Chapter 10
Why Do the Radionuclide Concentrations of Pacific Cod Depend on the Body Size?

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Abstract We examined year-class-related differences in radiocesium concentrations in Pacific cod (*Gadus macrocephalus*) and evaluated the potential factors affecting the differences after the release of large amounts of radionuclides from Fukushima Dai-ichi Nuclear Power Plant (FNPP) in March 2011. The concentration of radiocesium was highest in the 2009 and earlier year-classes (yc) (≤2009 yc), followed by the 2010 yc, and was rarely detected in the 2011 yc. Trawl surveys throughout the year revealed that a proportion of Pacific cod born in or before 2009 and 2010 were distributed in the coastal area from winter to early summer, whereas all individuals were on the upper continental slope from early summer to winter. The concentration of radiocesium decreased more rapidly in the 2010 yc than in the ≤2009 yc. The diet of cod changed ontogenetically and spatiotemporally. The organisms preyed upon on the upper continental slope by cod of all year-classes and in the coastal area by the 2010 yc contained very low concentrations of radiocesium. However, some food items ingested in the coastal area by the ≤2009 yc had relatively

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high radiocesium levels. These results suggest that Pacific cod primarily accumulated radiocesium during the first few months after the FNPP accident. Age- and body size-dependent differences in growth, metabolic rate, and diet, as well as seasonal migration patterns, also affected the rate of decrease in radiocesium levels, which likely led to the differences we observed between year-classes.

Keywords Pacific cod • Nuclear Power Plant accident • Radiocesium • Year-class • Seasonal migration • Ontogenetic shift of diet

10.1 Introduction

Huge amounts of radionuclides were released from the devastated Fukushima Daiichi Nuclear Power Plant following the Great East Japan Earthquake on 11 March 2011. The radionuclides contaminated the air, land, and ocean both directly and indirectly. Model estimates suggest that 3.5 ± 0.7 PBq radiocesium 137 was emitted directly to the ocean (Tsumune et al. 2012). A number of marine organisms ingested radionuclides into their body via the water and their diet. As a result, high concentrations of radiocesium were detected in almost all fish that inhabit the coast of Fukushima Prefecture within a year after the tsunami (Buesseler 2012). The level of contamination has decreased over time, and has now stabilized at a low level in pelagic fish species and invertebrates (Wada et al. 2013; Sohtome et al. 2014). In contrast, the decline in radionuclide levels has occurred more slowly in demersal fishes, resulting in food safety problems.

Pacific cod (*Gadus macrocephalus*) are one of the most important species in the upper continental slope ecosystem for commercial fishermen in the North Pacific off northern Japan (Tohoku area). The concentration of radiocesium in demersal fishes such as bighand thornyhead (*Sebastolobus macrochir*) and threadfin hakeling (*Laemonema longipes*) that inhabit the upper continental slope was low and stable even soon after the Fukushima Daiichi Power Plant (FNPP) accident (MAFF 2014). Despite occupying a similar spatial niche as these species, the radiocesium levels in some Pacific cod individuals were higher than allowable values in Japan ($^{134}Cs + ^{137}Cs$, 100 Bq/kg-wet). Additionally, the majority of demersal fishes that had radiocesium levels exceeding this standard were clustered in Fukushima and neighboring prefectures. In contrast, unsafe levels of radiocesium were measured in Pacific cod over a much wider area in 2011 and 2012, including five prefectures in the Tohoku district.

Commercial fishing or landing of cod was prohibited for 8 months after the shipment of cod was regulated in May 2012 in Miyagi Prefecture. The cod fishery was partially restarted in September 2012 when small cod (<1 kg) were approved for harvest, because high levels of radiocesium were only detected in large fish (≥1 kg). Therefore, the concentration of radiocesium in Pacific cod appears to be a function of age and body length. Our objective was to evaluate the relationship between age, body size, and radiocesium concentrations in Pacific cod following the FNPP accident. We documented the seasonal change in the distribution of fish of two age classes. Additionally, we evaluated the feeding ecology of Pacific cod in two regions to document ontogenetic shifts in diet. We measured radiocesium concentrations in the primary diet items of Pacific cod. Based on these data, we estimated when and how radiocesium was taken up by Pacific cod and the rate of decrease. We then used these results to predict conditions in the near future.

10.2 Radiocesium Concentration of Pacific Cod

We recorded the standard length and body weight of Pacific cod that were captured from April 2011 to March 2014 off Fukushima Prefecture and then removed the sagittal otoliths. One of the sagittal otoliths was cut into slices with hard resin and used for age determination following the method of Hattori et al. (1992). We determined the birth year-class of all specimens. Muscle tissue samples were removed from the vertebrae and skin to measure radiocesium concentrations. We examined the temporal changes in radiocesium concentration following the nuclear accident and compared the levels among year-classes (ycs).

The radiocesium concentration of Pacific cod was always higher in the year classes of 2009 and earlier (≤2009 yc) than in the 2010 yc (Fig. 10.1). The radiocesium concentrations measured from April 2012 to March 2013 ranged from

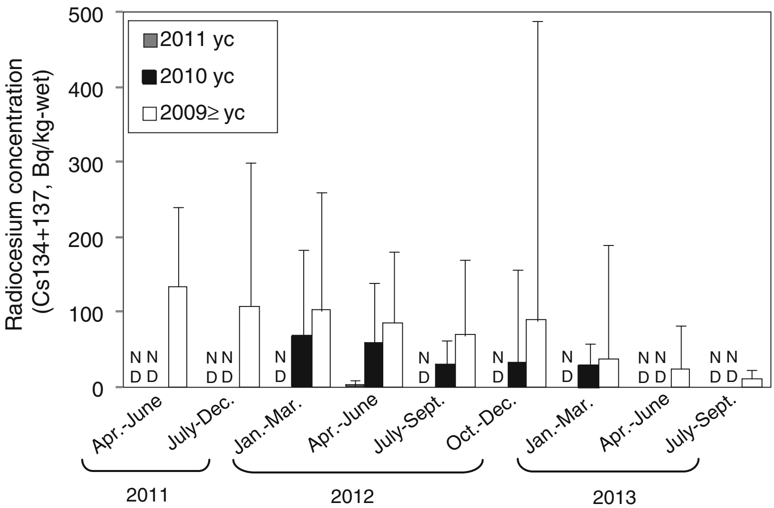

Fig. 10.1 Temporal changes in radiocesium (^{134}Cs + ^{137}Cs) concentration in the 2011, 2010, and ≤2009 year-classes of Pacific cod. *Boxes* and *bars* represent the average and maximum values, respectively. *ND* no data

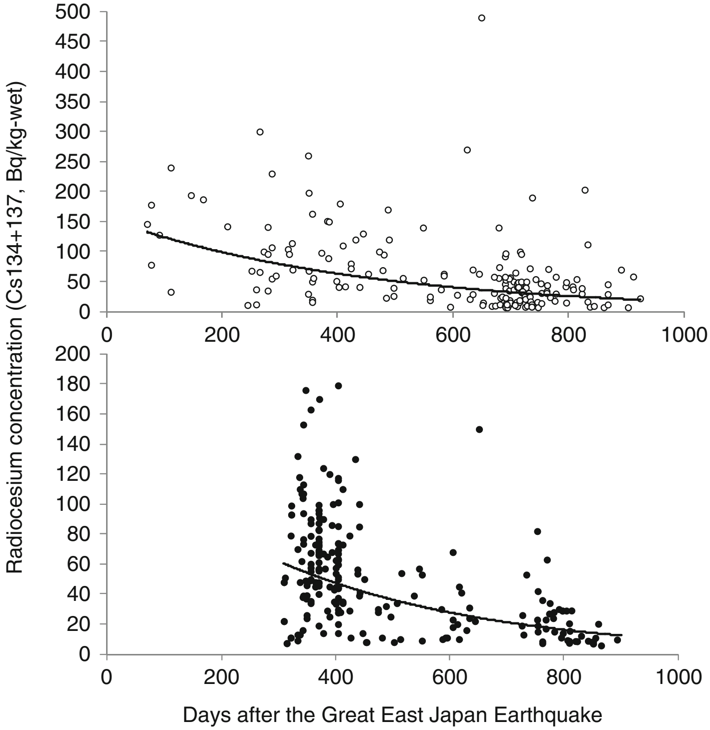

Fig. 10.2 Decay process of radiocesium in ≤2009 (*upper*) and 2010 (*lower*) year-classes of Pacific cod. The relationships were fitted for exponential function, expressed by the curved lines

0.37 to 0.75 times (average ± SD = 0.57 ± 0.16) lower in the 2010 yc than in the year-classes from 2009 and earlier. The concentration of radiocesium has decreased temporally since the nuclear plant accidents in both year-classes (Fig. 10.1). Interestingly, radiocesium was rarely detected, or detected at very low levels, in the 2011 yc.

The ecological half-life (Morita and Yoshida 2005; Iwata et al. 2013) was calculated using the exponential regression for surveyed concentrations of radiocesium and used to estimate the half-lives of radiocesium. This value can be used to predict future radiocesium concentrations. The regressions suggest that the ecological half-time of radiocesium was 309 and 258 days in the ≤2009 and 2010 year classes, respectively (Fig. 10.2). These results suggest that older and larger individuals concentrated higher levels of radiocesium and/or excreted radiocesium at a slower rate than younger and smaller Pacific cod individuals. The factors affecting age-related difference are examined in the subsequent sections.

10.3 Seasonal Change in Distribution

We conducted benthic trawl surveys from 2004 to 2013 in the northern Pacific off Honshu Island, Japan (Tohoku area) and in Sendai Bay using two research vessels (Table 10.1). Surveys off Tohoku area were conducted in April and in October–November at depths between 150 and 900 m (Fig. 10.3, Table 10.1). Surveys in Sendai Bay were conducted in January, February, April, June, July, and November at depths between 30 and 122 m. The details of the benthic trawl survey

Table 10.1 List of trawl survey cruises conducted in the present study by the research vessels *Dai-nana Kaiyo-maru* (D), or *Wakataka-maru* (W) in Sendai Bay (S) or offshore of Tohoku (T) giving the duration of the survey and number of benthic trawl tows (*N*)

Cruise	Vessel	Area	Duration	*N*
200407	W	S	28 Jun–2 Jul 2004	12
201006	W	S	20–23 Jun 2010	12
201202	D	S	2–6 Feb 2012	6
201204	W	S&T	17–25 Feb 2012	19
201210	W	S&T	20 Oct–21 Nov 2012	31
201304	W	S&T	16–23 Apr 2013	20
201310	W	S&T	15 Oct–25 Nov 2013	38

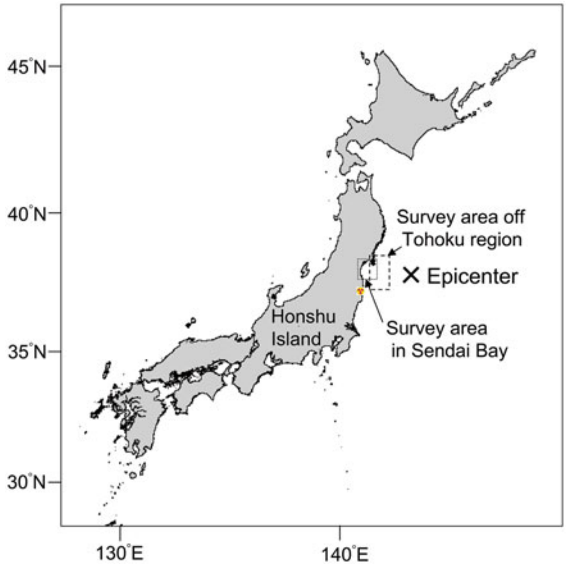

Fig. 10.3 Location of the study site and the epicenter of the Great East Japan Earthquake. Surveys were conducted at depths of 38–650 m in Sendai Bay and offshore of Tohoku

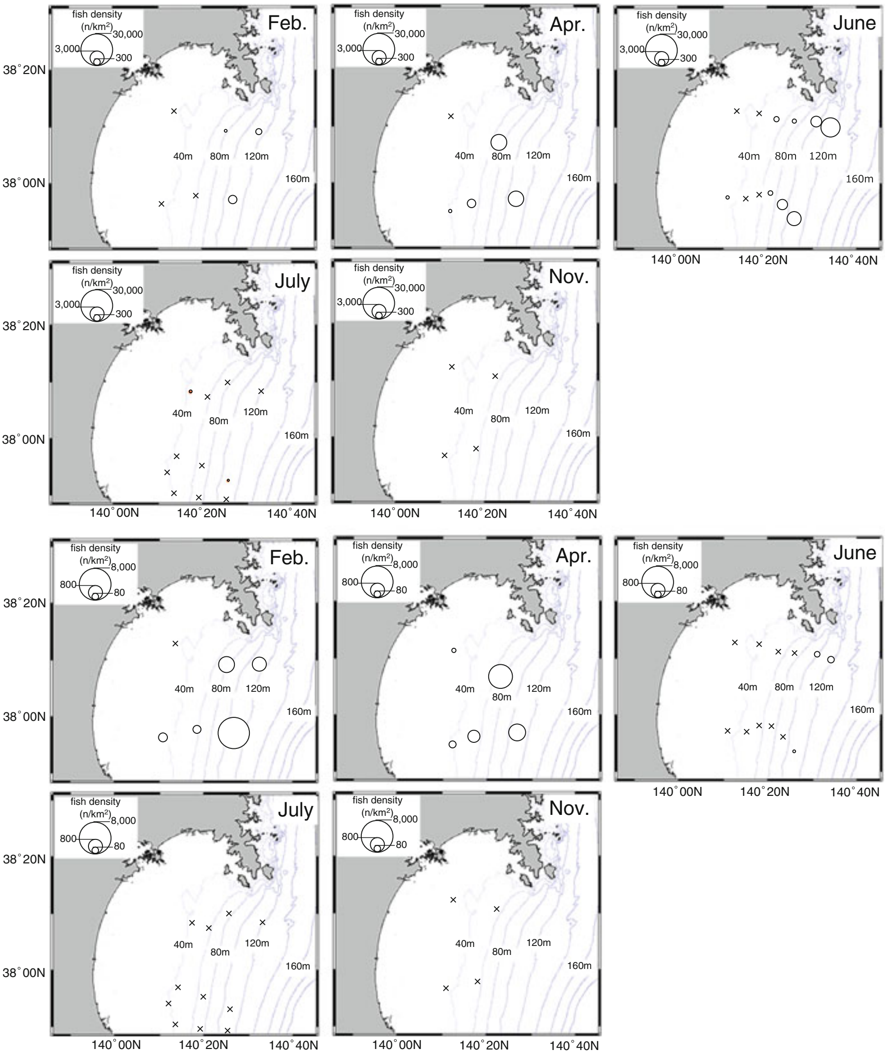

Fig. 10.4 Seasonal changes in the distribution of age 1+ (*upper*) and age ≥2+ (*lower*) Pacific cod in and off Sendai Bay. The timing of the surveys is described in Table 10.1

methodology are described by Hattori et al. (2008). We counted the number of age 1+ and 2+ Pacific cod caught in the net and estimated fish density (numbers/km^2) by dividing the number of fish captured by the trawl area.

Pacific cod aged 1+ year old were captured in shallow areas in Sendai Bay from February to June, but not in July and November (Fig. 10.4). In February and June, the majority of age 1+ cod were captured at depths >80 m, whereas in April they were captured in shallower waters. Pacific cod of age ≥2+ were also captured in Sendai Bay from February to June, with peak catches occurring in February and April. Only a few individuals remained in the Bay in June, and none was captured in the area shallower than 120 m in July and November.

Based on the results of this long-term trawl survey, Pacific cod appear to be widely distributed offshore of Tohoku in the spring and autumn (Fig. 10.5). In April, 1+-year-old Pacific cod tend to occupy the 100 to 400 m depth zone off Tohoku, but the density is highest at 100–200 m and very low at ≥300 m. In October–November, age 1+ cod occupied the depth zone from 200 to 500 m, with density peaking at 200–400 m. Cod were not captured in areas shallower than 200 m during these months. Age ≥2+ cod were captured at depths of 100–600 m and 200–600 m in April and October, respectively. The distribution of Pacific cod differed between months. The cod occupied depths that are about 100 m shallower in April (300–400 m) than in October.

The density of fish was compared between Sendai Bay and Tohoku for samples collected in April and in October–November. The density of 1+-year-old individuals was high at depths of 50–200 m, and particularly at 80–150 m (Fig. 10.5). Fish were seldom captured deeper than 300 m. The density of age 1+ Pacific cod was about four times higher at the 38–100 m depth than at 120–450 m in April. The age ≥2+ individuals were widely distributed, from 50 to 500 m. In contrast, in autumn, Pacific cod of both age classes were distributed from 200 to 600 m, but were most

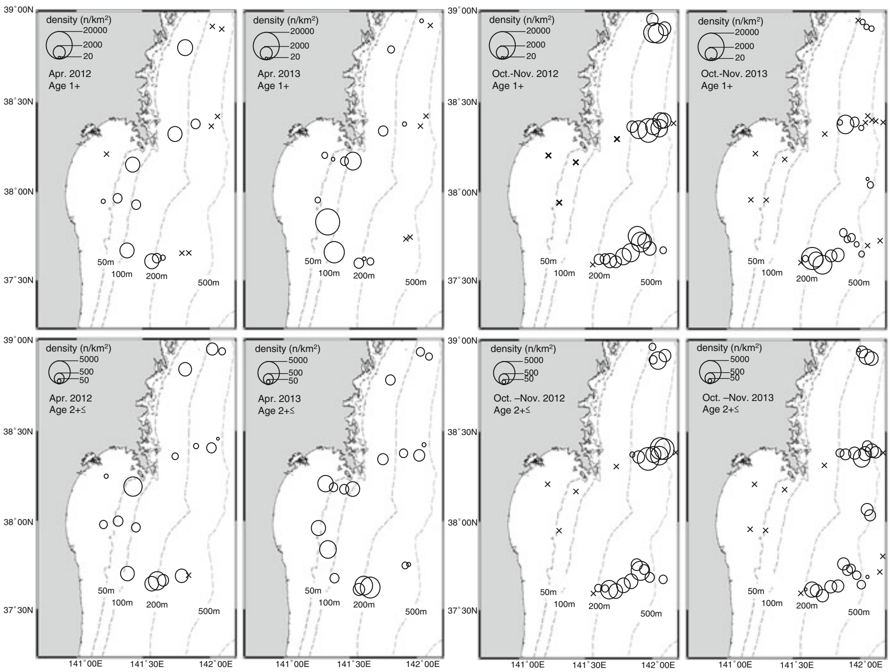

Fig. 10.5 Comparison of the distribution of age 1+ (*upper*) and age ≥2+ (*lower*) Pacific cod between spring and autumn. The timing of the surveys is described in Table 10.1

abundant at 200 to 500 m. The density of age ≥2+ Pacific cod was about two times higher at 38–100 m than at 120–450 m in April. These observations suggest that Pacific cod could inhabit the area near the FNPP at high density in April, during the time when cold water flows into Sendai Bay and offshore areas (Ito et al. 2004), but these fish migrate to the continental slope in July and remain there for several months.

Trawl surveys conducted off Tohoku throughout the year revealed that age 1+ and older Pacific cod were distributed at depths of 200–600 m in autumn, consistent with a previous report (Kitagawa et al. 2002), indicating that Pacific cod only inhabit the upper-continental slope during the autumn. In contrast, Pacific cod were distributed over both the upper continental slope and the continental shelf from winter to early summer. In Sendai Bay, age 1+ and ≥2+ individuals were represented in the catch from February to June. The older cod migrated into Sendai Bay and moved offshore slightly earlier than the younger individuals. In April, Pacific cod aged 1+ and ≥2+ years old were distributed throughout Sendai Bay, and their density was highest at the bay mouth (80–200 m deep). A large amount of radiocesium was released into the ocean after the FNPP accident in mid-March 2011, at a time when Pacific cod had likely moved into the shallower area. After occupying this area for a maximum of 3 or 4 months, the cod migrated off the continental shelf in July and did not return to the bay until February of the next year. Cod were distributed at depths similar to those of bighand thornyhead, *Sebastolobus macrochir* (Hattori et al. 2008), and threadfin hakeling, *Laemonema longipes* (Narimatsu et al. 2014), in offshore areas. The concentration of radiocesium in these two species remained very low or was nondetectable (Wada et al. 2013; MAFF 2014). Taking into consideration the pattern of seasonal migration, the rate of decline of radiocesium levels in Pacific cod, and the concentration of radiocesium in other species that occupy the upper continental slope, we conclude that contamination of Pacific cod with radiocesium occurred soon after the nuclear plant accident, from March to June in 2011.

10.4 Ontogenetic and Seasonal Diet Shift of Pacific Cod

Age 1+ and 2+ Pacific cod caught in Sendai Bay and off the Tohoku area, which is located off FNPP with a depth of 250 m, were used to evaluate their diet. Samples of fish were collected in April, June, and November in Sendai Bay, and in April and November off Tohoku. Fish were frozen soon after capture, their standard length and body weight were recorded, and they were dissected in the laboratory. The stomach was cut open and food items were sorted to the lowest possible taxon. Prey items were weighed to nearest 1 mg (wet weight). The percent contribution of each prey item to the diet of each age class was calculated. We compared the seasonal and spatial variation and ontogenetic shifts in the diet of Pacific cod.

A total of 247 fish stomachs were examined yielding 36 taxon or species of prey items. The primary prey items (>1 % of the total wet weight) differed among seasons, habitat types, and the body size of cod. In Sendai Bay, age 1+ Pacific cod

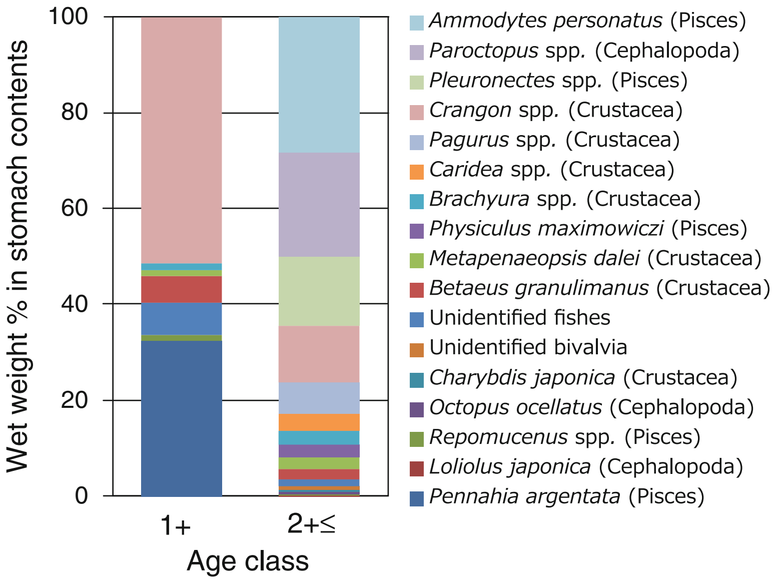

Fig. 10.6 Ontogenetic shift in diet for Pacific cod in Sendai Bay from April to June in 2012 and 2013

preyed primarily on *Crangon* spp. (Crustacea) such as *Crangon affinis* and *C. dalli*, followed by white croaker (*Pennahia argentata*, Pisces; Fig. 10.6). These two prey items accounted for 84 % of the total diet. Unidentified Pisces (6.9 %) and *Betaeus granulimanus* (Decapoda) were the next most common prey items. Age ≥2+ Pacific cod consumed a wider range of organisms compared with younger fish. In Sendai Bay, the older cod most commonly preyed on sand lance (*Ammodytes personatus*), followed by *Paroctopus* spp. (*P. dofleini and P. conispadiceus*), *Pleuronectes* spp. (*P. herzensteini and P. yokohamae*), and *Crangon* spp. A number of other fish and invertebrates were observed in the stomachs of age 2+ Pacific cod captured from April to June in Sendai Bay.

Age 1+ Pacific cod fed on the small pelagic invertebrates *Euphausia pacifica*, *Watasenia scintillans*, and *Themisto japonica* in April and June on the upper continental slope off Tohoku (Fig. 10.7). Age ≥2+ Pacific cod preyed primarily on flathead flounder *Hippoglossoids dubius*, followed by *Euphausia pacifica.* In October and November, benthic shrimp *Pandalus eous* were the most abundant (wet-weight) prey item of 1-year-old Pacific cod, followed by myctophid fish *Diaphus watasei* and unidentified fishes (Fig. 10.7). Older cod frequently fed on unidentifiable fishes, as well as *Diaphus watasei* and horsehair crab *Erimacrus isenbeckii*. These observations suggest that Pacific cod shift food items not only ontogenetically but also spatiotemporally.

Age 1+ cod fed on benthic *Natantia* euphausiids, small decapod cephalopods, small fishes, and cephalopod octopi whereas age ≥2+ individuals fed on Cephalopoda

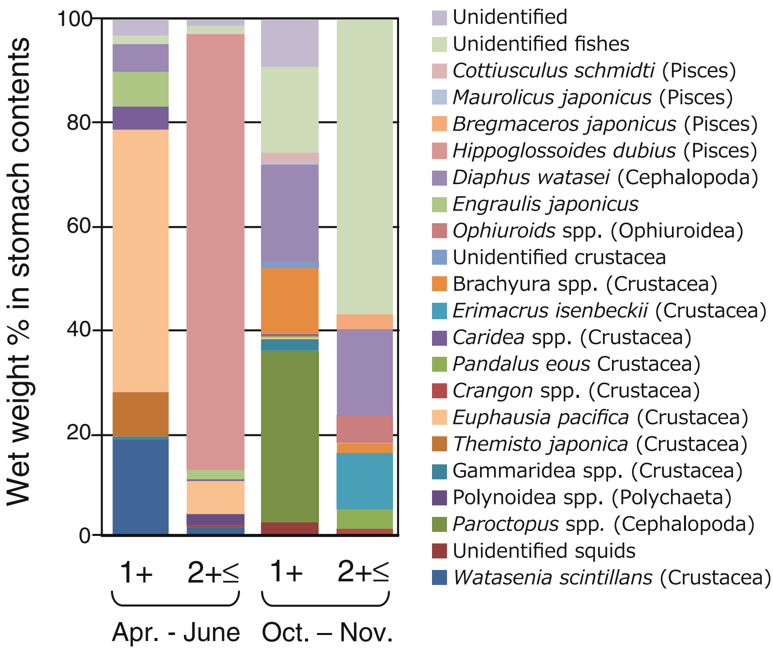

Fig. 10.7 Ontogenetic and temporal changes in diet for Pacific cod off Tohoku from October to November in 2012 and 2013

(octopods), benthic *Natantia*, *Brachyura*, and fish, including flatfish. Prior studies have documented a diet shift in Pacific cod distributed in areas deeper than 100 m (Hashimoto 1974; Yamamura 1994; Fujita et al. 1995). Cod smaller than 30 cm SL (corresponding to 1+-year-old individuals) primarily consume planktonic organisms. Cod in the range 30–40 cm SL (1+ to 2+ years old) also depend on Euphausiids, but the contribution to their diet is lower than for 30 cm fish, and they also feed on demersal organisms. Fish larger than 40 cm SL (≥2+ years old) primarily prey on fish and macrobenthos and rarely on planktonic invertebrates. Seasonal changes in diet were also observed in this population. Pelagic organisms such as euphasiids and mesopelagic fishes were the main prey items in the spring, whereas benthic species were the dominant prey item in autumn. Such variability in the type of prey items consumed by Pacific cod may reflect the general feeding characteristics of this species and seasonal changes in the biotic environment. Our observations suggest that large Pacific cod (age ≥2+) also consume mesopelagic invertebrates and that small individuals (age 1+) feed on similar items. However, Pacific cod basically shift their feeding habit from small plankton to macrobenthos with growth, and macrobenthic organisms such as large octopi and flatfishes can be prey items only for large cod because of the gape limitation of Pacific cod. The demersal fish such as sand lance and flatfish tended to accumulate radiocesium in their body and are only preyed on by large Pacific cod. The ontogenetic niche shift and species-specific difference in radiocesium concentration may result in the size-dependent difference in radiocesium concentrations observed in Pacific cod.

10.5 Radiocesium Concentration of Prey Items

A part of the species that occurred in the stomachs of Pacific cod were caught in the trawl surveys. The radiocesium concentrations of them and a part of prey items were measured by same method as the fish samples. The concentrations of the rest organisms were referred from the previous reports, respectively (MAFF 2014; Sohtome et al. 2014).

The radiocesium concentrations were analyzed for 17 species or taxon, which are the main prey items of Pacific cod in Sendai Bay and Tohoku (Fig. 10.8). The

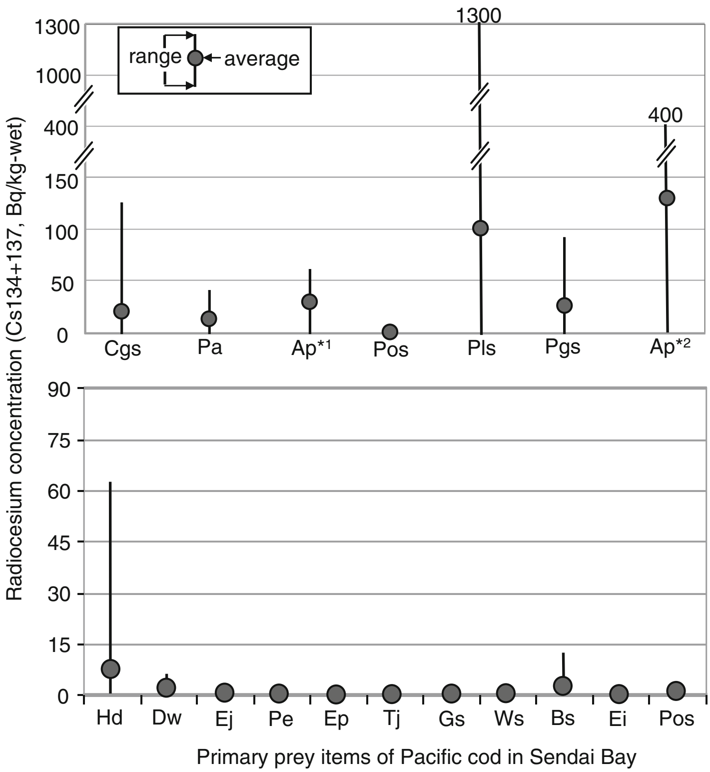

Fig. 10.8 Radiocesium concentrations in the primary prey items of Pacific cod in Sendai Bay (*upper*) and off Tohoku (*lower*). Species or taxon are shown by abbreviations: Cgs *Crangon* spp., Pa *Pennahia argentata*, Ap *Ammodytes personatus*, Pos *Paroctopus* spp., Pls *Pleuronectes* spp., Pgs *Pagurus* spp., Hd *Hippoglossoides dubius*, Dw *Diaphus watasei*, Ej *Engraulis japonicus*, Pe *Pandalus eous*, Ep *Euphausia pacifica*, Tj *Themisto japonica*, Gs Gammaridea spp., Ws *Watasenia scintillans*, Bs *Brachyura* spp., Ei *Erimacrus isenbeckii*. The indicators *1 and *2 indicate specimens caught from April 2011 to March 2012 and from April 2012 to December 2012, respectively

concentration of radiocesium in *Crangon* spp. and white croaker (*Pennahia argentata*, Pisces) ranged from below the detection limit (DL) to 126.3 Bq/kg-wet weight (mean ± SD = 19.5 ± 24.3) and below the DL to 41.0 Bq/kg-wet (12.5 ± 16.3), respectively. The concentration of radiocesium was higher within 1 year after the accident (134.5 ± 102.7) than 1 year after the accident (29.0 ± 21.8) in the sand lance *Ammodytes personatus,* the dominant prey item of age ≥2+ cod. Although the radiocesium concentrations in all *Paraoctopus* spp. and hermit crab *Pagurus* spp. (*Anomura*) were below the DL or relatively low (24.4 ± 24.3), high levels were detected in some *Pleuronectes* spp. specimens (102.5 ± 169.2). Almost all the prey items consumed on the upper continental slope had levels below the DL, except for the flathead flounder *Hippoglossoids dubius* (7.7 ± 14.7) and crabs (*Tymolus japonicus*, *Carcinoplax vestiva*: 2.8 ± 4.9). These results suggest that the concentrations of radiocesium were very low in the prey of Pacific cod (all age groups) off the FNPP at a depth of 250 m. In Sendai Bay, organisms consumed by age 1+ Pacific cod had relatively low radiocesium levels. However, some prey items observed in the stomach of age ≥2+ cod had relatively high radiocesium levels.

As described here, the timing of the migration from offshore to inshore and vice versa was similar between age classes, suggesting that the exposure to radiocesium was similar regardless of age and body size. However, the concentration of radiocesium was always higher in older and larger fish than in younger and smaller fish.

A number of marine organisms, including seaweeds, invertebrates, and fish, were contaminated by the radiocesium released from FNPP. The concentration and rate of decrease varied among species, likely because of differences in their biological characteristics (Wada et al. 2013). The levels of radiocesium were highest soon after the FNNP accident in all taxon (Wada et al. 2013). This pattern suggests that radiocesium contamination of all organisms primarily occurred in the first few months after the accident. Organisms that were distributed near the FNPP accumulated radiocesium from the seawater and prey items. The concentration of radiocesium in Pacific cod was variable, likely dependent on the initial intake of radiocesium, rate of decrease speed of radiocesium, the amount of additional intake of radiocesium from seawater, and the rate of growth (BW) during the first few months. However, additional intake of radiocesium only occurred via prey because radiocesium concentration in seawater was rapidly diluted/transported out of the area within a year, except for that in the port of FNPP (Buesseler et al. 2011; Aoyama et al. 2013; Kaeriyama et al. 2013, 2014); those levels in pelagic fish rapidly decreased (Iwata et al. 2013; Wada et al. 2013), and Pacific cod seldom inhabit and stay in the intertidal zone.

Pacific cod grow very rapidly (Hattori et al. 1992), resulting in dilution of the radiocesium in their body (dilution effect). Age 1+ cod are about 0.5 kg BW but grow to 1.5 kg BW in 1 year. Similarly, cod that are 1.0 kg BW (age 2+) grow to 2.3 kg BW in a year. A 0.5-kg BW individual has a 1.30 times higher dilution effect for radiocesium than does a 1.0-kg BW cod. The ecological half-time of radiocesium was estimated to be 258 and 309 days in the 2010 and the ≤2009 year-classes, respectively. Taking into consideration both the dilution effect and the age-specific decrease in concentrations, the level of radiocesium in the 2010 year-class is expected to decrease 1.56 times earlier than in the ≤2009 year-classes. The mean concentration of radiocesium in the ≤2009 year-classes was 1.75 times higher than in the 2010 year-class during the period January 2012 to March 2013. Assuming the initial concentrations were similar between year-classes, the difference between observed values and estimated values (based on dilution and age-specific effects) may be explained by the ontogenetic differences in prey items and their radiocesium concentration.

10.6 Conclusion

Large numbers of marine organisms were contaminated by radiocesium following the FNPP accident in March 2011. In some demersal fishes that inhabit the coastal regions, the rate of decrease in tissue radiocesium levels was lower than for other pelagic fishes and invertebrates, suggesting that additional radiocesium was taken up from the benthic ecosystem. This finding delayed the reopening of fisheries in the region. The estimated ecological half-life of radiocesium in Pacific cod was from 258 to 309 days; this value is consistent with values in other demersal fishes caught off Fukushima Prefecture (Wada et al. 2013). The half-life was longer in old and larger individuals than in young and small individuals, probably a result of differences in metabolic rate and growth rates between age and body size classes (Doi et al. 2012). Radiocesium concentrations decreased to low levels soon after the accident in seawater and prey items (Buesseler et al. 2011; Aoyama et al. 2013) and have continued to decease in the period up to 2014 (Sohtome et al. 2014). Thus, the potential for intake of radiocesium from the benthic ecosystem is very low in and after 2014. Additionally, radiocesium was rarely detected in the 2011 year-class. Pacific cod hatch during January to February in Sendai Bay (Narimatsu et al., unpublished data) and live a pelagic life for 3–4 months in the coastal zone. Some individuals of the 2011 year-class took in radiocesium via seawater and diet. However, the concentration of radiocesium in their body was diluted by growth, and the fish were only exposed to very low levels of radiocesium after settlement to benthic life. The Pacific cod of the following year-classes had already recruited into the ecosystem of the upper continental slope and were commercially caught in the Tohoku region. This population is primarily composed of young fish, and the generation cycle alters quickly (Narimatsu et al. 2010). We observed a decrease in radiocesium concentrations in the 2010 and ≥2009 year classes and an increase in the proportion of individuals born after the accident at the Nuclear Power Plant. Both these factors reduce the radiocesium concentrations at the population level and suggest the risk of restarting fisheries is minimal.

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