Evaluating radiocesium transfer for white-spotted char (*Salvelinus leucomaenis*) in forested headwater streams

森林渓流におけるイワナ (*Salvelinus leucomaenis*) へのセシウム移行評価

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Radioceium (137Cs) released from the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident severely contaminated forested areas in Fukushima and adjacent prefectures. 137Cs could move across terrestrial and aquatic ecosystems in forested headwater streams because of tight linkages between riparian areas and stream channels. White-spotted char (*Salvelinus leucomaenis*) is considered as a top predator in food web of headwater streams and important fishery resources. Although white-spotted char consumes various food sources from forest and stream, complex interactions for 137Cs movement from their multiple food sources have not been fully examined. Therefore, the primal objective of this thesis was to understand 137Cs movement and contamination levels of organisms in headwater streams. I developed a new method for investigating 137Cs transfer to white-spotted char by considering their multiple dietary sources with respective contamination levels. Then, I evaluated changes in 137Cs contaminations from 1st to 5th years after the accident for examining the temporal patterns of 137Cs activity concentrations in biota. Finally, I discussed the fate of 137Cs contamination levels in future and management applications for reducing contamination levels in complex headwater ecosystems.

Firstly, I reviewed approximately 100 previous studies related to 137Cs contamination in freshwater fish around the world since 1974. About 40 fish species in rivers and lakes were summarized. 137Cs activity concentrations in fish species such as brown trout (*Salmo trutta*) and perch (*Perca fluviatilis*) was associated with fallout volume of contaminants in rivers and lakes. Hence, the contamination levels of freshwater fish in similar fallout volume varied substantially with 1 to 2 orders of magnitude. Variability of 137Cs contaminations tended to be high in rivers species compared to the species of lake habitats in Fukushima. Differences of contamination
levels of fish species in similar fallout were associated with food consumptions and physiological conditions. Among them, dietary conditions are one of the important factors for controlling the contamination levels.

For examining dietary $^{137}$Cs contributions with multiple prey items, I developed food web-based transfer factor ($TF_{\text{web}}$) for white-spotted char in headwater streams draining Japanese cedar ($Cryptomeria japonica$) forest in Fukushima and Gunma. I estimated dietary contributions based on stable carbon ($\delta^{13}$C) and nitrogen isotope ratios ($\delta^{15}$N) using samples collected in 2012 and 2013. $TF_{\text{web}}$ was calculated as the activity concentration in char divided by the sum of activity concentrations in all prey items, using the lower and upper estimates of dietary contributions. Both terrestrial and aquatic species such as mayflies ($Ephemera japonica$), spider crickets (Raphidosiphoridae gen. spp.), and freshwater crab ($Geothelphusa dehaani$) contributed 3 to 12% of the fish diet. Despite the differences of $^{137}$Cs activity concentrations of char in Fukushima (704 to 6082 Bq kg$^{-1}$-dry) and Gunma (193 to 618 Bq kg$^{-1}$-dry), $TF_{\text{web}}$ had similar ranges from 1.1 to 3.8 in Fukushima, and from 1.3 to 4.3 in Gunma. $TF_{\text{web}}$ values suggested that $^{137}$Cs tended to be accumulated from prey to white-spotted char. $TF_{\text{web}}$ using multiple prey items also provided consistent values compared to the other transfer factors using single prey-predator.

Seasonal variations of $TF_{\text{web}}$ for $^{137}$Cs activity concentrations in white-spotted char was examined because dominant food items of white-spotted char changes from terrestrial ones in summer to aquatic ones in winter. In Fukushima, $TF_{\text{web}}$ tended to be consistent throughout seasons in summer (mean ± SD: 3.9 ± 1.3) and in winter (6.5 ± 1.5). In Gunma, the greatest $TF_{\text{web}}$ occurred in winter (7.5 ± 1.6) and the lowest values was estimated in summer (2.6 ± 0.9). Because the metabolic rate of char in summer was four times greater than that in winter, high excretion rate of $^{137}$Cs in summer promoted the low summer $TF_{\text{web}}$ in Gunma. Hence, the contamination of food resources in Fukushima were 5-folds greater than those in Gunma, seasonal differences of $TF_{\text{web}}$ was not apparent by overwhelmed $^{137}$Cs intake relative to excretion rates.

Because changes in $^{137}$Cs activity concentrations over time is important for projecting contamination levels in future, I examined $^{137}$Cs activity concentrations of char in the 1st and 5th years after the accident in Fukushima. Ecological half-life ($T_{\text{eco}}$) of $^{137}$Cs in char differed between samples collected in summer (1.4 y) and autumn (6.6 y). $T_{\text{eco}}$ in summer samples was within the ranges of the previous studies (1.2 to 2.7 y), while autumn samples exhibited longer $T_{\text{eco}}$. Rate for decreases in $^{137}$Cs activity concentrations in aquatic food items (29%) tended to be slower compared to those of terrestrial food items (82%). Therefore, high seasonal dependencies for terrestrial food items in summer induced greater reduction of $^{137}$Cs activity concentrations together with high metabolic rates. Similarly, short $T_{\text{eco}}$ in large-bodied char in summer samples possibly associated with high terrestrial food dependencies compared to small-sized char. The findings of this study suggested that differences of sampling season as well as body size need to be considered for the long-term projection using $T_{\text{eco}}$.

In conclusion, dietary contributions and their seasonal changes are important for explaining the variability of $^{137}$Cs contamination of char. Such seasonal conditions and body sizes were not incorporated into the sampling campaign in most of the previous studies. Therefore, the sources of variability for $^{137}$Cs contamination were not fully included in $^{137}$Cs transfer modeling. Findings of this study will help for improving a model of $^{137}$Cs transfer in ecosystems which had suggested by international organization of radiation projections and rehabilitation.