学位（博士）論文　要旨

Radiocesium Contamination in Japanese Fir (*Abies firma* Sieb. et Zucc.) After the Fukushima Daiichi Nuclear Power Plant Accident

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On 11 March 2011, the magnitude 9.0 Great East Japan earthquake and resulting tsunami caused the extensive damage to the coastal areas in the Tohoku region of Japan. As a result of this disaster, the number of recorded deaths rose to 15,893 and those still missing total 2,556.

The breakdown of cooling systems for the reactors at TEPCO's Fukushima Daiichi Nuclear Power Plant (the FDNPP) led to a severe nuclear crisis. The loss of cooling functions caused hydrogen explosions, and a large amount of radioactive material from the damaged reactor buildings was released into the atmosphere. Radioactive material released from the FDNPP have polluted the surrounding terrestrial and aquatic environment.

Approximately 70% of Fukushima Prefecture is covered with forests. A large amount of radionuclides, especially radiocesium (^{137}Cs), was deposited onto the forested areas. To understand the effect on forest wild organisms and for the safety of workers and residents near forests, once radioactive materials are released into the environment, contamination levels of various organisms must be promptly assessed. However, radioactive contamination of forest ecosystems is quite complex, consisting of various ecological factors. Hence, the effects radioactive pollution in Japanese forests may differ from the effects in North European forests caused by the Chernobyl accident. Ecological factors affecting North European forest ecosystems are quite different from those in Japan. Therefore, an understanding of the behavior of radiocesium in Japanese forest ecosystems is required.

Forest trees have a huge biomass above the ground, and they have potential to provide storage of huge amounts of radioactive material and to be a source of radiation emission. After the Chernobyl accident, many studies on tree contamination were conducted and these reported the heterogeneity of distribution of radiocesium in a tree body. Moreover there are large inter-individual variations in radiocesium contamination of forest trees, often affecting the results of statistical tests. To understand the true effects of ecological factors, we need to consider these large variations when investigating radioactivity contamination of forest trees; otherwise we cannot obtain an accurate assessment of the contaminated environment. Well-designed sampling methods help to avoid these large variations. In this dissertation, to establish an effective sampling method, I propose a new sampling method based on information obtained by my studies on endemic tree species in a Japanese forest ecosystem.

In this dissertation, I focused on the evergreen conifer, Japanese fir (*Abies firma* Sieb. et Zucc.). This species is commonly distributed in natural forests in coastal area of Fukushima Prefecture. *A. firma* has a specific branching pattern that allows us to identify the shoot age. Tree age is an important factor for the radiocesium distribution in tree bodies, and this information helps us to avoid a large variation caused by differences in age. Using this species, I provide information to establish an effective sampling method for the assessment of contaminated trees growing in Japanese forest ecosystems.

In Chapter 2, I show the distribution pattern of ^{137}Cs contamination in a young *A. firma* tree body. The results of this study indicate that visual classification of shoot age is a good working method for the assessment of ^{137}Cs contamination in *A. firma* tree organs. This study clarified the differences in ^{137}Cs contamination between different ages and between different tree organs such as needles, branches, wood and bark. Moreover, the vertical distribution of ^{137}Cs contamination in an individual tree body was also discussed. Both age and height information of trees allow us to distinguish external contamination from internal contamination. In conclusion, the heterogeneity of ^{137}Cs contamination in tree bodies was observed and this heterogeneity was brought about by (1) differences in organs such as needles, branches, wood and bark, (2) differences in age, and (3) position (height) of organs. Thus, standardization of sampling to avoid the effect of intra-individual variation is required for the assessment of radioactivity contamination in forest tree species.

The Chapter 3 presents additional information for highly accurate sampling methods. The branching pattern of *A. firma* is trifurcate. In this branching, we can see clear morphological differences between three shoots (one main shoot and two lateral shoots). I investigated the difference in ^{137}Cs concentration between three different shoots. The ^{137}Cs concentration in main shoots was significantly higher than those in lateral shoots. This indicates that there were differences in ^{137}Cs concentration between shoot type even for the same organs of the same age and at the same position (height). In conclusion, it is important to select samples while paying attention to shoot differentiation. Samples should be taken only from the main shoot or only from the lateral shoot (not a mix of shoots) for every sampled tree.

In Chapters 2 and 3, I discuss the intra-individual variation of ^{137}Cs concentration in *A. firma*. In these chapters, differences in ^{137}Cs concentration caused by different organs, ages and sampling positions when field sampling is conducted are considered important. Next, I tried to clarify the inter-individual variation of ^{137}Cs concentration in this species. A spatial autocorrelation is one of the factors affecting inter-individual variation in ecological data, causing a lack of independence of ecological data. Non-independence of ecological data leads to various statistical problems. Examination of the spatial structure of observations between ecological data is required to clarify the presence of spatial autocorrelation. However, the spatial structure of ^{137}Cs contamination in forest trees is still unclear. In Chapter 4, I investigated the spatial structure of ^{137}Cs concentration of *A. firma* in a natural secondary forest and examined whether or not spatial autocorrelation exists. A significant strong spatial autocorrelation was observed over short distance (<2.5 m), suggesting that spatial distribution needs to be considered in the evaluation of radioactive contamination in trees. Therefore, I strongly recommend taking position data of sampled trees when sampling is being conducted, because we can adjust the non-independence of data due to the spatial autocorrelation with the position data. Furthermore, I mentioned the number of samples required to evaluate radioactive contamination in trees based on the results of spatial analysis. According to the sample-size analysis, a sample size of seven trees was required to determine the mean contamination level within an error of the mean of no more than 10%. This required sample size may be feasible for various fields.

In Chapter 5, I examined the low contamination levels in *A. firma* seeds. This result, together with the limited root uptake of ^{137}Cs due to a strong fixation of ^{137}Cs to clay minerals, suggests that ^{137}Cs contamination in future generations of this species growing in forests surrounding the FDNPP will be low. However, the risks of chronic radiation exposure for trees have been reported recently. There is still insufficient field data on the consequences of chronic radiation exposure for tree populations. Consequently, studies on the long-term biological consequences of radiation exposure after a nuclear crisis are needed in future.