}\text{Cs}$  in edible wild plants and its time dependence after the Fukushima Dai-ichi nuclear accident. *Scientific Reports*, 12, 5171.
- Takahashi, H. (2009) *Edible Wild Plants in Japan*. Gakken, Tokyo, 256pp, (in Japanese).
- Tamukai, K. (1998–2022) "Tam's shirōto shokubutsu zukan (Tam's Amateur Field Guide to Plants)", <http://www.jpplants.sakura.ne.jp/index.html>, (in Japanese) (accessed 2022-12-17).
- Toho University Faculty of Pharmaceutical Science Medicinal Herb Garden (2022), "Yakuyō shokubutsu en—Hābu en—Yasō gun (Medicinal Herb Garden—Herb Garden—Wild Plants)", <https://www.lab2.toho-u.ac.jp/phar/yakusou/index.html>, (in Japanese) (accessed 2022-12-17).
- Toriyama, J., Kobayashi, M., Hiruta, T. and Shichi, K. (2018) Distribution of radiocesium in different density fractions of temperate forest soils in Fukushima. *Forest Ecology and Management*, 409, 260–266.
- Uchida, S. and Tagami, K. (2018) Comparison of radiocesium concentration changes in leguminous and non-leguminous herbaceous plants observed after the Fukushima Dai-ichi Nuclear Power Plant accident. *Journal of Environmental Radioactivity*, 186, 3–8.
- Ueno, A. and Terada, Y. (1984) *Ueno Akira Terada Yoko no sansai to yasō no ryōri (Ueno Akira and Terada Yoko's Edible Wild Plants and Their Cooking)*. Kurashi-no-sekkei, 157, Chuokoron-sha, Tokyo, 168pp, (in Japanese).
- Urushi Works Gallery Nissen Okayama (2022) "Urushi—sono fushigina kōyō (sono 2) [Urushi—Its Mysterious Utility (Part 2)]", <http://nissen0803.blog35.fc2.com/blog-entry-59.html>, (in Japanese) (accessed 2022-12-17).
- Umata, H., Ota, Y., Yamada, M., Watanabe, Y. and Gale, S. W. (2013) Germination of the fully myco-heterotrophic orchid *Cyrtosia septentrionalis* is characterized by low fungal specificity and does not require direct seed-mycobiont contact. *Mycoscience*, 54, 343–352.
- Van Valkenburg, J. L. C. H. and Bunyapraphatsara, N. (2001) *Medicinal and poisonous plants 2. Plant Resources of South-East Asia (PROSEA)*, 12 (2), Backhuys Publishers, Leiden, 782pp.
- Xu, J. and Mu, C. (1990) The relation between growth of *Gastrodia elata* protocorms and fungi. *Acta Botanica Sinica*, 32, 26–33.
- Yamaguchi, N., Takata, Y., Hayashi, K., Ishikawa, S., Kuramata, M., Eguchi, S., Yoshikawa, S., Sakaguchi, A., Asada, K., Wagai, R., Makino, T., Akahane, I. and Hiradate, S. (2012) Behavior of radiocesium in soil-plant systems and its controlling factor: A review. *Bulletin of National Institute for Agro-Environmental Sciences*, 31, 75–129, (in Japanese with English summary).
- Yamaji, K., Nagata, S., Haruma, T., Ohnuki, T., Kozaki, T., Watanabe, N. and Nanba, K. (2016) Root endophytic bacteria of a  $^{137}\text{Cs}$  and Mn accumulator plant, *Eleutherococcus sciadophylloides*, increase  $^{137}\text{Cs}$  and Mn desorption in the soil. *Journal of Environmental Radioactivity*, 153, 112–119.
- Yamato, M. and Yagame, T. (2009) Symbioses of orchids and fungi. *Japanese Journal of Mycology*, 50 (1), 21–42, (in Japanese with English summary).
- Yokoyama, J., Takahashi, M. and Yoshida, M. (2013) *Fukushimaken iwakishi no sugibayashi nai ni seiiku suru ginryōsō no kinkonkin (Mycorrhizal fungi of *Monotropastrum humile* growing in a *Cryptomeria japonica* forest in Iwaki City, Fukushima Prefecture)*. Faculty of Science, Yamagata University Urabandai Limnological Report, 20, 4–8, (in Japanese).
- Yonekura, K. and Kajita, T. (2003–) "BG Plants Japanese name – scientific name index (YList)", <http://ylist.info>, (in Japanese) (accessed 2022-12-17).
- Zhao, Y., Wang, M. and Xu, B. (2021) A comprehensive review on secondary metabolites and health-promoting effects of edible lichen. *Journal of Functional Foods*, 80, 104283.

### Supplementary data

Supplementary data can be found at

<https://www.ffpri.affrc.go.jp/pubs/bulletin/467/467toc-en.html>

#### Table S1. Descriptions of species and parts sampled in this study.

a) Perennial includes biennial herbs. b) Habitat tree-covering (1, open land; 2, forest edge; 3, forest); c) Habitat moisture environment (1, dry; 2, medium; 3, wet); d) Life span of the individual, as an indicator of the time required for total biomass replacement, or the reciprocal of the turnover rate (1, annual plant; 2, biennial plant, perennial plant, terrestrial cyanobacterium, or shrub with a trunk lifespan of ~2 years such as *Rubus* spp.; 3, other shrub or epilithic lichen; 4, tree); e) Habitat temperature during leaf growth (1, spring ephemeral or non-evergreen winter green plant; 2, evergreen plant, summer green plant, mycoheterotrophic plant, terrestrial cyanobacteria, or epilithic lichen); f) Species showing adherence to surfaces such as rock or tree bark, e.g., plants with adhering roots, or epiphytes including lithophytes, the ground-creeping species *Lycopodium clavatum* var. *nipponicum*, epilithic lichens, and terrestrial cyanobacteria (1, without; 2, with). g)  $\text{Weight}_{\text{dry matter}} / (\text{weight}_{\text{water}} + \text{weight}_{\text{dry matter}})$  mean values of the samples. h) O-horizon and soil to a depth of 0.05 m. i) The authors of this paper take no responsibility for any adverse health effects ensuing from the

consumption or medicinal use of the organisms discussed in this study. Please seek advice from a professional before consuming or using any of these organisms. j) 1) Andersen (2021), 2) Bhattarai et al. (2013), 3) Choi (2021), 4) Crawford (2015), 5) Fern (2022a), 6) Fern (2022b), 7) Hashimoto (2007), 8) Hattori (2011–), 9) Heibonsha (2007), 10) Henmi (1967), 11) Japan Herb Federation (2022), 12) Julia's Edible Weeds (2022), 13) Konoshima et al. (1987), 14) Li and Guo (2018), 15) Łuczaj et al. (2013), 16) Matsumura (2022), 17) Ministry of Agriculture, Forestry and Fisheries (2022), 18) Ministry of Health, Labour and Welfare (2004), 19) Ministry of Land, Infrastructure, Transport and Tourism and Japan Wildlife Research Center (2022), 20) Moge (2021), 21) Nagano Prefecture (2021), 22) Nakaike and Kawasaki (2007), 23) National Agriculture and Food Research Organization (NARO) (2022), 24) Okada et al. (2002), 25) Oyediji et al. (2011), 26) Plants For A Future (2010–2022), 27) Shimada (2006–), 28) Shimatani (2016), 29) Shogakukan (1994), 30) Shuto and Shimizu (2020), 31) Takahashi (2009), 32) T. K. (2022), 33) Tamukai (1998–2022), 34) Toho University Faculty of Pharmaceutical Science Medicinal Herb Garden (2022), 35) Ueno and Terada (1984), 36) Urushi Works Gallery Nissen Okayama (2022), 37) Van Valkenburg and Bunyapraphatsara (2001), 38) Zhao et al. (2021).

## 食用野生光合成生物のセシウム 137 の面移行係数

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### 要旨

放射線被ばくによる健康上のリスクを減らすうえで、食用野生種の放射性物質濃度を知ることが重要である。2011年の福島第一原発事故の影響を受けた地域に生育する食用野生光合成生物種(植物、陸生シアノバクテリア、岩石上生地衣類) 380種2094部分、非食用野生光合成生物27種72部分、食用栽培植物15種22部分、計422種2187部分のサンプルを2015~2019年に採取し、生育地の堆積有機物層と土壌から生物体に移行する放射性セシウム137 ( $^{137}\text{Cs}$ ) の面移行係数 ( $T_{\text{ag}}$ ) 値を求めた。野生種の食用部位 $^{137}\text{Cs}$   $T_{\text{ag}}$  平均値は種によって大差があった(種 $T_{\text{ag}}$ の最大/最小比は栄養器官で約2000、有性繁殖器官で約920)。食用野生種の代表的食用部位の種 $T_{\text{ag}}$  平均値について、栄養器官、有性繁殖器官別に重回帰分析を行ったところ、森林に生育する種は林外に生育する種より $T_{\text{ag}}$  値が高い傾向があった( $P < 0.023$ )。また、データが得られた栄養器官で、付着根を持つなど樹幹や石などに生物体を付着させて生育する種は $T_{\text{ag}}$  値が高かった( $P < 0.010$ )。種の生態的特性は種の $^{137}\text{Cs}$   $T_{\text{ag}}$  に大きな影響を与えた。種によって $^{137}\text{Cs}$   $T_{\text{ag}}$  が大きく異なることから、食用光合成生物の放射能の食品安全性評価は種を単位とすることが重要である。

キーワード：野生食用植物、地衣類、 $^{137}\text{Cs}$   $T_{\text{ag}}$ 、シアノバクテリア、食の安全、福島第一原子力発電所事故、共生

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