In the Wake of Fukushima: Cesium Inventories of selected North Pacific Fish

Undergraduate Thesis Submitted to

The Geology and Geophysics Department of the

University of Hawai'i at Mānoa.

May 2016

by

Hannah R. Azouz

Thesis Advisor

Dr. Henrietta Dulai

I certify that I have read this thesis and that, in my opinion,

it is satisfactory in scope and quality.

THESIS ADVISOR

_____

Dr. Henrietta Dulai

Department of Geology and Geophysics

ACKNOWLEDGMENTS

Henrietta Dulai for her patience and utmost help through this process.

Kenneth Inn for his statistical analysis advice and direction.

The Honors department and UROP at the University of Hawai'i at Mānoa for funding.

Abstract

To this day there are global efforts in evaluating the effects in wake of the 2011 Fukushima Nuclear Power Plant disaster. The estimated 500 tons of contaminated wastewater that entered the nearby marine ecosystem (Watabe 2013) was dispersed into the Pacific Ocean and due to biological uptake in migratory fish species (Madigan 2012) was detected in the water as well as in fish as far as the West coast of US. The FDA accepted intervention limit for cesium isotope intake is 300 Bq/kg annually for fish. The question we are left with is how much cesium is in the fish we consume, a thought the community of Hawai'i should consider since our fish products are caught in the Pacific Ocean.

Thirteen most commonly consumed types of locally bought fish samples were analyzed using gamma spectroscopy to measure Fukushima-derived ^{134}Cs and ^{137}Cs isotopes. All fish samples had detectable ^{137}Cs and nine out of the thirteen samples had detectable ^{134}Cs, an isotope indicative of Fukushima releases. The highest ^{134}Cs and ^{137}Cs concentration in the examined species was the Ahi tuna carrying 0.098 Bq/kg and 0.62 Bq/kg respectively. The highest concentrations occurred in high trophic level species with migratory patterns from Japan to Hawai'i or residing in the most northern Pacific Ocean. Nine out of the thirteen samples showed traces of ^{134}Cs, with only five of those activities outside the range of uncertainty. All activities are significantly below intervention limits but are informative to the community on what is being consumed. Results should also provide a basis for future work on cesium bioaccumulation in fish.

Table of Contents

Tables Page

Figures

Equations

Introduction

The world is quite aware of the 9.0 magnitude great Tohoku earthquake that led to the 9.3-meter tsunami and ultimately the breach of tsunami protection walls at the Fukushima Daiichi Nuclear Power Plant in March 2011. Emergency cooling generators were disabled by the tsunami leading to hydrogen explosions, which cracked the reactor containment pools allowing radioisotopes to escape into the atmosphere and nearby marine ecosystem (Buesseler 2011). Additionally, over 500 tons of contaminated wastewater was released into the Pacific Ocean (Watabe 2013). Bally Du Bois and colleagues (2012) explain that the contamination discharged directly into the marine environment following the Fukushima power plant accident denotes the most important artificial radioactive flux into the sea ever known by man. Alongside, Buesseler and colleagues (2011) point out that the total impact still remains unclear, as the peak concentration of cesium isotopes off the coast of Japan was one month after the disaster, hinting an intricate discharge pattern. Three months after the release, levels of ^{137}Cs were still 10 000 times more intense off the coast of Japan than levels measured the previous year hinting a lack of attenuation (Buesseler 2011).

Eric J Hall, a professor of radiology at Columbia University, rationalizes that "Life on earth has developed with an ever present background of radiation. It is not something new, invented by the wit of man: radiation has always been there." The concern of radiation arises when it occurs in the environment unnaturally, as some anthropogenic problems are yet to have reasonable solutions. The concern of unknown attenuation patterns of man-made radionuclides put in the environment fuels motivation for constructive research to help the community. Many aspects of Fukushima runoff have been a frequent topic of study as a result of the global concern, and articles continue to call for more research on the topic. This is the first study in the state of

Hawai'i targeting the post-Fukushima radiocesium bioaccumulation in the most commonly consumed North Pacific fish. The FDA has a standard of Derived Intervention Levels, setting the concentration boundary of cesium in one's diet at 300 Bq/kg. These parameters are far above the 6.3±1.5 Bq/kg concentrations of cesium found in the Pacific Bluefin tuna caught off the California coast only a year after the incident (Madigan 2012). Based on the Derived Intervention Limits, the FDA has no anticipation of any public health side effects on seafood safety and perceives it as an unlikely scenario that the pollutants could adversely affect fish traveling from Japanese waters (FDA 2014). Unrecognizing current scientific data, the media does not put weight on the sizeable radionuclide limits as the public is solely exposed to the exaggerated news headlines that are written to cause fear rather than inform and ensure safety. The focus of this study is to build on Madigan et al. (2012) research to provide local data for Oahu's community by investigating the actual levels of cesium isotopes in fish sold in local stores.

Since the incidence in March of 2011, models have been created to track the radiation plume and many thousands of liters of ocean water have been analyzed—concluding that radionuclide levels in the ocean outside of the immediate vicinity of Fukushima are below public safety levels. However, the most often used safety level these arguments refer to is the standard set for drinking water. I want to argue that there are better ways to derive safety limits for ocean radioactivity, one of these on the perspective of food safety – i.e. How high radionuclide concentrations would have to be in the environment for the fish that grows in it to become contaminated above the set safety limits (300 Becquerel of ^{137}Cs per kg of fish). The objective of this study is motivated by this perspective, and will provide current radionuclide inventories of commonly consumed fish in the North Pacific, translated into the dose received by consumption.

Before 2011, the levels of ^{137}Cs in the central Pacific Ocean were around 1.5 Bq/ m^3 from remnants of fallout from the nuclear weapons tests performed in the 1960's and 1970's (Smith 2014) and levels of ^{134}Cs were nonexistent due to its short, two-year half life. Therefore, ^{134}Cs may be used as the target Fukushima contamination since it is its only anthropogenic source validated recently. The Fukushima Dai-ichi power plant has just recently been completely shut down and decommissioned in 2015, although radiation is still leaking to this day (NDF 2015). Quantities of released radionuclides have been estimated but large uncertainties exist regarding the range of their released amounts. In 2012 TEPCO reported seawater contamination at only 3.6 PBq of ^{137}Cs (TEPCO 2013), meanwhile Bally Du Bois proposed a range of 12-41 PBq of ^{137}Cs that was released between the period of March 25 and July 28 in 2011 (Bally Du Bois 2012), while Tateda et al. estimated a direct leakage into the ocean at 2.8-4.2 PBq of ^{137}Cs with a total of up to 36 PBq (Tateda 2013). More recent estimates of direct escape into the ocean range from 14.5 PBq (Lai Z 2013) and 16.2 PBq (Rypina 2013), from a mean range incorporating all contamination models.

According to ocean circulation and dispersion models the radiation plume was supposed to have reached the main Hawaiian Islands in 2014 (Rossi 2013), and the predicted levels were significantly diluted to about 5 Bq/ m^3, which is deemed negligible from an immersion, ingestion, and inhalation health effects perspective. Fukushima derived trace elements reached the Canadian continental shelf in June 2013 in correspondence with original time estimations by Rossi and colleagues (Rossi 2013). Peak concentrations were found in February of 2014 at about 3.64 Bq/m^3 of ^{137}Cs, and values are estimated to remain between 3-5 Bq/m^3 in the Pacific (Smith 2014). In February of 2013 Kameník and colleagues observed only the preexisting ^{137}Cs base line around the Hawaiian Islands (Kameník 2013), from Station Aloha (45N, 158W) to the

southernmost Kona Coast (19N, 156W). Sample sites located closest to the main Hawaiian Islands had no detectable ^{134}Cs, but in 2012 the southeastern most boundary of the radiation plume brushed just north of the Midway Islands with low activities only about 1 Bq/m^3 above the pre-Fukushima concentration (Kameník 2013). The plume has still not necessarily reached the islands, but it did travel within established fishing grounds across major migratory paths northeast of the islands in the Kuroshio and Kuroshio extension currents (Madigan 2012, Kameník 2013). The travel of radionuclides via migratory species seems to be the most efficient way of spreading the contamination out of the plumes reach.

The literature data and models did not account for any type of bioaccumulation of radiation throughout marine trophic levels outside of the immediate vicinity of Japan and few estimations have been made regarding what corresponding cesium contamination levels we would find in fish the Hawaiian community is currently consuming. Bioaccumulation has proved to be an in-depth study of its own, and concentration factors rely on many abstract concepts as concentration factors in marine biota range drastically from 23-144 (Aarkrog 1997). This study will provide an inventory of current contamination concentrations in local fish, as the known data is insufficient to properly detail a valid trophic pyramid of concentration factors. Studies have shown that accumulation factors between trophic levels are relevant across the foodweb, and because humans are at the top of the trophic pyramid, cesium content data on high demand fish species concentrations should be kept up to date. For example, Heldal et al. witnessed a ten-fold increase in cesium concentrations between the upper trophic level, a harbor porpoise, versus the lowest level of krill samples (Heldal 2003). The IAEA recommends a concentration value of 40 for the bottom trophic level of zooplankton, while median values observed by Buesseler and colleagues were 44 for ^{137}Cs and 36 for ^{134}Cs (Buesseler 2011). These levels at the base of the

food chain are close enough to require investigation of trophic levels to examine the existing consequence of the Fukushima Dai-ichi runoff, especially when copious agricultural implications in local Japanese waters occurred, including fish species with well over the Japan limit at radiocesium concentrations above 500 Bq/kg (Watabe 2013).

The core objectives of this study are initially to quantitatively determine Fukushima-derived radiocesium concentrations in the selected fish we consume on the islands. I hypothesize radioactivity concentrations will heavily rely on habitat location relative to the plume, which will be analyzed by testing multiple species from different areas of the North Pacific. The main goal of this project is to determine human dose received from consuming those cesium concentrations found in the selected fish. The hypothesis for this part is that we are ultimately safe, since the food is being sold in public stores. The third objective, is to raise awareness of the findings by disseminating the information to the community.

Methods: Radioanalysis

Sample Selection

Fish sample selection and identification:

The goals of this study were to test cesium content in fish that are caught in the Pacific Ocean, species that may be affected by Fukushima-derived cesium releases, and at the same time are in high demand with Hawaiian consumers. This study began in March 2015, when a survey was performed

Table 1. Below, displaying expected wet to dry mass ratios and physical quantities purchased based on the 120 mL containers.

Wet %	Dry %	Dry Mass (g)	Wet Mass (g)	Wet Mass (lb)
80	20	120	480	1.06
75	25	120	360	0.8
70	30	120	280	0.62
65	35	120	223	0.5
60	40	120	180	0.4

about specific fish species that were offered and vendors where the fish came from.

Knowledge of the specific vendor aided in determining the actual fish species and their breeding grounds as each individual vendor has their own designated fishing grounds. We used an open access resource, FishBase (http://www.fishbase.org/), and specific information from the fishery that the fish were purchased from to narrow down the available fish pool to those caught strictly in the northern Pacific Ocean. The information compiled from FishBase is displayed in Table 2. Geographic location was the key factor determining sample selection as the contamination plume did not travel south of the Hawaiian Islands and therefore fish caught below 20°N were left out of this study. Samples bought consisted of any fish living above 20 degrees North, the southernmost part of the Hawaiian Island Chain. A variety of feeding depths and range of average ages/fish size were also identified from FishBase. This information will aid in clarification to just how deep into the ocean the radiation is penetrating and how far the radionuclides have actually traveled.

Table 2. Sample selection data acquired via FishBase.

Selected Fish	Species	Geographic Location				Habitat Depth		Trophic Level		Size (cm)		Maximum Age Reported
		N	S	E	W	Maximum	Minimum		±	Maximum	Average	
Ahi (Bigeye Tuna)	*Thunnus obesus*	45N	43S	180E	180W	250	0	4.5	0	250	180	11
Albacore Tuna	*Thunnus alalunga*	9N	46S	180E	180W	600	0	4.3	0.2	140	100	13
California King Salmon (Chinook)	*Oncorhynchus tshawytscha*	72N	27°N	136E	109W	375	0	4.4	0.7	150	70	9
Alaskan Cod	*Gadus macrocephalus*	63N	31°N	119E	119W	1280	0	4.2	0	119	67	25
Dover Sole	*Microstomus pacificus*	65N	31N	180E	180W	1370	10	3.2	0.1	76	40	56
Alaskan Halibut	*Hippoglosus stenolepis*	73N	42N	138E	123W	1200	0	4.1	0.2	258	-	55
Mahi Mahi (Dorado)	*Coryphaena equiselis*	47N	38S	180E	180W	85	0	4.5	0.6	127	50	4
Monchong (Pomfret)	*Taractichthys steindachneri*	26.5	18	180	157W	700	50	4.3	0.5	60	-	8
Onaga (Long-Tail Red Snapper)	*Etelis coruscans*	35 N	32 S	29E	142W	400	0	4.4	0.2	120	50	-
Opakapaka (Crimson Snapper)	*Pristipomoides filamentosus*	35N	26S	31E	144W	400	40	4.2	0.4	100	50	44
Opah (Moonfish)	*Lampris guttatus*	70N	45S	180E	180W	500	100	4.2	0.62	200	120	11
Swordfish	*Xiphias gladius*	61N	50S	180E	180W	800	0	4.5	0.2	455	300	20
Yellowfin Tuna	*Thunnus albacares*	52N	45S	180E	180W	250	0	4.4	0.4	239	150	9

The specific wet weight of fish tissue needed for the gamma spectrometry process was determined before purchasing all samples. Radioisotope concentrations vary widely between different tissues in the species, so we focused solely on the main fillet that is consumed (Aarkrog 1997), targeting the muscle tissue flesh. To achieve better detection limits on the gamma-spectrometry and match the volume of the available standard reference material (see below),

fifty-gram dry mass was desired for each sample. Because the preparation process of freeze-drying (described below) significantly alters weight since all water is removed, large enough samples had to be purchased to yield at least fifty grams of dry sample. We used information from the Food and Agriculture Organizations of the United Nations (fao.org) to estimate water content for each species. The typical water content differed drastically between fish species with extremes of 30% to as high as 85%. All wet to dry ratio calculations were done for each fish species before time of purchase. Table 1 shows the basic calculations established off the 50 grams of dry sample, and to account for variability in individuals, we padded the estimate to gain 120 grams given the 120 mL capacity of the polypropylene containers.

The range of wet weight to dry weight ratios were determined using the most fatty fish, California King Salmon, and the fish with the highest water content, Opakapaka. These initial test runs for the two ends of the water content spectrum verified water and fat percentages provided by the Food and Agriculture Organizations of the United Nations (fao.org). The fat content is more difficult to properly estimate and actual measurements were not performed. From the freeze-drying experiments we observed that the fattier fish needed longer processing time. We also observed that if the fillet had veinlets of muscle it was more likely to have a lower fat content, compared to a fillet that lacked muscle bands (Figure 1). Typically the fattier the fish, the less water percentage. This conceptual idea regarding fat content was only used for species

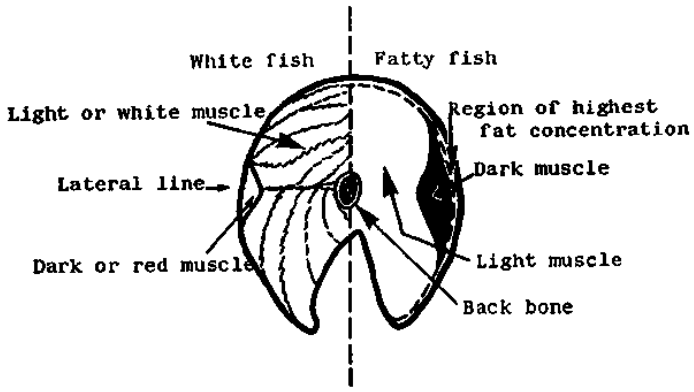


Figure 1 is provided by the FAO to compare fish quality of high fat content versus high water content.

with an unknown water percentage. For these samples, quantities were purchased based off the highest water content to be safe.

The choice of fish samples in this study reflected the variation between each species in their water content and samples available for consumption in Hawaii. Due to time demands of fish analysis (sample counting times of >7days) I had the option of focusing only on one or two selected samples of each species of fish to get a statistically meaningful average cesium activity by analyzing multiple individuals of the same species, or to scan a larger variety of species and get approximate values of expected cesium levels. Because of a lack of any preliminary information on expected activities within various species, the best approach was to analyze one individual from 13 selected species of fish. The following data should therefore be interpreted accordingly with the caveat that the variation among individuals in each species is not captured in this study. It is acknowledged that variation in cesium activity in each species of fish will depend on multiple factors that are not captured in this analysis, but only the key parameters will be discussed. Therefore each sample was individually analyzed and incorporated into a group analysis of expected cesium activities in the North Pacific. By no means does this dataset represent the whole Pacific Ocean nor a statistically representative dataset for individual species of fish analyzed. Rather, this study provides an overview of expected activities.

Sample Preparation

Freeze Drying:

For gamma-spectrometric analysis fresh fish muscle is usually processed by freeze-drying (e.g. Madigan et al. 2011). In order to turn the sample into a homogeneous, dry, powder-like substance, the VirTis Benchtop freeze dryer was used to extricate all water from the fish

tissue. To prepare the freeze dry glass jars, all jars were subject to a 10% HCl bath for duration of at least four hours. Each jar was filled about one quarter with acid and the top covered with a petri dish. After the HCl soak, each jar was rinsed with deionized water three times, dried, the top covered with tinfoil and then combusted at 105°C for 24 hours. The fish filet tissue was then sliced into no larger than 1-inch size cubes for better surface area and left in the freezer at -18 °C until completely frozen. Once the sample was frozen, the cubes were broken up and placed into the freeze dry jars not more than three quarters full. Each jar was labeled with the sample name. Before attaching the jars to the freeze dryer branches, the freeze dryer was properly prepared to ensure functionality. About four or five jars were attached simultaneously for each run. The freeze dryer was constantly checked throughout the procedure to ensure proper operation and no leaks. The samples were dried within three to five days depending on fat content and amount of samples attached. This process was repeated for all 13 samples.

Pulverization/Milling:

The dry fish samples were at first ground to a powder using the mortar and pestle technique, but the oily fish were difficult to grind into a powder, as they would just smear along the bowl. Due to this problem and to preserve consistency in the processing methodology, all samples were processed in a kitchen blender to obtain a fine powder for homogeneity. Most of the fish were easily turned into a fine powder; the samples with higher fat content were blended longer as the fibers remained quite flakey and fibrous. The blender was thoroughly scrubbed and sanitized between each sample to avoid cross-contamination. The powdered samples were then packed into polypropylene 120 mL gamma spectrometry containers individually labeled with names and weight. All samples were filled to a pre-determined volume to match the standard

geometry. The mass per volume differed, but was corrected for in the calculations. See below for more details.

Reference Standard

The gamma-spectrometric efficiency was determined using certified reference fish tissue material obtained from Dr. Chushiro Yonezawa from the Japanese Society for Analytical Chemistry. Thirteen different labs participated in the certification of this fish sample. The sample was prepared using an oven drying process. The fish tissue was dried at 105° C for five hours, milled, and homogenized. The reference date for the given Certified Reference Material (CRM) is 31 October 2014. When received, this sample was packed into a 120 mL polypropylene container. Efficiency was calculated using decay corrections to the given reference date compared to actual test date. The CRM counts were compared with our own counts of ^{134}Cs, ^{137}Cs and ^{40}K. The results from the various labs determined reference standards of ^{134}Cs concentration as 62.43 ± 6 Bq/kg, ^{137}Cs 195.81 ± 23 Bq/kg, and ^{40}K at 348.36 ± 34.5 Bq/kg. All samples were then filled to the same level as the standard.

Since the dry mass in this study was dehydrated using a different technique than the certified reference material, an already freeze-dried sample of California King Salmon was then oven dried, and compared the counts of the oven and freeze-dried sample versus solely the freeze dried sample of Salmon. The salmon was put into a ceramic jar and dried at 105° C using a Thermolyne Benchtop Muffle Furnace. Although there was a change in density causing a 57.1% change in mass, the difference in counts per wet weight was negligible, and we decided that the two drying procedures resulted in comparable samples.

Measurement

An Ortec HPGe (model GEM40) was commissioned for measurement of cesium in the fish tissue. Each sample was kept on the counter for approximately one week depending on time adjustments to achieve lower counting errors. Maestro software was used for peak detection. Hypermet PC software was used to verify the peaks in the energy spectrum provided by Maestro. For the samples with unidentifiable peaks of 604 or 661 KeV, representing cesium 134 and 137 respectively, the gross and net peak areas were taken directly from Maestro. One empty container was used as the control to identify background and establish detection limits and efficiencies. The typical critical level limits were .011, .0010, and .18 Bq/kg for 604, 661, and 1461 keV peaks respectively. The concentrations were decay corrected to time of purchase in March 2015.

Statistical Processing

All standard deviations are derived incorporating detector efficiency, background and net counts and are reported at one sigma. Radionuclide concentrations were calculated using Equation 1, where C_N represents the net count rate evaluated for each peak in Hypermet, C_B, represents the count rate in the region of interest of each peak in the blank. Y is the percent yield per decay. V is the wet mass of the sample measured in grams, and l represents the live time the sample was actually counted. Lambda is the known radioactive decay constant, and t is the time lapse from the sample purchase to the date of its measurement.

Equation 1. $$Rc = \frac{C_N - C_B}{Y * \varepsilon * V * e^{-\lambda t} * l}$$

The efficiency of the detector for each gamma energy, represented by epsilon, is acquired using the certified reference standard fish material. The average measurements from the reference material data were corrected to the actual concentrations compared to the reference dates. A_0 are the values given with the reference sample, and $e^{-\lambda t}$ corrects the activity on the reference date to the one at analysis time.

Equation 2. $Rc = A^t = A_0 * e^{-\lambda t}$

Nuclide	Kev	Efficiency	1 σ
Cs-134	604	0.0231	0.0005
Cs-137	661	0.0249	0.0002
K-40	1461	0.0142	0.0003
Th-234	63	0.0374	0.0102
Ac-228	911	0.0175	0.0048
Bi-214	609	0.0234	0.0064
Pb-212	238	0.0441	0.0120
Pb-214	351.9	0.0402	0.0109
U-235	143.7	0.0492	0.0134
Pb-210	46.5	0.0107	0.0013

Table 3. Selected detection efficiencies calculated from the certified reference fish material. Uncertainty at 1 sigma.

The Critical Level (CL) of the utilized method was calculated for all designated energies. Several samples had lower concentrations of cesium 134 than the CL. New variables in Equation 3 are: m for the wet mass of the sample, N_b representing the blank counts provided by Maestro, t_s for the standard's counting time divided by the counting time of the blank, t_b .

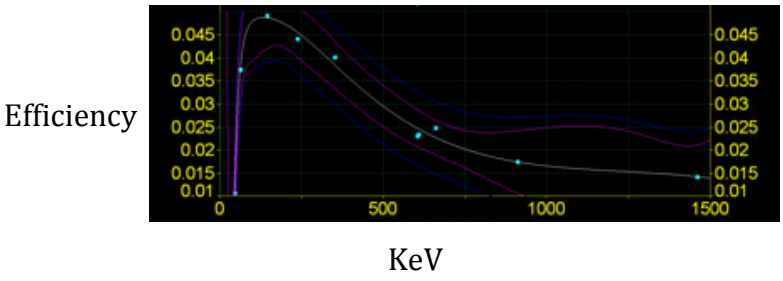
Equation 3. $CL = \frac{2.33 * \sqrt{N_{b * \frac{t_s}{t_b} * (1 + \frac{t_s}{t_b})}}}{m * \varepsilon * Y * t}$

Efficiency

The calculated efficiency for Cs-134 at 604 KeV is 0.023 and Cs-137 at 661 KeV is 0.025. See Table 3 for various detected energies used and their associated efficiencies found with the standard reference material. These efficiencies along with

counting times of about 7 days for each sample resulted in critical level activities for each isotope analyzed provided in Table 3. Figure 2 illustrates the detector efficiency.

Figure 2. Efficiencies of the GEM-40 HPGe detector plotted against radioisotope energies for the fish SRM in a 120 mL container used in this investigation.



Results

1. Body Mass

The water content of each fish varies between species due to specific biologic osmosis predispositions and fat content. We recorded the mass of each fish muscle before and after the drying process. The dry versus wet mass content, i.e. the dry mass divided by the total mass exhibited, doubled in variation from 15% of dry mass of total muscle tissue to over 36% depending on the species. Table 4 exposes the range of water content between each species of fish incorporated in this study. The two highest dry mass contents were in the fish

	Wet Mass (g)	Dry Mass (g)	% Dry Mass
California King Salmon	480.48	174.83	36.4
Swordfish	493.85	161.35	32.7
Opakapaka	351.6	108.61	30.9
Ahi	327.73	91.86	28.0
Yellowfin Tuna	403.37	111.52	27.6
Albacore Tuna	362.34	97.95	27.0
Alaskan Halibut	489.45	120.41	24.6
Monchong	363.37	83.61	23.0
Opah	664.16	151.86	22.9
Onaga	607.42	137.3	22.6
Alaskan Cod	653.14	130	19.9
Mahi Mahi	503.82	82.38	16.4
Dover Sole	295	45.54	15.4

Table 4. Each species and the given total wet and dry mass before and after the freeze-drying process and dry to total mass ratio expressed as % Dry Mass.

with the highest fat content (salmon), and the fish with the most dense muscle tissue (swordfish). The opah and salmon samples had similar high fatty textures while the rest of the samples were generally less oily. The samples with higher fat content took an extra day in the freeze dryer and were harder to homogenize. The tuna, opakapaka, cod, and flounder samples were very easy to homogenize due to their low fat content and low density of muscle tissue.

2. Activity

The total radiocesium concentrations measured in the fish specimens range from 0.08 to 0.72 Bq/kg of wet weight, far below the FDA safety limit of 300 Bq/kg of fish. While the ^{134}Cs: ^{137}Cs ratio released from Fukushima was close to 1:1 (Buesseler 2011), for releases from March 2011 this ratio would be 1:3.4 (~.29) presently in 2015 due to the faster ^{134}Cs decay of a two year half life compared to the 30 year half life of ^{137}Cs. Accordingly, Table 5 shows quite a few fish samples that had detectable $^{134}Cs/^{137}Cs$ have ratios closer to zero than to the maximum observed of 0.16 (Ahi).

Table 5. Cesium isotope ratios in each dry fish sample, for reference the Fukushima releases had ^{134}Cs:^{137}Cs = 1 in March 2011. In January 1, 2015 this ratio would be 0.29. Also listed are total cesium inventories (Bq/kg) of Fukushima-derived plus pre-Fukushima levels in each specimen.

Species	Cs134:Cs137		Cs134 + Cs137
Ahi	0.158		0.72
Albacore Tuna	0.154		0.37
California King Salmon	0.008		0.18
Cod	-		0.15
Dover Sole	0.005		0.56
Halibut	0.076		0.23
Mahi Mahi	0.077		0.16
Monchong	-		0.70
Onaga	-		0.72
Opah	0.014		0.08
Opakapaka	0.008		0.16
Swordfish	0.134		0.55
Yellowfin Tuna	-		0.22

Five samples showed Fukushima tracer ^{134}Cs, present above critical levels and at 68% confidence interval (CI at 1-sigma uncertainty) but only three of those fish exhibited activities outside the range of their 2 sigma uncertainty representing 95% CI. Table 6 presents that the highest ^{134}Cs concentration resided in the local ahi sample but did not exceed 0.098 Bq/kg. The highest trophic level migratory species along with the Alaskan residents were the only samples with ^{134}Cs evident above the critical level. The CL for ^{134}Cs ranged from 0.0040-0.0068 Bq/kg, but the method was still not sensitive enough to account for the very low ^{134}Cs activities since two half-lives have already passed for the 134 isotope since the accident by the time of sampling.

Table 6. RESULTS: Cesium isotope activities measured in 13 fish samples in this study. Radionuclide concentrations are in Becquerels per kilogram per wet weight and critical levels are provided for cesium-134, cesium-137, and potassium-40 for each sample. All radionuclides are decay corrected to the date of purchase in the beginning of 2015. Uncertainty at 1 sigma.

Species	Decay Corrected Radionuclide Concentrations (Bq/kg)								
	Cs-134	1 σ	CL	Cs-137	1 σ	CL	K40	1 σ	CL
Ahi	0.098	0.02	0.0054	0.62	0.02	0.0041	135.6	2.8	1.06
Albacore Tuna	0.05	0.02	0.0054	0.32	0.02	0.0041	119.8	2.6	1.06
California King Salmon	0.0014	0.006	0.0040	0.18	0.03	0.0030	156.1	3.3	0.79
Cod	0	-	0.0056	0.15	0.03	0.0042	99.5	2.2	1.10
Dover Sole	0.0026	0.005	0.0052	0.56	0.06	0.0039	42.8	1.0	1.02
Halibut	0.016	0.03	0.0051	0.21	0.02	0.0038	126.7	2.6	0.99
Mahi Mahi	0.011	0.01	0.0045	0.15	0.03	0.0034	110.2	4.5	0.88
Monchong	0	-	0.0062	0.70	0.08	0.0047	96.7	2.2	1.22
Onaga	0	-	0.0068	0.72	0.03	0.0051	118.4	2.6	1.32
Opah	0.001	0.003	0.0040	0.08	0.01	0.0030	161.2	3.3	0.78
Opakapaka	0.0013	0.012	0.0050	0.16	0.01	0.0038	49.1	1.1	0.98
Swordfish	0.065	0.03	0.0049	0.49	0.03	0.0037	115.7	2.4	0.97
Yellowfin Tuna	0	-	0.0053	0.22	0.02	0.0040	124.5	8.8	1.04

All samples had radiocesium-137 present at levels above CL and 95% CI. The maximum ^{137}Cs concentration found was 0.72 ± .03 Bq/kg. The highest concentrations resided in the Japanese reef fish onaga (*Etelis coruscans*), and the high trophic species with Japan to Hawai'i migration routes, monchong (*Taractichthys steindachneri*). The critical level activity for ^{137}Cs

ranges from 0.0030-0.0051 Bq/kg, but the lowest concentration is 0.15 ± 0.03 Bq/kg so all ^{137}Cs activities are above detection limits. None of the samples revealed activities over one Bq/kg of ^{137}Cs , nor did the samples reveal a total radiocesium concentration of over that concentration. None of the samples exceeded concentrations of total radioactive cesium above 0.72 Bq/kg, which is less than 1% of the FDA derived intervention limit for seafood contamination of cesium radioisotope.

The naturally occurring potassium-40 on the other hand revealed concentration levels ranging from over 42 Bq/kg to about 160 Bq/kg. The highest concentration of 161.2 ± 3.3 Bq/kg exists in the fatty local gamefish opah (*Lampris regius*) sample, while the lowest concentration of 42.8 ± 1.0 Bq/kg resides in the Alaskan species, the Dover sole (*Microstomus Pacificus*). The

	Th-234	1 σ	CL	Ac-228	1 σ	CL	Bi-214	1 σ	CL
Ahi	1.48	0.41	0.10	-	-	0.03	-	-	0.03
Albacore Tuna	0.26	0.07	-	-	-	-	0.17	0.05	0.12
California King Salmon	0.28	0.08	-	0.04	0.01	-	0.03	0.01	0.09
Cod	1.12	0.31	0.05	-	0.00	0.01	0.16	0.02	0.12
Dover Sole	1.46	0.40	-	-	0.00	-	0.04	0.00	0.12
Halibut	2.19	0.60	0.08	0.05	0.01	0.02	0.00	0.00	0.11
Mahi Mahi	0.77	0.21	-	0.06	0.02	-	0.01	0.00	0.10
Monchong	0.24	0.07	0.17	0.13	0.04	0.05	0.00	0.00	0.14
Onaga	3.33	0.91	-	0.28	0.08	-	0.00	0.00	0.15
Opah	0.47	0.13	0.02	0.05	0.01	0.00	0.01	0.00	0.09
Opakapaka	0.78	0.22	0.04	-	-	0.01	0.00	0.00	0.11
Swordfish	1.36	0.37	-	-	-	-	0.02	0.01	0.11
Yellowfin Tuna	1.15	0.32	0.05	-	-	0.01	1.15	0.32	0.12

	Pb-210	1 σ	CL	Pb-212	1 σ	CL	Pb-214	1 σ	CL	U-235	1 σ	CL
Ahi	-	-	1.1	0.105	0.029	0.03	-	-	0.028	-	-	0.054
Albacore Tuna	-	-	4.7	-	-	0.12	-	-	0.114	0.099	0.029	0.224
California King Salmon	-	-	3.5	-	-	0.09	-	-	0.085	-	-	0.168
Cod	0.417	0.053	4.9	0.049	0.014	0.12	-	-	0.118	-	-	0.233
Dover Sole	3.863	0.483	4.5	-	-	0.12	-	-	0.110	0.025	0.008	0.216
Halibut	-	-	4.4	0.079	0.022	0.11	-	-	0.107	-	-	0.210
Mahi Mahi	-	-	3.9	-	-	0.10	-	-	0.094	0.068	0.019	0.185
Monchong	-	-	5.4	0.170	0.047	0.14	-	-	0.131	-	-	0.258
Onaga	1.628	0.223	5.9	-	-	0.15	-	-	0.143	-	-	0.280
Opah	-	-	3.5	0.016	0.005	0.09	-	-	0.085	-	-	0.166
Opakapaka	-	-	4.3	0.036	0.010	0.11	-	-	0.105	-	-	0.207
Swordfish	5.285	0.709	4.3	-	-	0.11	-	-	0.104	0.257	0.074	0.205
Yellowfin Tuna	-	-	4.6	0.051	0.014	0.12	0.016	0.004	0.112	0.098	0.028	0.220

Table 7. Naturally occurring gamma-emitting radionuclides in fish samples. Activities are reported as (Bq/kg). Uncertainties at 1 sigma.

CL for ^{40}K was fluctuated around one Bq/kg, specifically between 0.78 - 1.22 Bq/kg falling far below the detectable levels in each sample. Although much more ^{40}K is detected in the fish due

to natural occurrences, the anthropogenic ^{137}Cs has a much lower limit to regulate anthropogenic contamination of food sources. Dose expressed per weight, rather than activity of these isotopes, suggests that because of its shorter half-life cesium gives a higher dose per mass to the community with 88 curies/gram than the $0.71x10^{-5}$ curies/gram the ^{40}K holds. The government intervention limits for naturally occurring abundances of radioisotopes like potassium-40 are generally in the upper thousands of Becquerels range (14).

Other isotopes identifiable by gamma spectroscopy were detected along with the Fukushima tracers. ^{210}Pb, which is an indicator of natural atmospheric fallout, was detected in cod, onaga, Dover sole, and swordfish. No ^{7}Be was detected in the samples similarly to findings by Madigan et al (2012). ^{234}Th was present in each sample, this isotope is usually in equilibrium with its parent ^{234}U but no ^{234}U activity was detected above background levels. Other isotopes of the natural decay chains were evaluated but none showed any significant pattern or elevated activity in the fish samples; these include ^{235}U, ^{212}Pb, ^{228}Ac, and ^{214}Bi (Table 7). ^{228}Ac , ^{214}Bi, ^{235}U, and ^{212}Pb are daughters of the primordial uranium decay chain series.

Discussion

Enrichment Factors

There are thousands of fish species in the Pacific Ocean, out of these less than twenty species are most commonly caught for human consumption. One of those is the Pacific Bluefin tuna that received a good amount of attention after Madigan et al. (2012) found Fukushima-derived radionuclides in individuals caught off the California coast. This study expands on their findings by looking at a wider variety of species of fish. There was an already existing baseline of ^{137}Cs concentrations in the Pacific Ocean prior the Fukushima disaster. Nuclear fallout from

weapons testing and other historic sources of cesium in the 1960's have left a relatively evenly distributed level of 1-2 Bq/m^3 of ^{137}Cs across the surface Pacific Ocean. Fish inhabiting the pacific have been subjected to cesium activity since the 1960 when ^{137}Cs activities were above 50 Bq.m^{-3} (Duran, 2006). Those levels dropped to 1-2 Bq/ m^3 due to radioactive decay, dispersion in the atmosphere and surface ocean, and physical and biological removal from the surface ocean. Table 8 shows the total cesium estimates in fish parsed out to radiocesium linked to the Fukushima accident and the baseline concentrations pre-Fukushima. Any ^{137}Cs levels in the surface ocean above 1-2 Bq/ m^3 after 2011 are attributed to the Fukushima Dai'ichi Nuclear Power Plant accident. All detectable ^{134}Cs activity is directly attributed to the accident, as its half-life of only two years is so short that any fallout from the sixties has decayed away. In this study we present all fish cesium activities decay corrected to the date of purchase in 2015 and are therefore the combination of remnants of radionuclides from the 2011 release and the 1960's weapons tests. Only fish that had ^{134}Cs above 2-sigma uncertainty could be identified as being influenced by Fukushima releases at 95% CI. The rest of the fish are assumed to have accumulated cesium from pre-Fukushima sources.

There are many factors that play a role in how much cesium a fish will accumulate. This study is not designed to target these factors, rather an investigation sparked from the measured

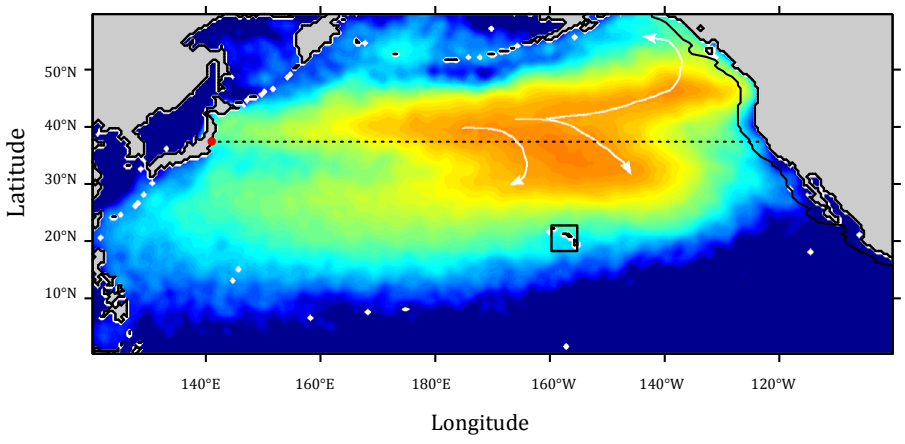


Figure 3. Modeled expected Fukushima radiocesium concentration in the Pacific Ocean (Rossi et al., 2013) as of 2014.

activities to derive any common relationships. The parameters influencing bioaccumulation are broad, but only the key factors are analyzed in this section. All fish were purchased locally on the island of O'ahu, caught solely in the north pacific and this was decided based on plume movement models (e.g. Rossi et al., 2013) providing information on cesium transfer across the north pacific with very little leakage into the southern hemisphere. I anticipated that several principal governing factors determine radiocesium concentration in fish: fish habitat overlapping high-cesium regions (Figure 3) and shallow feeding depth, along with fish physiological factors such as water content, trophic level, age of each species. Because of our study design, actors such as age and size when caught and diet of species that are among the many influences on cesium content in each fish were not captured in this study. Biomagnification was not captured in this study either because the common fish we consume are all high trophic species (i.e.>4.0). Select governing factors that were analyzed here were species habitat regarding geographic location, feeding depth, and water content of fish.

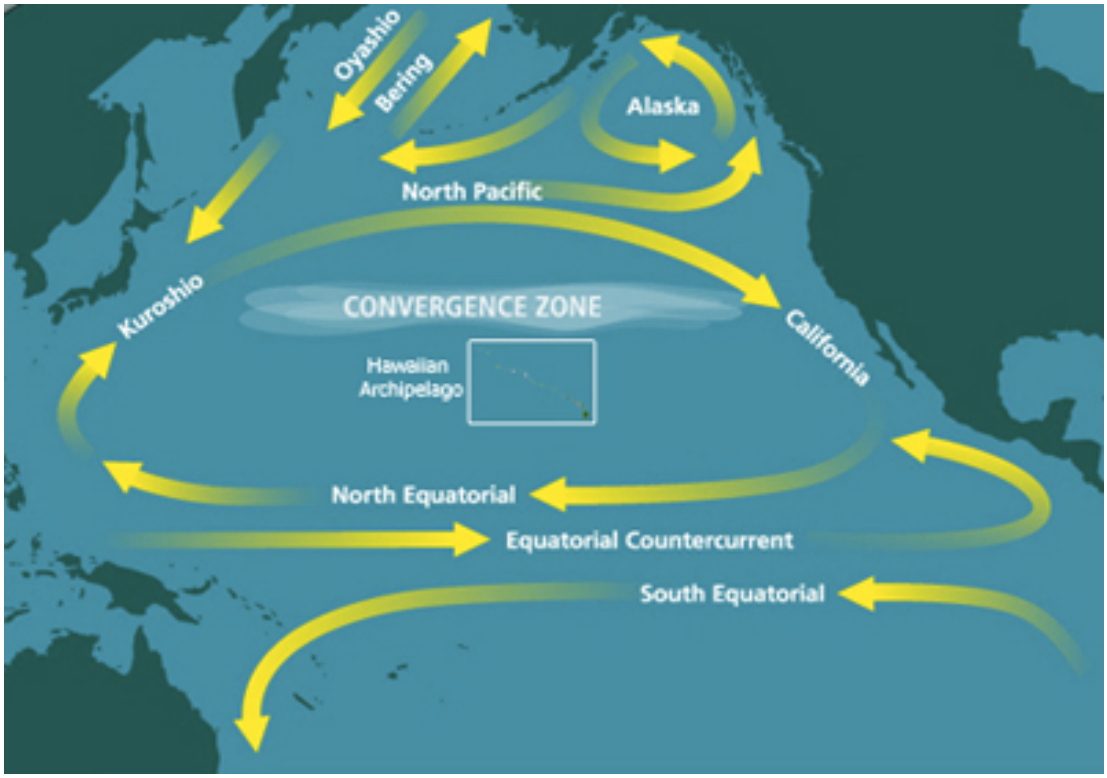
1. Geographic Location of Fish

Five of the 13 fish samples had detectable ^{134}Cs above CL, with only three of those values outside the range of 2-sigma uncertainty suggesting that those had ^{134}Cs levels distinguishable from zero at 95% CI. The common characteristics of species with the highest cesium concentrations is the proximity of their feeding grounds to Japan. Fish samples with any detectable ^{134}Cs generally traced to a habitat very close or north of Japan. Rossi and colleagues (2013) predicted the path of the Fukushima plume in the North Pacific Ocean for 2014 based on ocean circulation models (Figure 3). Cesium uptake in fish correlates with the plume location, and the species with detected ^{134}Cs have migratory routes from Japan to Hawai'i or to the west

coast of North America. Displayed by Figure 4, the Kuroshio Extension and North Pacific Current were expected to carry the radiation plume towards the north pacific based on ocean current conditions, so fish with migration patterns and feeding grounds in the near the source and in northern pacific were expected to have higher levels. This was an accurate assumption confirmed by the elevated levels in high migratory swordfish (*Xiphias gladius*), albacore (*Thunnus* alalunga),and ahi species (*thunnus obesus*). Mahi (*Coryphaena equiselis*) is also a highly migratory species traveling from Japan to the west coast of North America, another high trophic species with expected effect from Fukushima Dai'ichi accident (albeit only at 60% CI).

Alaskan species were also expected to have elevated activities due to the fishing grounds' overlapping with radioisotopes traveling with the currents heading north from the Fukushima site (Figure 4). The Alaskan bottom feeder, Dover sole (*Microstomus pacificus*) displayed elevated

Figure 4. North Pacific Ocean current map. Buesseler 2015.



total cesium with ^{134}Cs not distinguishable above one sigma of uncertainty (Table 5). The detected activity may be due to its feeding habits connected to cesium accumulating in bottom sediments. Other Alaskan samples, such as halibut (*Hippoglosus stenolepis*), California king salmon (*Oncorhynchus tshawytscha*), and cod (*Gadus macrocephalus*), did not accumulate a Fukushima signature or a large quantity of cesium perhaps because little time spent in the plume because of life habits or other biological factors. The depth of habitat occurrence for the Dover sole was most likely the major reason why it accumulated more cesium when comparing the sample to its Alaskan colleagues.

Estimated geographic locations of the habitat and migration routes of several analyzed species come in close contact with Japanese fish feeding grounds and the high north pacific. Monchong (*Taractichthys steindachneri*) and onaga (*Etelis coruscans*) generally reside in waters near Japan sometimes migrating towards the Hawaiian Islands, and were therefore expected to have elevated levels of Fukushima-derived radiocesium compared to the rest of the pacific species. Table 8 shows the opposite, a lack of Fukushima related contamination in the Japanese fish samples. While they had the highest detected ^{137}Cs, they had no detectable ^{134}Cs suggesting currently no contribution from Fukushima.

Based on the initial 1:1 release ratio of $^{134}Cs/^{137}Cs$ (Buesseler et al 2011), if we decay

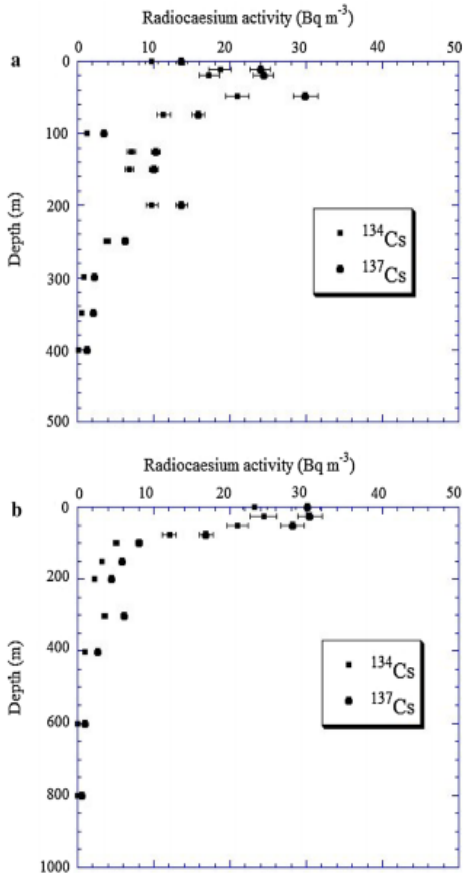
	Decay Corrected to 11 March 2011					
	Cs-134	Cs-137	Total 2011	Total 2015	Total New	%
Ahi	0.332	0.676	1.01	0.7	0.60	60
Albacore Tuna	0.175	0.348	0.52	0.4	0.61	61
King Salmon	0.005	0.134	0.14	0.2	0.03	3
Cod	0.000	0.149	0.15	0.1	0.00	0
Dover Sole	0.009	0.606	0.62	0.6	0.02	2
Halibut	0.056	0.232	0.29	0.2	0.31	31
Mahi Mahi	0.038	0.160	0.20	0.2	0.31	31
Monchong	0.000	0.695	0.69	0.7	0.00	0
Onaga	0.000	0.717	0.72	0.7	0.00	0
Opah	0.004	0.178	0.18	0.1	0.06	6
Opakapaka	0.004	0.084	0.09	0.2	0.03	3
Swordfish	0.214	0.529	0.74	0.6	0.50	50
Yellowfin Tuna	0.000	0.242	0.24	0.2	0.00	0

Table 8. Detected radiocesium levels (Bq/kg dry weight) date corrected to March 2011 in order to determine old vs. new Fukushima contribution of ^{137}Cs in fish.

correct ^{134}Cs detected in the fish to the date of the accident of 11 March 2011 we can estimate ^{137}Cs levels present in the fish only from the accident (as ^{137}Cs barely decayed since 2011 and 90% is still remaining) and derive old versus new ^{137}Cs. Table 8 displays that only <30% of samples express direct impact from Fukushima. Only cesium in specimens that have detectable ^{134}Cs can be directly related to the nuclear power plant disaster. Due to the multiple biomagnification and bioaccumulation factors inside the biologic pyramids the levels of ^{137}Cs alone cannot be used to infer the presence of Fukushima-derived cesium.

Although every sample had detectable ^{137}Cs, the ^{134}Cs isotopes were only found in three of the thirteen samples at 95% CI. This may be for two reasons: 1. ^{134}Cs has a two-year half-life and since 2011, two half-lives have passed therefore ^{134}Cs should decayed to 25% of originally present and our detection method was not sensitive enough to detect it. 2. Pre-Fukushima levels of ^{137}Cs are 1-2 Bq/m^3 across the Pacific Ocean so it is expected that all fish that feed in the surface 200 m of ocean will have some ^{137}Cs. ^{134}Cs would only occur where the Fukushima derived plume resides, therefore fish living outside the geography of the plume or in deeper water would not accumulate any ^{134}Cs.

Figure 5. Aoyama et al. 2015 depth profiles at (a) 35.01° N, 165°E and (b) 40.03° N, 165.01°E



2. Depth of Occurrence

Cesium preferentially travels through surface currents, dispersing in the surface mixed layer of the water column in the ocean. This mixed layer is in the upper 50-200 meters of the Pacific as illustrated by the cesium depth profile created by Aoyama (2015) (Figure 5). In this investigation, Figure 6 examines depth of occurrence for each species of analyzed fish related to the total cesium accumulation in each species. Cesium travels laterally through the pacific but has relatively high biologic loss rates due to which it gets transported to the bottom sediments by sinking particles. Buesseler 2012 showed that sediments near Japan represented a continuous source of cesium contamination, affecting cesium in demersal bottom dwellers. Similarly in our study, for this reason Dover sole likely acquired a higher contamination than surface feeders like the other Alaskan residents.

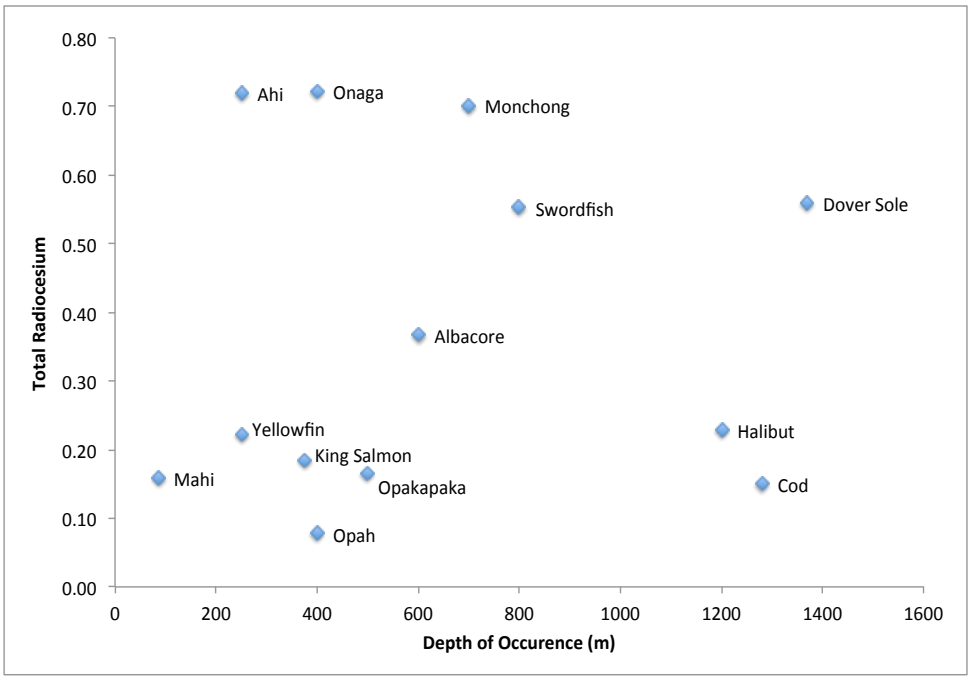
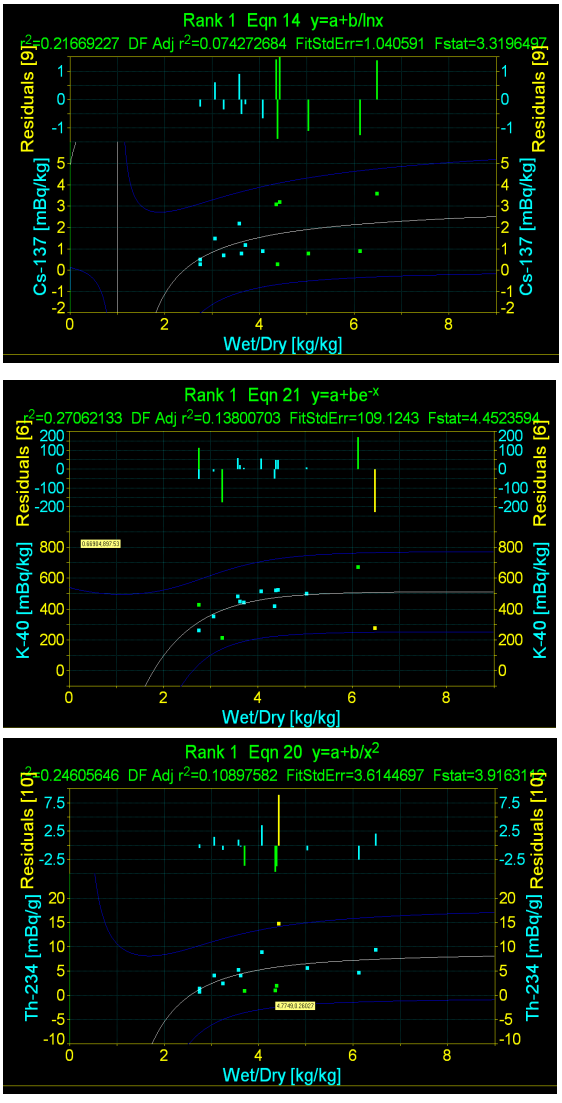


Figure 6. Depth of occurrence vs. total cesium concentration in Bq/kg.

Most high trophic species follow the surface feeding pattern, eating in the upper 200 meters of the ocean in discontinuous but direct contact with the cesium plume (Duran 2004). The onaga and monchong thrive in the surface currents between Japan and Hawai'i, which

contributes to their enhanced concentrations of radiocesium. Ahi and swordfish travel such great distances through various depths of the ocean achieving their enhanced concentrations through direct contact with the radioactive plume as well as consuming epipelagic and neuston ocean species that have been in contact with the top 200 m of the ocean surface. Figure 6 suggests that the depth of fish occurrence is scattered and therefore not a straightforward factor in cesium accumulation, but the actual feeding depth and geographic location of the high trophic fish is a more reliable predictor for cesium uptake. This data set lacks a conclusive relationship with depth of occurrence.

Figure 7. Below, a relationship between Cesium-137 (top), Potassium-40 (middle), and Thorium-234 (bottom) and the water content of sampled species.



3. Water Content

The relationships in Figure 7 suggest that a higher water content of each fish results in higher concentration of cesium within the fish tissue. This could be explained by the theory that each fish species have designated “K channels” that manage the intake of potassium and like elements (Duranton 2000 & Rowan 1998). More water in a fish would provide a greater opportunity for cesium accumulation. The exponential fit is could be attributed to other bioaccumulation factors as fat

content in a species would replace water and skew the relationship. Previously discussed factors of location and feeding depth also influence the relationship. The trends' r-squared values are quite low probably because of the limited sample size and also because multiple other factors affect bioaccumulation.

This trend is also evident with the wet to dry mass ratio against potassium-40 and thorium-234, the latter of which represents uranium-238 uptake. Potassium-40 and radiocesium are expected to behave similarly within the fish tissue as they enter the biological system through the K-channels in the gills (Goulet 2011). The thorium isotope seems correlated with cesium and potassium as its designated uptake path into the fish is via gills as well. The exponential fit of each curve is interpreted to be due to the fact that only so much water can be taken through the gills at any given time.

The degree of freedom (DF adj r^2) exposes an even lower level of confidence in each curve. This value is caused by a low quantity of samples. Only one sample of each species was counted, correlation should improve with multiple analyses of each sample. The DF is also comparing a diverse species of fish who carry unique diets and metabolic rates; a more in depth study could examine multiple individuals of a single species as Madigan and colleagues demonstrated in their post-Fukushima Pacific Bluefin tuna investigation (Madigan 2012).

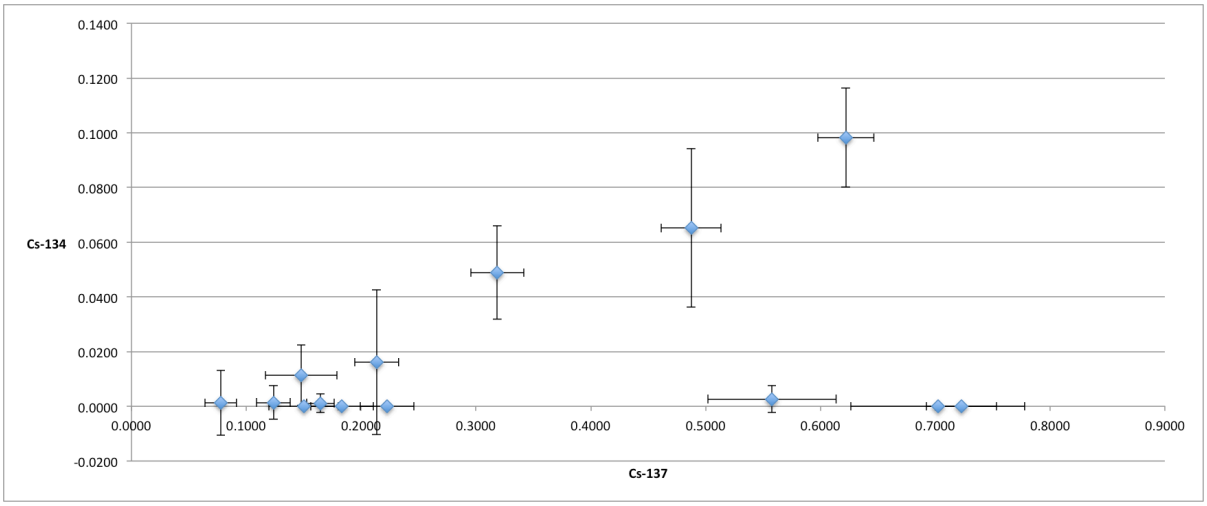
Trend Analysis and Dose Calculations

1. Cesium Isotope Ratios and their Trends

Buesseler and colleagues determined that the initial $^{134}Cs/^{137}Cs$ ratio for Fukushima-derived activity was 1 in 2011 (Buesseler 2011) and therefore should be 0.29 in 2015 when the fish analyzed in this study were caught. The ratio of cesium isotopes relationship illustrated in

Figure 8 shows three distinct patterns 1) in fish with detectable ^{134}Cs there appears to be a linear trend with a slope of XX which is a combination of Fukushima-derived $^{134}Cs/^{137}Cs$ and pre-Fukushima ^{137}Cs; 2) A group of high ^{137}Cs and no trace of ^{134}C; and 3) a group with hardly any cesium detected. The group 1) is represented by the high migratory, high trophic level species. The lowest cesium activities in group 3) each have their own individual reasoning for muted concentrations based on the bioaccumulation factors discussed above. In this group we find opakapaka, an indo-pacific fish, usually only living in the south Kuroshio current of Japan migrating to Hawai'i. Since Kameník et al. (2012) showed that the Kuroshio Current was a strong barrier preventing the southward dispersion of Fukushima-derived cesium; any fish migrating south of the Kuroshio would completely avoid the Fukushima cesium plume. This explanation can rationalize why there is no ^{134}Cs, but historical ^{137}Cs is well mixed in the ocean and should be available for these fish displayed by all species having ^{137}Cs concentrations. Opah is a fish local to the Hawaiian reef, occurring generally south of the islands in the subtropical gyre (Polovina 2007). An elevated plume of radiocesium never actually reached Hawai'i

Figure 8. The relationship of Fukushima tracers cesium 134 and 137 between species in Bq/kg. Uncertainties at one sigma.



(Kameník et al. 2012), therefore opah never had a chance to pick up any Fukushima-derived cesium. Even though these fish may have lived in direct contact with the cesium plume; the Pacific cod, California king salmon, and Yellowfin tuna samples remain to be held to unquantifiable biologic factors not investigated in this study. The cod and salmon do not mature until about three years of age, when migrating to the open ocean for feeding finally occurs (National Wildlife Federation). The reasoning behind the repeated unquantifiable terms are encouraged by the species migration patterns from fresh water ecosystems to ocean at a certain age, relating that younger fish had not remained in the north pacific long enough to accumulate any cesium isotopes that have remained concentrated in the ocean since the weapons tests of the 1960's.

Dose

The US Food & Drug Administration designated an intervention limit for radiocesium isotopes in fish to be at 300 Bq/kg. To compare the intervention standards to human dose equivalent, methodical dose concentration conversions (DCC) are utilized in the calculation (Fisher et al 2014). The DCC for ^{137}Cs is 13 nSv/Bq (Buesseler 2015). A Sievert, Sv, is the biological effect of one joule of radiation energy in one kilogram of tissue. For perspective, an average banana has about 98 nSv of radiation coming from ^{40}K. Figure 9 below reveals that the highest concentration of total radiocesium in our fish samples is less than 0.75 Bq/kg, a dose rate equivalent of 2.25 nSv/hour. Table 9 displays the human effective dose based on the dose correlations of 19 nSv/Bq for cesium-134 and 6.2 nSv/Bq for ^{40}K (Fisher et al 2014). The conversion of numerical disintegrations per second to human tissue destruction reveals that ^{40}K is responsible for a higher dose than the cesium isotopes combined (Table 9).

Radioactive cesium emits gamma radiation, which penetrates vital organs in the human system causing tissue damage and cell disruption. Unfavorable health effects range from nausea to death (Environmental Health & Toxicology); with illness including hematologic and cardiovascular failure, and reproductive impedance.

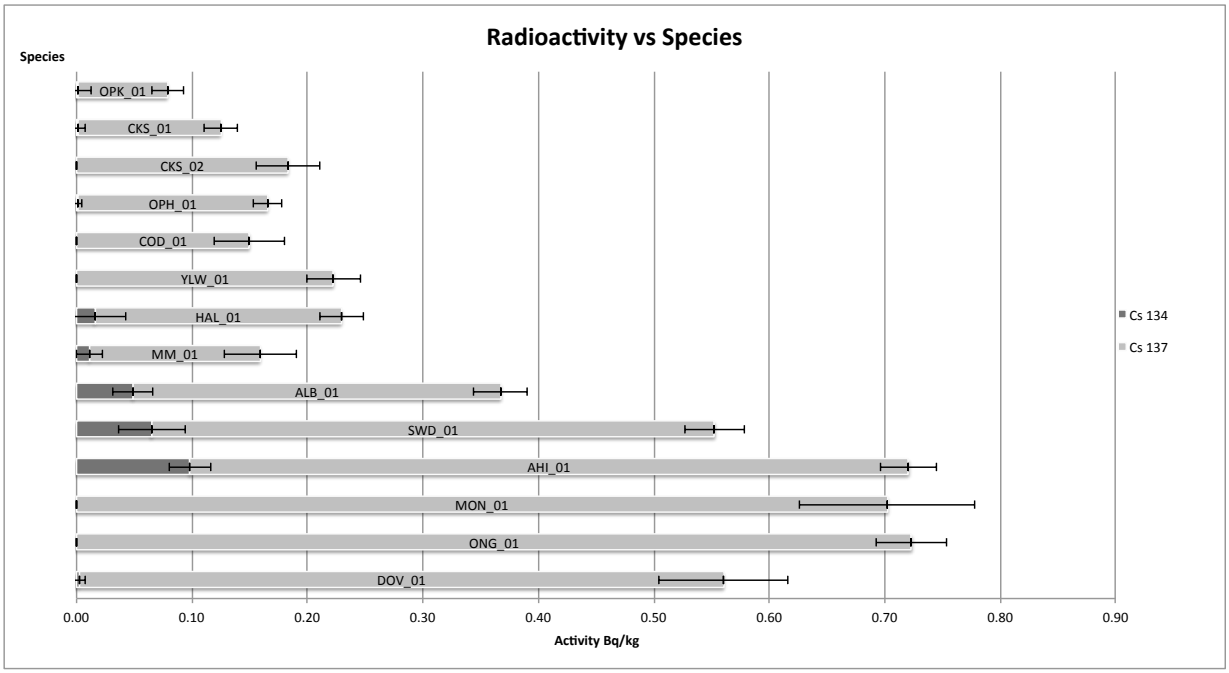
The effective dose given by the fish in this investigation from 2015 is incredibly low compared to the range reported in fish near Japan (Buesseler 2015). High cesium concentrations directly discharged into the north Pacific Ocean led to the closure of near shore fisheries in Japan in three prefectures for over a year. In 2012 just after the incident, Madigan's Pacific Bluefin tuna was reported to contain an average of 10.6 Bq/kg of ^{137}Cs (Madigan 2012), one to two orders of magnitude higher than the activities calculated in this investigation. This correlates with the expected radioactive decay in three years of time

Table 9. Effective dose of each species to humans based on a 24.1 kg/year US average annual consumption of fish. Dose was corrected to wet weight of each sample.

species	Cs-134 nSv/yr	Cs-137 nSv/yr	K-40 nSv/yr
Ahi	45.0	195	20266
Albacore Tuna	22.4	100	17905
California King Salmon	0.6	39	14236
California King Salmon	0.0	57	23320
Cod	0.0	47	14874
Dover Sole	1.2	175	6401
Halibut	7.4	67	18931
Mahi Mahi	5.2	46	16459
Monchong	0.0	220	14454
Onaga	0.0	226	17699
Opah	0.4	18	17827
Opakapaka	0.7	70	9904
Swordfish	29.8	153	17281
Yellowfin Tuna	0.0	70	18598

between this and their study along with biologic metabolic rates, on average, a few percent loss per day (Buesseler 2012). A recent study by Pearson and colleagues examined cesium contamination in New Zealand fisheries only to find a lack of ^{134}Cs and only 47% of the specimens containing trace level ^{137}Cs ranging in activities from 0.05 to 0.14 Bq/kg of ^{137}Cs (Pearson 2015). Although only this one study is available for comparison, this verifies the assumptions that strictly north pacific fish species succeeded in acquiring Fukushima-derived signature as suggested by the original cesium plume models from 2011 (Pearson 2015). The effective biological half-lives of cesium within the fish affect bioaccumulation as well, since excretion of the radiocesium is high and the source of contamination is not continuous when referring to surface conditions. The largest anthropogenic deposit of radioactivity into the local marine ecosystem of Japan became diluted enough throughout the pacific to not affect the foods currently caught in the rest of the pacific. The International Commission on Radiological Protection recommends an annual 50 mSv limit of exposure, while the fish sampled in this study are about 2.4e-4 % of that limit. The fish have bioaccumulated a low concentration of radiocesium compared to what was initially released into the marine environment in the vicinity of Japan.

Figure 9. Bar graph of ^{137}Cs (grey) and ^{134}Cs (black) activities in each sample of selected fish species.



Conclusion

^{134}Cs and ^{137}Cs activities of each specimen were far below the FDA's derived intervention limit of 300 Bq/kg, and even the World Nuclear Associations limit of 100 Bq/kg. All samples were less than 1 Bq/kg of total radiocesium activity, and only five samples showed plausible evidence of ^{134}Cs. The higher concentrations were found in the migratory species that move from Japan to Hawai'i. The highest activity was found in the Japanese migratory ahi and onaga. The annual doses from the selected fish in this study would not pose over a 6% total dose threat of the annual intervention limits. This study exposes the majority of fish consumed on the islands of Hawai'i are not exposed to the path of plume travel towards the northern rim of the Pacific following the Kuroshio Current and into the north pacific gyre.

This investigation has combined numerous sources to establish the key factors responsible for the radioactivity concentrations currently found in each examined species and should set the foundation for further bioaccumulation studies. Enrichment of radiocesium links bioaccumulation of each species and varies immensely, bioaccumulation being one of the many factors for cesium uptake. This study suggests governing factors affecting concentrations heavily rely on migration and habitat location relative to the plume, high water saturation in the species, and depth factors of surface feeders and bottom dwellers. As a result of diverse variables influencing bioaccumulation, each fish was analyzed in its own case. This is one of the first studies targeting Hawaii's fish consumption through a radioactive lense.

It is of utmost importance for studies like this to occur in order to view a glimpse of the broader impacts within the repercussions of anthropogenic disasters. Investigations relating to food consumption safety are essential to a foundation of global and community awareness and should not cease to continue even if the pollution is not a significant hazard. The ocean has bared the burden of pollution for human kind once again, diluting the radioactivity to lower dose rates than eating a banana posing minimal contribution to the total dose for a high seafood diet. These low levels of contamination will remain in the environment for decades to come, cesium will continue to be monitored for anthropogenic releases via techniques of this manor to enforce decay trends and further establish biomagnification developments.

References

Aarkrog, A., M.S Baxter, A.O. Bettencourt, R. Bojanowski, A. Bologa, S. Charmasson, I. Cunha, R. Delfanti, E. Duran, H. Nies., I. Osvath, Li Pingyu, P.P. Povinec, A. Sanchez, J.N. Smith, and D. Swift. "A Comparison of Doses from 137Cs and 210 Polonium in Marine Food: A Major International Study." *Journal of Environmental Radioactivity* 34.1 (1997): 69-90.

Aoyama et al 2015. 134Cs and 137Cs in the North Pacific Ocean derived from the March 2011 TEPCO Fukushima Dai-ichi Nuclear Power Plant accident, Japan. Part one: surface pathway and vertical distributions. Journal of Oceanography. November 2015.

Bally Du Bois et al 2012. Estimation of marine source-term following Fukushima Dai-ichi accident. Journal of Environmental Radioactivity.

Bois et al. (2012). "Estimation of Marine Source-term following Fukushima Dai-ichi Accident." *Journal of Environmental Radioactivity* 114 (2012): 2-9.

Buesseler et al. (2011) "Impacts of the Fukushima Nuclear Power Plants on Marine Radioactivity". Environmental Science & Technology 45.23 (2011)

Buesseler (2012). "Fishing for Answers". Woods Hole Open Access Server. August 2012.

Buesseler et al 2015. "Tracking the fate of Particle Associated Fukushima Daiichi Cesium in the Ocean off Japan". Environmental Science and Technology.

Duranton et al. 2000. Potassium channels in primary cultures of seawater fish gill cells. II. Channel activation by hypotonic shock.

E.B. Duran et al. Journal of Environmental Radioactivity 76 (2004) 139-160. Environmental Health & Toxicology. "Cesium, Radioactive: Human Health Effects". HSDB. Toxnet. October 2006.

Fisher et al. 2012 "An evaluation of radiation doses and associated risk from the Fukushima nuclear accident to marine biota and human consumers of seafood" PNAS.

Goulet 2011. "Uranium Toxicity to Fish. Abstract of the journal article published in Fish Physiology Volume 31b: Homeostasis and Toxicology of Non-Essential Metals". Canadian Nuclear Safety Commission.

Heldal et al. (2003) "Bioaccumulation of 137Cs in Pelagic Food Webs in the Norwegian and Barents Seas." *Journal of Environmental Radioactivity* 65.2 2003: 177-85.

IAEA, I. A. E. A. Sediment Distribution Coefficients and Concentration Factors for Biota in the Marine Environment; International Atomic Energy Agency: Vienna, Austria, 2004.

Kameník et al. (2013) Cesium-134 and 137 activities in the central North Pacific Ocean after the Fukushima Dai-ichi Nuclear Power Plant Accident. Biogeoscience. 2013.

Lai Z et al. (2013) Initial spread of 137Cs from the Fukushima Dai-ichi Nuclear Power Plant over the Japan continental shelf: A study using a high-resolution, global-coastal nested ocean model. Biogeosci. 10:5439–5449.

Madigan et al. (2012) Pacific Bluefin tuna transport Fukushima radionuclides from Japan to California. PNAS. 2012.

NDF. "Technical Strategic Plan 2015 for Decommissioning of the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Company." (2015)

Pearson, Gaw, Hermanspahn, Glover. “Activity concentrations of 137 Caesium and 210 Polonium in seafood from fishing regions of New Zealand and the dose assessment for seafood consumers”. Journal of Environmental Radioactivity 151 pg 542-550. 2015.

Polovina, Jeffrey J., Donald Hawn, and Melanie Abecassis. "Vertical Movement and Habitat of Opah (Lampris Guttatus) in the Central North Pacific Recorded with Pop-up Archival Tags." *Marine Biology Mar Biol* 153.3 (2007): 257-67.

Rossi et al (2013) “Multi-decadal Projections of Surface and Interior Pathways of the Fukushima Cesium-137 Radioactive Plume” *Deep Sea Research Part I: Oceanographic Research Papers* 80 (2013):37-46.

Rowan, David J., Lorna A. Chant, and Joseph B. Rasmussen. "The Fate of Radiocesium in Freshwater Communities—Why Is Biomagnification Variable Both within and between Species?" *Journal of Environmental Radioactivity* 40.1 (1998): 15-36.

Rypina et al. (2013) Short-term dispersal of Fukushima-derived radionuclides off Japan: Modeling efforts and model-data intercomparison. Biogeoscience, 10:4973–4990.

Smith et al. (2014) “Arrival of the Fukushima radioactivity plume in North American continental waters”. December 2014. PNAS.

Tateda et al. (2013) "Simulation of Radioactive Cesium Transfer in the Southern Fukushima Coastal Biota Using a Dynamic Food Chain Transfer Model." *Journal of Environmental Radioactivity* 124 (2013): 1-12.

Watabe et al. (2013) Radiocesium contamination of Marine fish muscle and its effective elimination. Agricultural Implications of the Fukushima Nuclear Accident. University of Tokyo. 2013.

1971 *Radioactivity in the Marine Environment*, National Academy of Sciences.

http://www.fda.gov/NewsEvents/PublicHealthFocus/ucm247403.htm

http://www.tepco.co.jp/en/press/corp-com/release/2012/1204659_1870.html