Cs/K Atom Ratios of Marine Organisms of Different Trophic Levels in Japanese Coastal Waters

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Cs/K atom ratios were examined in Japanese coastal waters and biota. The Cs/K atom ratios in coastal waters, chlorophyta (3 species), rhodophyta (10 species), phaeophyta (4 species), invertebrates (7 species), teleosts (15 species) were 2.1, 2.1, 1.9, 4.6, 3.5, $12 (\times 10^{-7})$, respectively. The Cs/K atom ratios were especially large in teleosts examined.

Cs/K atom ratios in organisms increased with the elevation of the trophic levels of the organisms. An "increase ratio" of Cs/K ratio was approximately 1.62 per one step elevation of trophic level.

The highest Cs/K atom ratios observed in teleosts suggested both the discrimination of Cs from K in teleosts and the discrimination of Cs from K in transferring these elements along food chains.

Key words: cesium, potassium, concentration factor, atom ratio, food chain, radionuclide, Cs-137, neutron activation analysis

Cs/K ratios were investigated in marine organisms. Original studies of Cs/K ratios in crabs,¹⁾ lobster and prawn,²⁾ were described, showing relatively higher Cs/K ratios in tissues than in blood of these invertebrates. Further study of brackish water invertebrates suggested that the relative increase of Cs concentration to K in tissues was possibly caused by active osmotic and ionic regulation.^{3,4)} The physiological reason of this increase of Cs/K ratio in tissue was attributed to the differences in the crystal radii of these ions, and the preferential binding of K relative to Cs in cells.¹⁾

While, some studies of food chains reported an increase in Cs/K ratios in organisms of higher food trophic ranking. Cs/K ratios in the Southern California marine biota,⁵⁾ off the California Bight, and the South Pacific⁶⁾ suggested that Cs/K ratios increased with elevation of trophic level, showing a factor of 1.5-2.2 in the Cs/K ratio per one trophic level up. The conclusion of the studies was that Cs was discriminated from K and accumulated during alkali element transport in the food chains.

In this report, the Cs/K atom ratios were measured in marine organisms of different taxa and trophic levels, aiming to clarify a magnitude of Cs discrimination from K in marine organisms, and alkali element transfer through marine food chains. To evaluate the magnitude of Cs discrimination from K, Cs/K atom ratios were used instead of Cs/K concentration ratios, which had been used in past studies.^{1-3,5,6)} As discrimination was assumed to have occurred due to the difference of crystal radii of these ions,²⁾ we should compare the increases in the numbers of each ion in various marine organism tissues by calculating atom ratios, and not by concentration ratios.

Materials and Methods

From 1984 to 1990, biological samples and seawater were collected from the coastal areas of Japan (Oshoro

Bay, Hachinohe, Rokkasho, Sanriku, Sakata, Sado, Katsuura, Tsuyazaki), as shown in Fig. 1. Twelve samples of seawater, 57 samples of algae, including 17 different species, 12 samples of invertebrates, including 7 different species, 22 samples of fish, including 15 different species, were collected by a SCUBA diver, underwater traps, set nets and hooks. Sample sites were carefully chosen to eliminate areas affected by extreme river run-off, as freshwater inflow alters the element composition of seawater and biological conditions.

The stomach contents of organisms were sorted by taxon to assign the organisms to the appropriate trophic level. Biological samples were rinsed with clean seawater to remove attached organisms and substances. The whole-body of algae, except rhizoid, was cleaned with a paper towel to

Fig. 1. Location of sampling sites.

remove moisture from its surface, then the wet weight was measured. Samples of algae, fish flesh, muscles of sea cucumber and sea squirt, muscles and mantles of mollusks, were oven-dried for 24 hours at 110°C and were ashed at 250°C for 24 hours, followed by 450°C for 48 hours. The ash rate of samples was 3.6–7.8% for algae and 1.1–2.3% for animals. Seawater samples were filtered through 0.45 µm of pore size Millipore filters, then HNO₃ was added for string.

For analysis of stable Cs in biological samples, ashed samples (300 to 500 mg) were irradiated in nuclear reactor facility JRR-4 of the Japan Atomic Energy Research Institute for 20 minutes with a flux of about 8×10^{13} n/cm²/sec. After 28 to 57 days-cooling, gamma-radioactivity of 0.796 MeV was measured for 10,000 sec by a Ge (Li) detector (ORTEC GEM-10195) and a multichannel analyzer (TRACOR NORTHERN TN-1750), and the concentration of Cs was determined by comparing it with the irradiated standard Cs. For analysis of stable Cs in seawater, samples (3 to 10 ml) were freeze dried, packed into quartz glass tubes, and irradiated in a nuclear reactor facility JRR-2 of the Japan Atomic Energy Research Institute, for 265.5 hours with a flux about 3×10^{13} n/cm²/sec. After 31 to 60 days-cooling, gamma-radioactivity was measured by the same method as the biological samples.

For analysis of K, ashed samples (300 to 500 mg) were digested with HNO₃ and analyzed by an atomic absorption spectrometer (HITACHI Z-6000). Seawater samples were diluted and acidified by HNO₃, and analyzed by the same method.

The errors of stable Cs analysis were $< \pm 7\%$, $< \pm 31\%$, $< \pm 14\%$ of the values for seawater, algae and marine animal samples, respectively. The errors of K analysis were $< \pm 3\%$, $< \pm 8\%$ of the values for seawater and biological samples, respectively. The sensitivity limits of Cs determination were 0.01 µg/l for seawater and 0.1 ng/g for biological wet samples. Those of K determination were 10 mg/l for seawater and 0.05 mg/g for biological wet samples.

The accuracy of the values of analysis were assured by the reference standard materials of NIES No. 1 (pepper bush), NIES No. 6 (mussel), NBS SRM 1572 (citrus leaves), and IAEA SL-1 (lake sediment), as shown in Table 1. The

results of the analyses showed a satisfactory good agreement with the reference values.

Results

Cs/K Atom Ratio in Japanese Coastal Waters

The Cs/K atom ratio in seawater are shown in Table 2. Here, we used the atom ratio of Cs and K to estimate the number of atoms in samples, instead of the concentration ratio often used in other reports.⁵⁻⁷ The reported Cs concentrations in seawater were 0.15 to 0.5 µg/l.^{8,9} The K concentration in seawater is said to have a near universal value of 399 to 400 mg/l.⁸ My result showed a values of 0.24 to 0.34 µg/l for Cs and a value of 370 to 420 mg/l for K in Japanese coastal waters. The results indicates that the sampling sites were not affected by river run-off. The Cs/K atom ratios were ranging from 1.8 to 2.5×10^{-7} , which gave the geometric mean value 2.1×10^{-7} .

Cs and K Concentration in Marine Organisms

The results of the analyses of Cs and K in organisms are shown in Table 3. Examination of Table 3 reveals two features: (1) A high concentration of Cs in fish muscle; Cs concentrations in teleosts ranged from 8.8 to 19 ng/g wet weight, distinctively larger values than those seen in other organisms. (2) High concentrations of K in Phaeophyta; K concentrations in phaeophyta ranged from 1.7 to 58 mg/g wet weight, which were approximately two times higher than those of other algae and marine animals.

Except for *Gloiopeltis furcata*, the Cs/K atom ratios in algal taxa showed an order of magnitude of 10^{-7} , while Cs/K atom ratios in teleosts showed an order of magnitude of 10^{-6} .

Trophic Level Assignments in Food Chains

Table 4 summarizes the stomach contents of investigat-

Table 1. Analyzed values of standard reference materials

Element	Reference material	Certified value	Analyzed value
Potassium	Pepperbush (NIES No. 1)	1.51 ± 0.06	1.47 ± 0.04
	Mussel (NIES No. 6)	0.54 ± 0.02	0.54 ± 0.03
	Citrus Leaves (NBS 1572)	1.82	1.81
			(Wt. / %)
Cesium	Pepperbush (NIES No. 1)	(1.2)*	1.2
	Citrus Leaves (NBS 1572)	(0.098)	0.096
	Lake sediment (IAEA SL-1)	7.01 ± 0.88	7.00 ± 0.70
			(µg/g dry)

* Values in parentheses are not certified.

Table 2. Cs/K atom ratio in Japanese coastal water (0.45 µm filtered)

Location	Sampling date	Concentration		Atom ratio* ₂ Cs/K ($\times 10^{-7}$)
		Cs µg/l	K mg/l	
Oshoro	1984. 7. 11	0.28	390	2.1
	1987. 7. 15	0.3* ₁	400	2.2
	1989. 7. 12	0.30	410	2.2
	1990. 7. 18	0.25	370	2.0
Rokkasho	1989. 8. 3	0.33	400	2.4
	1990. 7. 3	0.24	370	1.9
Sakata	1984. 5. 22	0.29	420	2.0
Sado	1985. 5. 21	0.26	400	1.9
Katsuura	1984. 5. 16	0.25	400	1.8
Tsuyazaki	1985. 6. 27	0.34	390	2.5
	1987. 6. 26	0.31	370	2.5
	1989. 7. 5	0.3* ₁	400	2.2
		0.29 ± 0.01* ₃	390 ± 10	2.1 ± 0.1

*₁ 0.3 µg/l cited from Bowen⁸.

*₂ Cs/K atom ratio = $\frac{\frac{\mu\text{g/l}}{10^6} \times \frac{6.02 \times 10^{23}}{133}}{\frac{\text{mg/l}}{10^3} \times \frac{6.02 \times 10^{23}}{39.09}}$

*₃ geometric mean and standard error of mean value.

Table 3. Cs/K atom ratio in marine organisms collected from Japanese coastal waters

Species	Location	Sampling date	Concentration		Atom ratio* ¹ Cs/K ($\times 10^{-7}$)	Trophic level* ²
			Cs ng/g wet	K mg/g wet		
Chlorophyta						
<i>Ulva pertusa</i>	Oshoro	1984. 7. 11	10	16	1.8	I
<i>Ulva pertusa</i>	Oshoro	1985. 7. 16	26	12	6.7	I
<i>Ulva pertusa</i>	Sanriku	1986. 6. 25	2.9	6.0	1.4	I
<i>Ulva pertusa</i>	Oshoro	1986. 7. 3	1.0	1.5	2.0	I
<i>Ulva pertusa</i>	Oshoro	1989. 7. 13	3.0	5.6	1.6	I
<i>Codium fragile</i>	Tsuyazaki	1985. 6. 25	5.6	8.1	2.0	I
<i>Codium fragile</i>	Tsuyazaki	1986. 6. 10	1.3	8.2	0.46	I
<i>Enteromorpha intestinalis</i>	Oshoro	1985. 7. 16	22	9.7	6.6	I
<i>Enteromorpha intestinalis</i>	Oshoro	1986. 7. 3	5.7	6.2	2.7	I
Phaeophyta						
<i>Undaria pinnatifida</i>	Oshoro	1984. 7. 11	19	33	1.7	I
<i>Undaria pinnatifida</i>	Oshoro	1995. 7. 16	12	12	2.9	I
<i>Undaria pinnatifida</i>	Oshoro	1986. 7. 3	6.1	8.6	2.1	I
<i>Undaria pinnatifida</i>	Oshoro	1989. 7. 13	5.0	7.7	1.9	I
<i>Eisenia bicyclis</i>	Tsuyazaki	1984. 6. 28	13	17	2.2	I
<i>Eisenia bicyclis</i>	Tsuyazaki	1985. 6. 25	9.3	8.6	3.2	I
<i>Laminaria religiosa</i>	Oshoro	1984. 7. 11	6.9	15	1.4	I
<i>Laminaria religiosa</i>	Oshoro	1985. 7. 16	12	9.6	3.7	I
<i>Laminaria religiosa</i>	Oshoro	1985. 7. 13	7.2	16	1.3	I
<i>Sargassum thunbergii</i>	Oshoro	1984. 7. 11	25	58	1.3	I
<i>Sargassum thunbergii</i>	Oshoro	1985. 7. 16	16	16	3.0	I
<i>Sargassum thunbergii</i>	Oshoro	1986. 7. 3	7.3	17	1.3	I
<i>Sargassum thunbergii</i>	Sanriku	1986. 6. 25	10	18	1.6	I
<i>Sargassum patens</i>	Katsuura	1984. 5. 17	6.4	19	0.96	I
<i>Sargassum patens</i>	Tsuyazaki	1985. 6. 25	8.3	12	2.0	I
<i>Sargassum yezoense</i>	Oshoro	1984. 7. 11	26	22	3.5	I
<i>Sargassum yezoense</i>	Oshoro	1985. 7. 16	11	13	2.4	I
<i>Sargassum yezoense</i>	Oshoro	1986. 7. 3	6.3	13	1.4	I
<i>Sargassum horneri</i>	Tsuyazaki	1984. 6. 28	10	11	2.9	I
<i>Sargassum horneri</i>	Katsuura	1984. 5. 17	5.2	13	1.1	I
<i>Sargassum horneri</i>	Oshoro	1984. 7. 11	33	55	1.8	I
<i>Sargassum horneri</i>	Oshoro	1985. 7. 16	17	11	4.5	I
<i>Sargassum horneri</i>	Tsuyazaki	1986. 6. 10	5.1	10	1.5	I
<i>Sargassum horneri</i>	Sanriku	1986. 6. 25	4.2	4.0	3.1	I
<i>Sargassum horneri</i>	Katsuura	1986. 5. 26	17	15	3.3	I
<i>Sargassum horneri</i>	Oshoro	1986. 7. 3	6.6	11	1.7	I
<i>Sargassum horneri</i>	Oshoro	1989. 7. 13	6.2	9.0	2.0	I
<i>Sargassum ringgoldianum</i>	Katsuura	1984. 5. 17	7.7	24	0.92	I
<i>Sargassum ringgoldianum</i>	Tsuyazaki	1984. 6. 28	6.6	15	1.3	I
<i>Sargassum ringgoldianum</i>	Tsuyazaki	1985. 6. 25	3.6	7.1	1.5	I
<i>Sargassum ringgoldianum</i>	Katsuura	1985. 5. 22	11	18	1.8	I
<i>Sargassum ringgoldianum</i>	Tsuyazaki	1986. 6. 10	4.8	10	1.4	I
<i>Hizikia fusiformis</i>	Katsuura	1984. 5. 17	5.2	20	0.76	I
<i>Hizikia fusiformis</i>	Tsuyazaki	1984. 6. 28	7.2	18	1.2	I
<i>Hizikia fusiformis</i>	Katsuura	1985. 5. 22	6.8	8.0	2.5	I
<i>Hizikia fusiformis</i>	Tsuyazaki	1985. 6. 25	9.3	3.0	9.2	I
<i>Hizikia fusiformis</i>	Sanriku	1986. 6. 25	6.4	22	0.86	I
<i>Desmarestia ligulata</i>	Sanriku	1986. 6. 25	2.3	1.7	4.0	I
Rhodophyta						
<i>Neodilsea yendoana</i>	Oshoro	1984. 7. 11	27	26	3.0	I
<i>Neodilsea yendoana</i>	Oshoro	1985. 7. 16	16	15	3.2	I
<i>Neodilsea yendoana</i>	Oshoro	1986. 7. 3	9.7	8.3	3.4	I
<i>Neodilsea yendoana</i>	Sanriku	1986. 6. 25	4.1	4.6	2.6	I
<i>Neodilsea yendoana</i>	Oshoro	1989. 7. 13	8.0	8.7	2.7	I
<i>Laurencia nipponica</i>	Oshoro	1984. 7. 11	13	4.6	8.3	I
<i>Laurencia nipponica</i>	Oshoro	1986. 7. 3	7.9	3.8	6.1	I
<i>Laurencia nipponica</i>	Oshoro	1989. 7. 13	3.9	2.0	5.9	I
<i>Condorus ocellatus</i>	Sanriku	1986. 6. 25	7.5	6.2	3.6	I
<i>Gloiopeltis furcata</i>	Sanriku	1986. 6. 25	14	2.2	19	I
Echinodermata						
<i>Stichopus japonicus</i>	Oshoro	1986. 6. 10	1.1	0.62	5.2	II-III
Gastropoda						
<i>Hariotis discus</i>	Katsuura	1986. 7. 9	2.7	2.6	3.3	II
<i>Hariotis discus</i>	Hachinohe	1987. 6. 25	2.6	3.5	2.2	II

Tabel 3. (continued)

Pelecypoda							
<i>Patinopecten yessoensis</i>	Hachinohe	1986. 6. 3	2.1	3.7	3.6	II-III	
<i>Patinopecten yessoensis</i>	Hachinohe	1987. 8. 28	6.6	4.7	4.1	II-III	
Cephalopoda							
<i>Paroctopus dolfeini</i>	Hachonohe	1986. 6. 3	3.0	3.3	2.6	III-IV	
<i>Loligo bleekeri</i>	Katsuura	1986. 5. 27	2.3	2.0	3.4	II-III	
<i>Todarodes pacificus</i>	Hachinohe	1986. 6. 3	4.6	4.1	3.3	III-IV	
<i>Todarodes pacificus</i>	Hachinohe	1987. 7. 9	3.2	3.7	2.6	III-IV	
<i>Todarodes pacificus</i>	Hachinohe	1988. 10. 20	2.6	2.4	3.2	III-IV	
Tunicata							
<i>Halocynthia roretzi</i>	Hachinohe	1986. 6. 3	5.2	1.3	12	II-III	
<i>Halocynthia roretzi</i>	Hachinohe	1987. 6. 4	3.9	5.5	2.1	II-III	
Teleost							
<i>Parapristipoma trilineatum</i>	Katsuura	1985. 8. 19	10	4.1	7.5	III-IV	
<i>Hexagrammos otakii</i>	Katsuura	1985. 10. 1	11	2.1	16	III-IV	
<i>Hexagrammos otakii</i>	Katsuura	1986. 7. 9	13	1.5	26	III-IV	
<i>Hexagrammos otakii</i>	Hachinohe	1990. 7. 19	19	4.1	13	IV-V	
<i>Ditrema temmincki</i>	Hachinohe	1986. 6. 3	13	3.6	11	III-IV	
<i>Ditrema temmincki</i>	Katsuura	1986. 7. 9	14	4.0	9.6	III-IV	
<i>Ditrema temmincki</i>	Katsuura	1985. 10. 2	11	3.6	9.2	III-IV	
<i>Sebastes inermis</i>	Katsuura	1985. 8. 26	17	4.0	13	IV-V	
<i>Sebastes marmoratus</i>	Katsuura	1985. 8. 21	15	4.0	11	IV-V	
<i>Microstomus ache</i>	Hachinohe	1986. 6. 3	11	2.3	14	III-IV	
<i>Paralichthys olivaceus</i>	Katsuura	1986. 5. 28	15	4.1	11	IV-V	
<i>Paralichthys olivaceus</i>	Hachinohe	1986. 6. 3	11	3.6	9.0	IV-V	
<i>Paralichthys olivaceus</i>	Hachinohe	1989. 12. 6	13	3.1	12.	IV-V	
<i>Paralichthys olivaceus</i>	Hachinohe	1987. 5. 28	16	3.5	13	IV-V	
<i>Kareius bicoloratus</i>	Katsuura	1986. 5. 28	9.4	4.2	6.5	III-IV	
<i>Hippoglossoides dubius</i>	Hachinohe	1987. 6. 25	12	2.7	13	III-IV	
<i>Myoxocephalus stelleri</i>	Oshoro	1990. 7. 19	12	3.5	11	IV-V	
<i>Sebastes pachycephalus</i>	Katsuura	1985. 9. 24	8.8	3.6	7.3	IV-V	
<i>Sebastes schloegeli</i>	Hachinohe	1986. 6. 3	17	4.7	11	IV-V	
<i>Hexgrammos agurammus</i>	Tsuyazaki	1986. 6. 23	13	3.5	11	III-IV	
<i>Sebastes baramenuke</i>	Hachinohe	1986. 6. 3	13	2.8	14	IV-V	
<i>Oncorhynchus keta</i>	Hachinohe	1987. 10. 25	16	2.2	22	IV-V	

$$^{*1} \text{ Cs/K atom ratio} = \frac{\frac{\text{ng/g}}{10^9} \times \frac{6.02 \times 10^{23}}{133}}{\frac{\text{mg/g}}{10^3} \times \frac{6.02 \times 10^{23}}{39.09}}$$

^{*2} See Table 4. and text.

ed animal samples and the food habits shown in other studies. The trophic levels of each organism were assigned by the trophic level assignment of prey organisms found in stomachs and also determined by food habits reported in other studies. The trophic level categorizations of investigated organisms were basically as follows; trophic level I: producers, which included algae, phytoplankton, and detritus originated from phytoplankton and algae; trophic level II: herbivores, which included herbivorous zooplankton, herbivorous invertebrates, herbivorous fish, detritus originated from zooplankton and bacteria; trophic level III: primary carnivores, which included carnivorous invertebrates and fish; trophic level IV, V: secondary, tertiary carnivores, which were piscivorous fish.

However, organism stomach contents were not so simple to classify. Assignment of trophic level was difficult because most organisms depend on a wide range of prey, including those from different trophic levels. As common prey organisms such as mysids, amphipods, ophiuroids, decapods, and copepods were assigned to the intermediate trophic levels II and III (expressed as II-III in Table 4), most predator organisms were assigned to intermediate trophic levels III and IV (expressed as III-IV). In the same

way, the predator organisms that ingested prey organisms of trophic level III and IV were assigned to intermediate levels IV and V (expressed as IV-V). As reports on both of stomach content and food habits were scarce for *Patinopecten yessoensis*, *Sebastes marmoratus*, *Sebastes pachycephalus* and *Sebastes baramenue*, we assumed their trophic levels were the same as those of organisms of the same taxonomical species. The final trophic level categorization of each organism is shown in Table 3.

In natural environments, trophic levels of the same species were known to vary reflecting dietary changes with predator growth,¹⁰⁾ the seasonal changes in trophic structures and species composition in ecosystems.¹¹⁾ But in this study, a radical change of feeding habits did not occur from May to August.¹¹⁾ Thus we could assume that stomach contents of samples reflected the feeding habits of investigated organisms during the previous few months.

Discussion

Cs and K Concentration Factors in Marine Organisms

K is known as an essential element, while Cs is not recognized as an essential element in marine organisms at the

Table 4. Trophic level assignment by stomach contents and reported food items

Species	Location	Sampling date	Stomach contents (wet weight percentage)	Reported food items	Trophic level assignment
<i>Hariotis descus</i>	Katsuura	1986. 7. 9	algae	<i>Undaria, Desmarestia, Alaria, Eisenia</i> ²²⁾	II
<i>Halocynthia roretzi</i>	Hachinohe	1987. 6. 4	mud, phytoplankton, detritus		II-III
<i>Stichopus japonicus</i>	Oshoro	1990. 7. 13	mud, detritus		II-III
<i>Loligo bleekeri</i>	Tsuyazaki	1986. 6. 13	fish larva		II-III
<i>Todarodes pacificus</i>	Hachinohe	1988. 10. 20	mysids, fish, cephalopods		III-IV
<i>Paroctopus dolfeini</i>	Hachinohe	1988. 10. 20		decapods ²³⁾	III-IV
<i>Parapristipoma trilineatum</i>	Katsuura	1985. 8. 19	amphipods	mysids, copepods, bivalves ²⁴⁾	III-IV
<i>Ditrema temmincki</i>	Hachinohe	1986. 6. 3	decapods	gammarids, amphipods ²⁵⁾	III-IV
<i>Ditrema temmincki</i>	Katsuura	1986. 7. 9	amphipods		III-IV
<i>Microstomus achne</i>	Hachinohe	1986. 6. 3	amphipods (98%), annelids		III-IV
<i>Kareius bicoloratus</i>	Katsuura	1986. 5. 26		polchaeta, Pinnixa, Ammodytes ²⁶⁾	III-IV
<i>Hippoglossoides dubius</i>	Hachinohe	1987. 6. 25	Ophiuroids		III-IV
<i>Hexagrammos agurammus</i>	Tsuyazaki	1986. 6. 23	amphipods, annelids	amphipods, isopods ²⁷⁾	III-IV
<i>Sebastes inermis</i>	Katsuura	1985. 8. 26	amphipods, decapods	amphipods, isopods ²⁷⁾	III-IV
<i>Hexageammus otakii</i>	Katsuura	1985. 10. 1	fish, decapods, gastropods	annelids ²⁴⁾	III-IV
<i>Hexagrammos otakii</i>	Hachinohe	1986. 6. 13	fish (50%), amphipods (40%), egg		III-IV
<i>Hexagrammos otakii</i>	Katsuura	1985. 7. 9	amphipods, annelids, decapods		III-IV
<i>Hexagrammos otakii</i>	Hachinohe	1990. 7. 19	fish (61%), decapods (22%)		IV-V
<i>Paralichthys olivaceus</i>	Katsuura	1986. 5. 28	fish (90%), amphipods	<i>Ammodytes, Engraulis</i> ²⁶⁾	IV-V
<i>Paralichthys olivaceus</i>	Hachinohe	1986. 6. 3	fish (90%), cephalopods		IV-V
<i>Myoxocephalus stelleri</i>	Oshoro	1989. 7. 19	fish (95%), cephalopods		IV-V
<i>Sebastes schelegeli</i>	Hachinohe	1986. 6. 3	fish, cephalopods	fish, Natantia, <i>Branchiura</i> ²⁷⁾	IV-V
<i>Oncorhynchus keta</i>	Hachinohe	1987. 10. 25	fish, amphipods	fish ²⁸⁾	IV-V

Trophic levels of prey were estimated as follows; phytoplankton, algae: I, detritus: I, II,²⁹⁾ bacteria: II, mysids: II, III,³⁰⁾ amphipods: II, III,³¹⁾ ophiuroids: II, III,³²⁾ decapods: II, III,³³⁻³⁵⁾ copepoda: II, III,^{36,37)} annelids: II, III,²⁹⁾ fish: III, IV,³⁸⁾ shrimp: II, III,³⁹⁾ bivalves: II, III.⁴⁰⁾

present time.³⁾ Therefore, some difference of behavior of the elements during metabolism in organisms could be expected, which will cause the concentration factors of these two elements to differ.³⁾

The concentration factors of Cs and K in organisms of different taxa investigated are shown in Table 5. The data distributions shown log-normal distributions as shown in Figs. 2 and 3. As normalities were assured by taking natural logarithms of the data, statistic comparisons were completed by the analysis of variance tests with a significant level of $p < 0.05$.

The results as shown in Table 5 reveal the differences in the order of concentration factors among different taxa. In the marine animals examined, K concentration factors were relatively small and showed the same order of magnitude in invertebrates and teleosts, while the Cs concentration factors were significantly larger in teleosts than in invertebrates. This result suggests that Cs shows different characteristics than K in alkali element metabolism of teleosts. K concentration factors in algae were significantly larger than those in animals, while the Cs concentration factors in algae were not significantly different from those of teleosts, but larger than those of invertebrates.

Among the algal taxa, The Cs concentration factors of chlorophyta were significantly lower than those of the other two algal taxa, as shown in Fig. 2, while K concentration factors were significantly larger in phaeophyta than those in other algal taxa as shown in Fig. 3. There were two contradictory reports about Cs concentration factors in algae. One was a report by Pentreath¹²⁾ on algae in the North Sea, which showed that chlorophyta accumulated Cs more than phaeophyta and rhodophyta. The other report was a recent CF review by Gomez *et al.*,¹³⁾ which in-

Table 5. Cs and K concentration factors in marine organisms of different taxa

	n	Concentration factor of Cs* ¹		Concentration factor of K* ²	
		mean $\pm$ S.E.* ³	range	mean $\pm$ S.E.	range
Chlorophyta	9	17 $\pm$ 11	3.6-90	18 $\pm$ 4	3.8-41
Phaeophyta	34	29 $\pm$ 4	7.9-110	33 $\pm$ 5	4.3-150
Rhodophyta	10	33 $\pm$ 7	13-93	15 $\pm$ 6	5.1-67
Invertebrates	12	10 $\pm$ 2	3.8-23	7.0 $\pm$ 1	1.6-14
Teleosts	22	45 $\pm$ 2	30-66	8.7 $\pm$ 0.4	3.8-12

*¹ Estimated concentration factor by the equation: (Cs ng/g wet in organism) / (Cs 0.29 ng/ml in Japanese coastal waters from Table 2).

*² Estimated concentration factor by the equation: (K mg/g wet in organism) / (K 0.39 mg/ml in Japanese coastal waters from Table 2).

*³ Geometric mean and standard error of mean value.

indicated that concentration factors of phaeophyta was the largest, followed by those of rhodophyta and chlorophyta, respectively. My findings of Cs concentration factors did not agree with either the results shown by Pentreath¹²⁾ or Gomez *et al.*¹³⁾ The reason for this inconsistency can likely be attributed to the fewer number of data used in those reports.

Cs/K Atom Ratio in Marine Organisms

Cs/K atom ratios in marine organisms are shown in Table 6, and the distributions of data are shown in Fig. 4. The data showed three salient features. (1) In chlorophyta and phaeophyta, Cs/K atom ratios showed no significant difference from those of seawater. This result means no obvious difference is present in uptake behavior of these two

Fig. 2. Cumulative plots of Cs concentration factors of biological samples.

Regression coefficients between cumulative and Cs concentration factor are shown with legends.

Fig. 3. Cumulative plots of K concentration factors in biological samples.

Regression coefficients between cumulative and K concentration factor are shown with legends.

elements between these two algal taxa. In contrast, rhodophyta showed significantly higher Cs/K atom ratios than those of seawater. This suggests the presence of relatively large stable Cs metabolic pools in this algal taxon. (2) In teleosts, a significant difference in Cs/K atom ratios was detected compared to those of other organisms. Suzuki⁷⁾ reported a mean value of 22×10^{-7} for 11 species of Japanese teleosts. Both my data and Suzuki's data indicated that Cs/K atom ratios were obviously high in teleosts. This suggests the Cs discriminated from K during alkali element metabolism in teleosts. (3) Marine invertebrates showed significantly smaller Cs/K atom ratios than those of teleosts. However, reported Cs/K ratios in squids had larger values (9.5×10^{-7} ¹⁴⁾ and 5.6×10^{-7} ⁶⁾ than those in my study. Additionally, some invertebrates were known to show larger ratios of (Cs concentration in tissue)/(Cs concentration in blood) or (Cs concentration in blood)/(Cs concentration in seawater) than ratios of (K concentration in tissue)/(K concentration in blood) or (K concentration in blood)/(K concentration in seawater).^{1,3)} Therefore, we can tentatively assume that the discrimination of Cs from K also occur in invertebrates. A possible explanation for the discrimination of Cs from K in invertebrates is the difference in permeability between these two ions on their body surfaces. Bryan showed, however, that similar blood/seawater concentration ratios of Cs relative to K in marine decapod crustaceans which have no ability

of osmoregulation.³⁾ Thus, the difference of permeability in passive diffusion would be the least probable. At present, further physiological study is desired.

Cs, and K Concentration Factors of Organisms and Trophic Levels

The results of concentration factors of Cs and K in coastal biota with their assigned trophic levels are summarized in Table 7. The concentration factors of Cs were significantly low in animals of lower trophic levels, such as detritivores and plankton feeders, while Cs concentration factors were significantly high in animals of higher trophic level, such a carnivores. These results agreed with the findings Osterberg *et al.*¹⁵⁾ However, concentration factors of

Table 6. Cs/K atom ratios in marine organisms of different taxa

	Cs/K ($\times 10^{-7}$) atom ratio		
	n	mean $\pm$ S.E.*	range
Seawater	12	2.1 ± 0.1	1.8–2.5
Chlorophyta	9	2.1 ± 0.8	0.5–6.7
Phaeophyta	38	1.9 ± 0.2	0.8–9.2
Rhodophyta	10	4.6 ± 1.6	2.6–19
Invertebrates	12	3.5 ± 0.8	2.1–12
Teleosts	22	12 ± 1	6.5–26

* Geometric mean and standard error of mean value.

Fig. 4. Cumulative plots of Cs/K atom ratios in biological samples. Regression coefficients between cumulative and Cs/K atom ratios are shown with legends.

Cs were not the lowest in producers, such as algae. In fact, the factors slightly decreased from trophic levels I to II; from algae to herbivores. The reason for higher concentration factors of Cs in the producers is considered to be the same as that for the significantly higher concentration of potassium in phaeophyta.

In freshwater ecosystems, Pendleton and Hanson¹⁶ reported that radiocesium in organisms was concentrated at a level exceeding that of what the organisms fed upon. In marine ecosystems, Osterberg *et al.*¹⁵ reported radioactive Cs was present in tuna and prawns; both are representatives of higher trophic levels, but not detected in organisms of lower trophic levels. These results seem to suggest a presence of radioactive Cs bioaccumulation along food

chain. However, Cs is conservative as an ionic species in marine environments,¹⁷ so that the degree of bioaccumulation is smaller than that observed for Pu, which showed 10–100 times higher concentration factors.¹⁸ My results indicated rather large concentration factors of stable Cs in higher trophic level organisms, while Cs concentration factors were not necessarily the lowest in producers. Thus, my conclusion is that Cs is less bioaccumulated along the steps of food chain than reported in other studies.

Cs/K Atom Ratio in Organisms of Different Trophic Levels

Changes in the Cs/K atom ratios with trophic levels are summarized in Table 8. The distinctive feature of this table is the significant increase of the Cs/K atom ratios along the trophic level steps. The ratio is the lowest in the producers and highest in the carnivorous predators. The values of Cs/K atom ratios in organisms of each trophic level were comparable to the ratios reported by others.^{5,6,14} The relation of Cs/K atom ratios and the trophic level in organisms is shown in Fig. 5, with 95% confidence limits. The relationship is expressed as an equation as follows: $\ln(\text{Cs/K atom ratio} \times 10^{-7}) = \ln 1.41 + 0.48 \times (\text{trophic level})$, $r = 0.72$, $p < 0.0001$. This equation suggests that the Cs/K atom ratio increased by 1.62 times per trophic level elevation in the food chain (a derived increasing ratio). Young *et al.*⁵ showed the derived increasing ratio of Cs/K through food chains in the Salton Sea and the San Pedro Channel, with the values of 1.23 to 1.52. Mearns *et al.*⁶ also reported the increase of Cs/K ratio in pelagic food webs in the Southern California Bight and the western tropical Pacific, where the derived increasing ratio was 2.39.

An increase in the Cs/K ratio along in the ascending steps of the food chain was first reported by Pendleton *et al.*,¹⁹ where the changes in Cs/K ratio between two consecutive trophic levels was expressed as an “increasing ratio [(Cs/K ratio in predator)/(Cs/K ratio in prey)]”. Young *et al.*⁵ and Mearns *et al.*⁶ presented their hypothesis for this phenomenon, which was that the difference in turnover rates of Cs and K caused the accumulation of Cs compared with K in organisms. This phenomenon was biomagnified as one stepped up the food chain.^{6,19} They mentioned that turnover rates of Cs and K were undoubtedly different in several animal metabolisms. For example, in freshwater pike, the biological half-lives of Cs and K were 1.1–1.64 and 0.46–0.66 years, respectively, whose average ratio was 2.4:1.²⁰ For bluegill, it was 4.5:1.²¹ The

Table 7. Cs and K concentration factors in marine organisms of different trophic levels

	Trophic level Assignment	Concentration factor of Cs* ¹			Concentration factor of K* ²	
		n	mean $\pm$ S.E.* ³	range	mean $\pm$ S.E.	range
Producer	I	57	27 $\pm$ 3	3.4–110	26 $\pm$ 4	3.8–150
Herbivores	II	2	5.9 $\pm$ 2.8	3.8–9.3	3.3 $\pm$ 2.5	1.6–6.7
Detritivores, Plankton feeders	II–III	6	11 $\pm$ 2.5	7.2–23	8.8 $\pm$ 1.0	5.1–12
Primary-Secondary carnivores	III–IV	14	31 $\pm$ 4.8	9.0–66	7.8 $\pm$ 0.8	3.3–14
Secondary carnivores	IV–V	12	44 $\pm$ 2.6	30–58	8.7 $\pm$ 0.5	5.6–12

*¹ Estimated concentration factor by the equation: (Cs ng/g wet in organism)/(Cs 0.29 ng/ml in Japanese coastal waters from Table 2).

*² Estimated concentration factor by the equation: (K mg/g wet in organism)/(K 0.39 mg/ml in Japanese coastal waters from Table 2).

*³ Geometric mean and standard error of mean value.

Table 8. Cs/K atom ratio in marine organisms of different trophic levels

	Trophic level Assignment	Cs/K ($\times 10^{-7}$) atom ratio		
		n	mean $\pm$ S.E. *	range
Seawater		12	2.1 $\pm$ 0.1	1.8–2.5
Producer	I	57	2.3 $\pm$ 0.4	0.5–19
Herbivores	II	2	4.1 $\pm$ 1.0	3.3–5.2
Detritivores, Plankton feeders	II–III	6	3.1 $\pm$ 0.3	2.2–4.1
Primary-Secondary carnivores	III–IV	16	8.7 $\pm$ 1.6	2.1–26
Secondary carnivores	IV–V	11	11 $\pm$ 1	6.5–22

* Geometric mean and standard error of mean value.

Fig. 5. Regression plot of trophic levels and Cs/K atom ratios in collected marine organisms.

The intermediate trophic levels are plotted as the intermediate values. The 95% confidence bands of geometric mean value are shown in dotted line.

same relation was observed not only in marine crustaceans,^{1–3,18)} but also in humans. In the case of humans, the biological half-lives of Cs and K were 20 and 10 days in infants (the ratio was 2:1, increasing ratios ranged from 1.3 to 2.5), 100 and 25 days in adults (the ratio was 4:1, increasing ratios ranged from 2.4 to 5.8).¹⁹⁾ Pendleton *et al.*¹⁹⁾ proved the correlation between the difference in turnover rates of both elements and the magnitude of increasing ratios in humans. Thus, it is probable that the increase of Cs/K ratios in marine animals was also attributed to the smaller turnover rates of Cs compared with K during alkali element metabolism.

As shown in Fig. 5, an increase of the Cs/K atom ratio along the food chain was detected. There is a probability that a higher Cs/K ratio in organisms of higher trophic levels may be attributed to the high Cs/K atom ratios of teleosts (Table 6). The large Cs/K ratio found in teleosts is probably a reflection of both the magnification of the Cs/K atom ratio by a relative accumulation of Cs along the food chain and the specific metabolism of the element in the organisms.

Conclusion

Cs/K atom ratios were studied to clarify the relation of Cs and K in the food chains of Japanese coastal waters. The results obtained are: 1) The Cs concentration factors in higher trophic organisms, such as fish, were the largest, while those of lower trophic level organisms in the food chain, such as algae, were not necessarily the lowest. 2) The higher the trophic level, the larger the Cs/K atom ra-

tios in the food chain. 3) The derived "increasing ratio" of the Cs/K atom ratio was approximately 1.62 in food chains. 4) The probable reasons of the higher Cs/K atom ratios in teleosts were not only the discrimination of Cs during the alkali element metabolism in animals, but also the Cs accumulation along the food chains.

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