



Enhancing highly unsaturated ω -3 fatty acids in phase-fed rainbow trout (*Oncorhynchus mykiss*) using Alaskan fish oils

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Abstract

Rainbow trout, average weight 185–187 g, were fed feeds containing menhaden oil, canola oil or fish oils (pollock, pink salmon or rockfish) produced from Alaskan seafood processing waste as the added oil for 8 weeks, at which time the fish weighed 391–411 g (average 404 g, pooled SE = 5.7). The fish were previously fed from 75 g average weight fed commercial feed containing poultry oil as the added oil. No significant differences were measured in final weight or feed conversion ratio among dietary treatment groups. Significant differences were found in fillet ω -3 fatty acid (FA) levels from fish receiving fish oil-supplemented feeds compared to those from fish receiving feeds containing canola oil. Fillet contents of eicosapentaenoic acid (EPA; 20:5 ω 3) and docosahexaenoic acid (DHA; 22:6 ω 3) were highest in the pollock oil treatment group, although all fish oils increased highly unsaturated ω -3 FA contents (mg 100 g⁻¹) of fillets. Fish oil used through the production cycle was reduced by 25% by supplementing feeds with poultry oil during the middle phase of production (75–175 g) compared to using feeds containing fish oil throughout the production cycle. Fish oils recovered from Alaskan seafood processing waste were suitable alternatives to conventional fish oil as ingredients in rainbow trout production feeds.

KEY WORDS: Alaskan fish oils, DHA, EPA, fatty acids, phase-feeding, rainbow trout

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Introduction

Fish oil is a limited commodity of extreme importance to the aquaculture feed industry. Tacon & Metian (2008) reported that in 2006, the aquaculture feed industry used 835 000 metric tons of fish oil, 88.5% of global fish oil production that year. Annual fish oil production from reduction fisheries ranges from approximately 830 000 to 1 390 000 mt, depending on landings of forage fish. Demand for fish oil to produce aquafeeds is expected to increase, making it necessary to substitute alternative oils for portions of fish oil in aquafeeds. One promising source to use in aquafeeds that is currently underexploited is fish oil recovered from seafood processing by-products (trimmings) in Alaska.

Capturing fish oil from Alaskan seafood by-products is attractive for several reasons. First, Alaskan fish oils are produced from the waste stream of fisheries that have been certified sustainable by the Marine Stewardship Council (MSC). Hence, their continuing availability is likely. Second, production levels, while difficult to document, could quickly reach 70 000 mt per annum under appropriate conditions (Smiley *et al.* 2006). Third, Alaskan fish oils contain low levels of persistent organic pollutants and mercury (Oliveira *et al.* 2008) compared to fish oils from other regions. Finally, Alaskan fish oils are rich in long-chain ω -3 fatty acids (FA), particularly eicosapentaenoic acid (EPA; 20:5 ω 3) and docosahexaenoic acid (DHA; 22:6 ω 3) (Oliveira *et al.* 2008). Fish oils that are currently produced from Alaskan seafood processing by-products are pink salmon (*Oncorhynchus gorbuscha*) oil, walleye pollock (*Theragra chalcogramma*) oil and rockfish (*Sebastes alutus*) oil. All contain levels of EPA (pollock, 16%; pink salmon, 10%; rockfish, 11%) and DHA (pollock, 5%; pink salmon, 13%; rockfish, 7%) similar to anchovy oil (EPA 17%; DHA 9%) and menhaden oil (EPA,

11%; DHA 9%) (NRC 1993; Oliveira & Bechtel 2005; Oliveira *et al.* 2008).

Both ω -3 and ω -6 FA are essential nutrients for all vertebrates (NRC 1993; Simopoulos 2000). Fish oil is the most important source of highly unsaturated ω -3 FA (ω -3 HUFA) for both fish and humans (NRC 1993; Simopoulos 2000). Fish oil also contains arachidonic acid (20:4 ω 6), a ω -6 FA. In contrast, linolenic acid, the precursor to ω -3 HUFA, is the predominant ω -3 FA in plant and animal oils (NRC 1993).

Currently, animal fats such as poultry fat and plant oils such as canola oil are used in rainbow trout feeds to reduce production cost associated with fish oil inclusion and to also alter the sensory characteristic of fillets (Hardy 2002; Liu *et al.* 2004). The FA profiles of poultry fat and canola oil differ markedly from fish oil (NRC, 1993). Compared to fish oils, poultry fat and canola oil contain high levels of oleic acid (18:1 ω 9) (~40% and 60%, respectively), are high in ω -6 FA, especially linoleic acid (18:2 ω 6), low in ω -3 FA and lack the highly unsaturated FA, EPA and DHA (NRC 1993). Animal fats and plant oils have been used to partially or completely replace fish oil in several fish species with no reduction in growth performance (Boggio *et al.* 1985; Hardy *et al.* 1987; Sargent *et al.* 2002; Bell *et al.* 2003; Regost *et al.* 2003; Liu *et al.* 2004). However, as a result of feeding animal fats or plant oils, the FA profile of the fish is altered to reflect that of the lipid source (Boggio *et al.* 1985; Hardy *et al.* 1987; Bell *et al.* 2003; Blanchet *et al.* 2005) which may reduce the beneficial human health attributes associated with eating fish high in ω -3 HUFAs (Simopoulos 2003; Wang *et al.* 2006).

To compensate for the reduction in ω -3 HUFAs in farmed fish reared using feeds containing animal fats or plant oils, fish may be fed feeds containing only added fish oil during the final months before harvest (Bell *et al.* 2003). The practice of sequentially using aquafeeds containing relatively inexpensive plant/animal oils in the grow-out stage of production and then switching to feeds containing fish oil prior to harvest is called phase feeding. For phase feeding to be successful, the length of time required to alter the FA profile of plant/animal oil-fed fish to the desired profile must be established. Robin *et al.* (2003) reported the findings of two studies where brown trout, *Salmo trutta*, and turbot, *Psetta maxima*, approaching market size, were fed diets containing 90 or 150 g kg⁻¹ soybean oil or linseed oil for 3 months and then switched to a 150 g kg⁻¹ fish oil diet for 2 months. The fillet FA profiles of the brown trout and turbot shifted towards that of the fish oil-fed control fish; however, neither species attained fillet FA profiles found in fish fed fish oil diets continuously (Robin *et al.* 2003). Bell *et al.* (2003) re-

ported the FA profile of Atlantic salmon, *Salmo salar*, previously fed diets in which rapeseed oil replaced 50% or 100% of fish oil over a period of 16 weeks and then fed a diet containing fish oil as the primary lipid source for an additional 12 weeks still had higher linoleic acid levels in the flesh than fish fed exclusively on fish oil-diets. However, during the same period, the percentages of flesh EPA and DHA were restored to levels found in fish oil-fed fish after 4 and 12 weeks, respectively (Bell *et al.* 2003). FA profiles of fish reared using phase feeding may be affected by previous feeding history, species and age of fish, environmental factors, dietary lipid level and the FA profile of the dietary lipid source. The FA profiles of Alaskan fish oils may be superior to menhaden oil, commonly used fish oil added to aquafeeds in the USA, in boosting ω -3 HUFA levels in rainbow trout during phase-feeding regimes because of their FA profiles.

Rainbow trout production in the USA in freshwater differs from brackish or salt water production in other areas of the world in that fish are typically harvested between 450 and 800 g rather than >2.5 kg for brackish- or seawater-produced fish (Hardy 2002). In this study, we investigated fillet FA deposition and the potential for altering the ω -3 to ω -6 FA ratio and EPA and DHA fillet tissue levels in 450 g fish. Rainbow trout fed diets containing poultry oil were switched to diets containing menhaden oil or Alaska seafood by-product fish oils. For comparison, we also investigated changes in the FA profile of rainbow trout phase-fed menhaden oil or canola oil.

Materials and methods

Experimental oils and diets

Five oils were tested in this study: canola oil (Canola Harvest[®] Canbra Foods Ltd., Lethbridge, Alberta, Canada), menhaden oil (Omega Protein Corporation, New Orleans, LA, USA) and pollock, pink salmon and rockfish oils produced from seafood processing by-products from Kodiak AK, USA. The FA profiles and lipid classes of the oils are presented in Table 1.

Five diets were used in the study: a control diet (147 g kg⁻¹ menhaden oil) or the control diet with the menhaden oil completely replaced with 147 g kg⁻¹ pollock oil, 147 g kg⁻¹ pink salmon oil, 147 g kg⁻¹ rockfish oil or 147 g kg⁻¹ canola oil. The FA profiles, ingredient formulations and nutrient composition of the diets are shown in Tables 1 & 2. Diets were formulated on a digestible dry basis to be iso-nitrogenous, iso-lipidic and to contain calculated digestible energy values of 15 MJ kg⁻¹ diet. Diets were compressed and pel-

Table 1 Fatty acid composition of test oils (mg FA g⁻¹ oil) and experimental diets (mg FA g⁻¹ diet)^{1,2,3}

Fatty acid	Poultry fat	Commercial diet A	Menhaden		Pollock		Pink salmon		Rockfish		Canola	
			Oil	Diet	Oil	Diet	Oil	Diet	Oil	Diet	Oil	Diet
14:0	0.9	6.9	72.9	12.8	35.9	6.7	36.6	6.9	40.9	8.3	0.0	1.6
16:0	298.0	31.9	173.4	32.1	146.9	26.7	112.0	22.1	122.0	25.6	39.7	11.1
18:0	44.3	7.7	30.3	5.7	28.5	5.2	22.1	4.4	19.4	4.3	17.1	3.6
16:1 ω 7	94.6	10.5	89.3	15.3	69.8	11.4	35.1	6.5	49.7	9.5	2.1	1.7
18:1 ω 9 <i>cis</i>	373.2	26.4	61.3	12.1	183.8	29.5	103.5	18.6	121.8	22.9	535.9	81.9
18:1 ω 7	0.0	5.4	23.3	4.3	79.8	12.1	18.7	3.5	40.6	7.6	0.0	5.5
20:1 ω 11	0.0	0.8	0.0	0.0	7.0	1.0	51.0	7.8	51.5	7.9	0.0	0.0
20:1 ω 9	0.0	2.1	8.1	1.6	9.0	1.6	23.3	3.9	24.3	3.9	12.3	2.2
22:1 ω 11	0.0	0.7	0.0	0.6	8.3	1.6	66.8	10.4	72.8	11.7	0.0	0.4
18:2 ω 6 <i>cis</i>	153.6	6.9	14.2	5.8	5.7	4.6	13.0	5.8	8.7	5.3	186.6	30.4
18:3 ω 3	4.9	1.3	9.0	1.9	4.0	1.0	9.3	1.9	4.9	1.2	85.7	10.8
18:4 ω 3	0.0	0.8	16.1	3.0	14.1	2.4	21.1	3.6	15.5	3.0	0.0	0.5
20:4 ω 6	0.0	1.9	10.0	1.7	3.0	0.7	4.5	0.8	3.6	0.8	0.0	0.0
20:4 ω 3	0.0	1.3	9.4	1.6	3.4	0.7	14.5	2.3	5.3	0.9	0.0	0.0
20:5 ω 3	0.0	14.6	91.5	17.0	141.5	22.6	80.2	13.8	90.2	17.5	0.0	2.7
22:6 ω 3	0.0	27.4	62.8	13.6	46.1	10.4	112.9	19.2	57.6	12.1	0.0	3.7
Σ EPA + DHA	0.0	42.0	154.3	30.6	187.6	33.0	193.1	33.0	147.8	29.6	0.0	6.4
$\Sigma\omega$ 3	4.9	45.4	209.0	37.1	221.1	37.1	262.1	41.1	185.1	34.7	85.7	17.6
$\Sigma\omega$ 6	153.6	8.9	35.3	8.6	11.5	5.3	22.6	7.2	15.3	6.4	186.6	30.6
$\Sigma\omega$ 3/ $\Sigma\omega$ 6	0.01	5.1	5.9	4.3	19.2	7.1	11.6	5.8	12.1	5.4	0.5	0.6
Σ SFA	343.2	53.2	297.5	57.5	219.4	44.6	181.2	38.6	195.2	42.9	66.2	17.7
Σ MUFA	467.8	47.1	195.4	37.0	407.9	60.5	340.3	58.6	394.8	70.1	585.1	91.7
Σ PUFA	158.5	56.4	248.9	48.9	243.3	43.6	287.1	48.7	205.7	42.1	279.5	49.8
Σ PUFA/ Σ SFA	0.5	1.1	0.8	0.9	1.1	1.0	1.6	1.3	1.1	1.0	4.2	2.8
Σ Saponifiables	969.6	156.7	741.8	147.3	870.5	150.2	808.6	146.6	795.8	156.8	930.9	160.3
Σ Unknown	30.4	50.6	258.2	4.0	129.5	1.5	191.4	0.7	204.2	1.8	69.1	0.5

FA, fatty acid; Σ SFA, sum of saturated FA; Σ PUFA, sum of polyunsaturated FA; Σ MUFA, sum of monounsaturated FA; EPA, eicosapentaenoic acid; DHA, decosahexaenoic acid.

¹ For clarity, mean FA values of <1% or <10 mg g⁻¹ oil for all oil types were not included in the table.

² For clarity, mean FA values of <0.1% or <1 mg g⁻¹ diet total FA for all diets were not included in the table.

³ Poultry fat data were provided by Rangen, Incorporated.

leted without steam using a California pellet mill (California Pellet Mill Company, Crawfordsville, IN, USA) to make 4-mm, slow-sinking pellets. The study was a completely randomized design for statistical evaluation of data, and each diet was assigned randomly to three replicate tanks within the fish-rearing laboratory at the University of Idaho Hagerman Fish Culture Experiment Station (HFCEs).

Fish and rearing

A domesticated strain of rainbow trout (House Creek strain, College of Southern Idaho) was used in this study. Prior to the study, the fish were reared at College of Southern Idaho Rock Creek Hatchery (Twin Falls, ID, USA) and fed a commercial feed (Rangen, Inc., Buhl, ID, USA; 450 g kg⁻¹ protein, 160 g kg⁻¹ lipid; lipid source menhaden oil) until they were 5 months old (~75 g per fish). Fish were then switched to another feed (Rangen, Inc. 450 EXD diet; 450 g kg⁻¹ protein, 200 g kg⁻¹ lipid) containing poultry oil as its primary lipid source and fed for an additional 2 months.

The fish were 7 months old (~186 g per fish) when they were transferred to HFCEs to begin the study.

At stocking, the fish were anaesthetized with 100 mg L⁻¹ tricaine methane sulphate (MS222; Argent Chemical Laboratories Inc, Redmond, WA, USA), counted in groups of 50 fish, weighed and stocked into 575-L fibreglass tanks. Each tank was supplied with 8 L min⁻¹ of constant temperature (14.5 °C), spring water. A fixed photoperiod, controlled by timers and fluorescent lights, was utilized (14 h L: 10 h D). Fish were fed two times per day during the feeding trial to apparent satiation, 6 days per week, for 8 weeks. Experimental protocols were approved by the Institutional Animal Care and Use Committee of the University of Idaho.

Sampling and sample analyses

Rainbow trout in each tank were bulk-weighed and counted at stocking and after 4 and 8 weeks. Fillets were collected from five randomly selected fish at the beginning of the experiment and from three fish from each replicate tank at 4

Table 2 The ingredient formulation and composition of experimental diets

Ingredients ¹	Amount (g kg ⁻¹)
Fish meal, sardine (CP = 660 g kg ⁻¹)	370.0
Test oil ²	147.0
Soybean meal (CP = 470 g kg ⁻¹)	120.0
Ground wheat (CP = 120 g kg ⁻¹)	239.0
Corn gluten meal (CP = 600 g kg ⁻¹)	100.0
Stable C (35% active)	3.0
Choline chloride (dry, 50% active)	5.0
Trace mineral premix ³	1.0
Vitamin premix ⁴	15.0
Sum	1000.0
Analysed composition (dry basis)	
Moisture (g kg ⁻¹)	695
Protein (g kg ⁻¹)	418
Lipid (g kg ⁻¹)	189
Ash (g kg ⁻¹)	72
Energy (MJ kg ⁻¹)	15.2

¹ Feed ingredients were purchased from Nelson & Sons, Inc., Salt Lake City, UT, USA.

² Test oils were Diet 1, Menhaden oil; Diet 2, Pollock oil; Diet 3, Pink salmon oil; Diet 4, Rockfish oil; Diet 5, Canola oil.

³ US Fish and Wildlife Service trace mineral premix No. 3 supplied the following (g kg⁻¹): Zn as ZnSO₄, 75; Mn as MnSO₄, 20; Cu as CuSO₄, 1.54; and I as KIO₄, 10.

⁴ Vitamin premix No. 30 supplied the following per kg: vitamin A as retinol palmitate, 6600 USP; vitamin D as cholecalciferol, 440 IU; vitamin E as *dl*- α -tocopheryl acetate, 352 IU; vitamin K as menadi-one sodium bisulphate, 11 mg; thiamin as thiamin hydrochloride, 35.2 mg; riboflavin, 52.8 mg; pyridoxine as pyridoxine-HCl, 30.8; pantothenic acid as Ca-*d*-pantothenate, 105.6 mg; niacin as nicotinic acid, 220 mg; biotin as *d*-biotin, 0.352 mg; folic acid, 8.8 mg; and vitamin B₁₂ as cyanocobalamine, 22 mg.

and 8 weeks. Additionally, to measure the FA profile of fish produced exclusively using menhaden oil, 10 fish from two size classes of rainbow trout (200 and 384 g per fish) were collected from production raceways at a local trout farm (Commercial farm A). These fish were being fed a closed formula diet (Commercial diet A, 450 g kg⁻¹ protein, 200 g kg⁻¹ lipid) that contained menhaden oil as the oil source. The FA profile of the commercial diet A is shown in Table 1. All fish and fillets were weighed to determine fillet yield and then stored frozen at -20 °C until analysed. Diet samples were also stored at -20 °C until analysed.

Trout fillets were thawed at 3–5 °C, skin-on weights were recorded, and fillets were then skinned and weighed to calculate skin-off fillet yield. A composite tissue sample was prepared by comminuting one fillet (right) from each of the three fish from the same tank to a paste. The composite samples were used for proximate and FA analysis. The unit of mg FA per kg of skinned fillet was used as it describes the actual amount of FA that a consumer would eat based on the

ingestion of a given quantity of flesh. Additionally, 100 g is the United States Department of Agriculture (USDA) standard reference portion size for nutritional measurement of food, and it also approximates the United States Food and Drug Administration (USFDA) standard serving size for fish (85 g).

Proximate and FA composition of the diets and fillet samples were determined in duplicate. AOAC (1990) methods were used to analyse protein (method 968.06), moisture (method 952.08) and ash (method 938.08), while the lipid content was analysed according to Folch *et al.* (1957). FA methyl esters were prepared according to the procedure of Maxwell & Marmer (1983) using C23:0 as internal standard. FA methyl esters were quantified as described by Oliveira & Bechtel (2005). Briefly, a GC model 6850 (Agilent Technologies, Wilmington, DE, USA) fitted with a DB-23 (60 m × 0.25 mm id., 0.25 µm film) capillary column (Agilent Technologies) was used. Hydrogen was the carrier gas at a constant flow of 1.0 mL min⁻¹. Detector and injector temperatures were held at 275 °C, and the split ratio was 25 : 1. Oven programming was 140–200 °C at a rate of 2 °C min⁻¹, 200–220 °C at a rate of 0.5 °C min⁻¹ and 220–240 °C at a rate of 10 °C min⁻¹ for a total run time of about 62 min. An auto-sampler injected standards and samples at 1 µL. Data were collected and analysed using the GC ChemStation program (Agilent Technologies). All standards used in the identification of peaks were purchased from Supelco® (Bellefonte, PA, USA). The standards used were Supelco 189-19, Bacterial Acid Methyl Esters Mix, Marine Oil #1 and Marine Oil #3.

Calculation of performance indices

To determine whether there were significant differences between the relative changes of fillet FA levels for each 4-week growing period, the relative changes in edible fillet FA levels (mg FA 100 g⁻¹ fillet) for each group were calculated as a percentage using the following formula:

$$\frac{(\text{final fillet FA content} - \text{initial fillet FA content}) \times 100}{(\text{initial fillet FA content})}$$

Other performance indices were calculated using the following formulae:

$$\text{Weight gain (g per fish)} = \text{final weight} - \text{initial weight};$$

$$\text{Specific growth rate (SGR)} = (\ln \text{final weight} - \ln \text{initial wt}) \times 100/\text{days of growth};$$

$$\text{Feed conversion ratio (FCR)} = \text{feed fed}/\text{body weight gain};$$

$$\text{Fillet yield (\%)} = \text{weight fillets} \times 100/\text{weight fish}.$$

Statistical analyses

The experiment was designed to be analysed using one-factor ANOVA for growth performance data and one-factor ANOVA for unequal sample sizes for fillet FA data. Two-factor ANOVA was used to determine the effects of dietary oil type (first factor; menhaden, pollock, pink salmon, rockfish or canola oil diet) and growth period (second factor; weeks 1–4 and weeks 4–8) on the relative change of fillet FA levels. Multiple regression analysis was used to assess the relationship between fillet lipid content and fillet moisture content. Statistical analyses were carried out using Statistica, Version 6.1 (StatSoft, Inc., Tulsa, OK, USA). Student–Newman–Keuls (SNK) test was used to identify significant differences among multiple treatments for growth performance and FCRs, and where necessary the unequal N HSD test, a modification of Tukey's HSD test, was used to identify significant differences among multiple treatments. A significance level of $P < 0.05$ was used, and with the exception of the initial fish ($n = 5$ individual fish), tank mean values ($n = 3$) were considered units of observation for statistical analysis. Unless otherwise stated, all values are reported as the mean \pm pooled standard error of the mean.

Results

Fatty acid profile and composition of the test oils and test diets

The sum of saturated (Σ SFA) and monounsaturated FA (Σ MUFA) in all Alaskan fish oils was similar ranging from 181 to 219 and 340 to 408 mg g⁻¹ oil for Σ SFA and Σ MUFA, respectively (Table 1). Poultry fat had a high Σ SFA value and canola oil contained the lowest, whereas Σ MUFA in canola oil and poultry fat was considerably higher than the other oils. Menhaden oil had a much lower Σ MUFA value than any of the other oils. The sum of polyunsaturated FA (Σ PUFA) values for all oils ranged from 159 to 287 mg g⁻¹ oil. Canola oil contained the greatest ratio of Σ PUFA to Σ SFA, while poultry fat possessed the lowest. Pollock, pink salmon and rockfish oils had ω -3 FA contents similar to menhaden oil, while canola oil was much lower and poultry fat contained practically none.

EPA and DHA were not detected in canola oil or poultry fat. Pink salmon oil had a larger proportion of DHA than EPA, while pollock, rockfish and menhaden oil contain more EPA than DHA. Pink salmon and pollock oils contained higher levels of the Σ EPA + DHA and also possessed higher ratios of ω -3 to ω -6 FA (ω 3/ ω 6) than menhaden oil. The

ratios of ω 3/ ω 6 in poultry fat and canola oil were considerably lower than for fish oils. The FA profiles of the diets reflected the FA profiles of the test oils, although the canola oil diet contained some EPA and DHA, presumably from residual oil in fishmeal.

Growth performance of fish

Fish accepted all diets equally, and there were two mortalities unrelated to dietary treatment over the course of the feeding trial. There were no significant differences in average initial (185–187 g) or final weights of fish fed the experimental diets (menhaden oil, 410 g; pollock oil, 404 g; pink salmon oil, 411 g; rockfish oil, 402 g; canola oil, 391 g per fish; pooled se, 5.72; $P = 0.233$). There were also no significant differences in SGRs (range, 1.26–1.34, $P = 0.180$) or FCR (range, 1.13–1.22, $P = 0.211$) among dietary treatments. Skin-on and skin-off fillet yields ranged from 50.9% to 54.3% ($P = 0.134$) and 36.1% to 38.3% ($P = 0.608$), respectively.

Proximate composition of fillets

A significant reduction in fillet moisture was only observed after 8 weeks in fish fed the pollock oil diet (Table 3). There was a significant relationship between lipid and moisture contents in fillet ($P < 0.001$; $R^2 = 0.865$; $y = -0.7195x + 57.62$). There was also a trend for fillet protein content to increase from initial values. However, a significant increase in the fillet protein content of fish fed the pollock oil diet only occurred after 8 weeks. Fillet ash contents were not significantly affected by dietary treatment.

Fatty acid composition of fillets

There were significant changes in the Σ SFA, Σ MUFA and the Σ PUFA levels in the fillets of fish among dietary oil treatments over time (Table 4). Compared to levels in fillets of initial fish, Σ SFA levels of fillets from canola oil-fed fish decreased significantly ($P < 0.05$) by 25.5% after 4 weeks of feeding. In contrast, the Σ SFA content of fillets from menhaden oil-fed fish was significantly elevated after 4 and 8 weeks of feeding. The Σ SFA levels of fillets from fish fed the Alaskan fish oils remained relatively unchanged after 8 weeks.

Σ MUFA levels of fillets from fish fed the menhaden oil diet were significantly lower than initial levels following 4 and 8 weeks of feeding. In contrast, the fillet Σ MUFA levels of fish fed canola oil were significantly higher after 4 and 8 weeks of feeding. The Σ MUFA levels of fillets from the

Table 3 Fillet proximate composition (g 100 g⁻¹ wet basis) of rainbow trout fed diets containing different fish and plant oils after 8 weeks of feeding^{1,2}

Item (g 100 g ⁻¹)	Initial	Week 8					Pooled SE	P
	Rangen 450EXD Poultry oil diet	Diet 1 Menhaden	Diet 2 Pollock	Diet 3 Pink salmon	Diet 4 Rockfish	Diet 5 Canola		
Moisture	76.1 ± 0.43 ^a	74.7 ^{ab}	72.8 ^b	74.4 ^{ab}	73.3 ^{ab}	74.3 ^{ab}	0.56	0.009
Protein	19.6 ± 0.18 ^b	20.2 ^{ab}	20.5 ^a	20.2 ^{ab}	20.8 ^{ab}	20.6 ^{ab}	0.23	0.019
Lipid	3.0 ± 0.42	3.9	5.4	4.1	4.7	3.0	0.54	0.135
Ash	1.3 ± 0.21	1.3	1.3	1.3	1.3	1.3	0.26	0.069

¹ Means (±pooled standard error) within the same row that share the same superscript are not significantly different (One-factor ANOVA, Unequal N HSD test, $P < 0.05$).

² The moisture, protein, lipid and ash content of 200 and 387 g rainbow trout from Commercial farm a were 77.3, 19.1, 2.72, 1.33 g 100 g⁻¹ and 76.2, 19.6, 3.15, 1.29 g 100 g⁻¹, respectively.

Table 4 The FA composition (mg fatty acid per g total fatty acid) of rainbow trout filets fed diets containing different fish and plant oils after 8 weeks of feeding (for clarity, mean values of <1% or <10 mg g⁻¹ total fatty acid were not included in the table)^{1,2,3}

Fatty acid (mg g ⁻¹ total FA)	Initial	378 g Rainbow trout Commercial diet A	Week 8					Pooled SE	P
	Rangen EXD450 poultry oil diet		Diet 1 Menhaden	Diet 2 Pollock	Diet 3 Pink salmon	Diet 4 Rockfish	Diet 5 Canola		
C14:0	20.6 ± 0.7 ^d	30.1 ± 1.1	42.2 ^a	29.5 ^b	27.0 ^{bc}	28.9 ^{bc}	15.0 ^e	0.9	<0.001
C16:0	159.1 ± 2.4 ^{ab}	134.1 ± 1.6	152.9 ^{abcd}	155.7 ^{abc}	140.1 ^{de}	144.7 ^{cde}	115.3 ^g	2.8	<0.001
C18:0	44.4 ± 0.5 ^a	31.8 ± 0.6	33.8 ^{cd}	36.5 ^{bc}	33.1 ^d	32.7 ^d	31.7 ^d	0.6	<0.001
16:1 ω 7	49.9 ± 1.7 ^{bc}	45.3 ± 1.2	67.3 ^a	56.4 ^{ab}	40.6 ^{cd}	44.2 ^{cd}	25.9 ^e	2.2	<0.001
18:1 ω 9 cis	204.3 ± 6.0	109.8 ± 2.8	110.3 ^e	160.6 ^{cd}	140.7 ^{de}	144.3 ^{cde}	280.1 ^a	7.2	<0.001
18:1 ω 7	20.4 ± 1.1 ^d	23.0 ± 0.4	25.4 ^{bcd}	46.8 ^a	25.1 ^{bcd}	30.8 ^{bc}	25.3 ^{bcd}	1.5	<0.001
20:1 ω 11	ND	3.7 ± 0.1	ND	2.8 ^b	21.5 ^a	23.2 ^a	3.6 ^b	1.2	<0.001
20:1 ω 9	7.7 ± 0.3 ^d	8.8 ± 0.3	8.2 ^d	9.2 ^d	14.5 ^{ab}	14.8 ^a	12.7 ^{bc}	0.4	<0.001
22:1 ω 11	ND	2.7 ± 0.8	ND	3.3 ^b	23.3 ^a	27.3 ^a	4.3 ^b	1.3	<0.001
18:2 ω 6 cis	204.3 ± 2.8 ^b	31.8 ± 0.9	110.3 ^e	160.6 ^{cd}	140.7 ^{de}	144.3 ^{cde}	280.1 ^a	3.6	<0.001
18:3 ω 3	9.3 ± 0.9 ^b	5.9 ± 0.2	9.0 ^b	6.3 ^b	8.5 ^b	6.9 ^b	26.6 ^a	1.1	<0.001
20:4 ω 6	10.2 ± 0.3 ^a	8.5 ± 0.1	9.6 ^a	5.7 ^b	6.1 ^b	6.3 ^b	6.6 ^b	0.3	<0.001
20:5 ω 3	20.3 ± 1.4 ^d	63.0 ± 1.7	51.6 ^{ab}	55.8 ^a	44.6 ^{bc}	44.5 ^{bc}	19.2 ^d	1.8	<0.001
22:6 ω 3	83.2 ± 3.3 ^{def}	120.6 ± 4.1	116.3 ^{bc}	98.9 ^{cde}	129.6 ^{ab}	111.8 ^{bc}	78.8 ^{ef}	4.3	<0.001
Σ EPA + DHA	103.4 ± 3.5 ^d	183.7 ± 2.7	167.9 ^{abc}	154.8 ^{bc}	174.2 ^{ab}	156.3 ^{abc}	97.9 ^d	4.5	<0.001
$\Sigma\omega$ 3	123.1 ± 3.3 ^d	198.9 ± 2.3	193.8 ^{ab}	173.5 ^{bc}	201.4 ^a	177.0 ^{bc}	133.4 ^d	4.3	<0.001
$\Sigma\omega$ 6	134.2 ± 2.9 ^a	40.5 ± 0.9	70.9 ^{bcd}	58.1 ^d	65.9 ^{cd}	64.5 ^{cd}	129.9 ^a	3.7	<0.001
$\Sigma\omega$ 3/ $\Sigma\omega$ 6	0.9 ± 0.1 ^d	4.9 ± 0.2	2.7 ^{ab}	3.0 ^a	3.1 ^a	2.8 ^{ab}	1.2 ^d	0.1	<0.001
Σ SFA	235.3 ± 3.4 ^{cd}	225.8 ± 3.0	260.0 ^{ab}	249.3 ^{abc}	225.3 ^{de}	229.3 ^{cde}	174.1 ^f	4.3	<0.001
Σ MUFA	291.6 ± 6.9 ^{cd}	197.8 ± 4.9	223.1 ^e	288.1 ^{cd}	292.6 ^{cd}	309.8 ^{cd}	360.0 ^a	8.9	<0.001
Σ PUFA	262.9 ± 3.9 ^{abcd}	248.4 ± 1.6	280.2 ^{ab}	239.8 ^d	271.6 ^{abc}	246.9 ^c	267.4 ^{abc}	5.0	<0.001
Σ PUFA/ Σ SFA	1.1 ± 0.0 ^{ab}	1.1 ± 0.0	1.1 ^{ab}	1.0 ^a	1.2 ^{bc}	1.1 ^{ab}	1.6 ^e	0.04	<0.001

FA, fatty acid; Σ SFA, sum of saturated FA; Σ PUFA, sum of polyunsaturated FA; Σ MUFA, sum of monounsaturated FA; EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid.

¹ Means (±pooled standard error) within the same row that share the same superscript are not significantly different (One-factor ANOVA, Unequal N HSD test, $P < 0.05$).

² Commercial diet A fish ($n = 10$) not included in statistical analyses. Fillet fatty acid compositions of 200 and 378 g were essentially identical, so only analysed values from 378g fish are shown.

³ ND, not detectable.

Alaskan fish oils–fed treatments were not significantly different from initial values.

There were no significant changes in fillet Σ PUFA levels among treatments; however, fish fed the canola oil diet had higher levels of linolenic acid and lower levels of ω -3 HUFAs after 4 and 8 weeks of feeding. The $\Sigma\omega$ -3 FA content of the

filets from fish fed the fish oil diets was significantly increased after 4 and 8 weeks of feeding, while concomitantly, the $\Sigma\omega$ -6 fillet FA levels for these treatments significantly decreased. There were no significant changes in the $\Sigma\omega$ -3 and $\Sigma\omega$ -6 fillet FA levels of fish fed the canola oil diet throughout the experiment. The ratio of ω -3 to ω -6 FA in the

fillets of all fish oil-fed treatments was significantly and progressively increased at 4 and 8 weeks, while they remained unchanged in the canola oil fish. Changes in the individual fillet FA levels (mg FA per g total FA) of fish over time were also related to dietary FA levels (Tables 1 & 4).

The predominant change in fillet ω -3 FA for canola oil-fed fish was observed in linolenic acid. Fillet linolenic acid levels tripled after 4 weeks of feeding and remained constant at 8 weeks, while fillet levels of EPA and DHA remained unchanged. The fillet EPA levels of fish oil-fed fish progressively increased to over double those recorded in the initial fish after 4 and 8 weeks. DHA levels in the fillets of fish fed the menhaden, pink salmon and rockfish oils were significantly elevated after 4 weeks and remained so after 8 weeks. Compared to initial levels, the DHA levels of fillets of pollock oil-fed fish were numerically higher at 4 and 8 weeks.

The relative changes of fillet FA levels in response to growth period and dietary oil type

Edible fillet FA compositions (Table 5) followed similar trends, as did FA compositions reported as a proportion of total FA. However, because of the different total lipid levels of the fillets, some differences were noted. In particular, the EPA + DHA levels of the pollock oil-fed fish at week 8

were numerically higher than all other treatments and significantly greater than the canola oil-fed fish. With the exception of Σ MUFA, the relative changes in fillet FA levels were numerically greatest during the first 4-week period (data not shown). Statistically significant greater relative changes were observed during the first growth period for linoleic acid, EPA, DHA, $\Sigma\omega$ -3 and $\Sigma\omega$ -6 FA and the ratios of ω -3 to ω -6 FA and Σ PUFA to Σ SFA (Table 6). Dietary oil type also significantly affected the relative changes of fillet linoleic acid, linolenic acid, EPA, DHA, $\Sigma\omega$ -6 FA and the ratios of $\Sigma\omega$ -3 to $\Sigma\omega$ -6 FA and Σ PUFA to Σ SFA. There were significant interactions between growth period and dietary oil type for linolenic acid, arachidonic acid and the ratio of Σ PUFA to Σ SFA. The interaction for fillet linolenic acid levels may be explained by a significantly greater increase in this FA for the canola oil-fed fish. For arachidonic acid levels, the interaction between dietary oil type and growth period may be explained by the significant reduction in the fillet FA levels for the menhaden oil-fed fish between the growing periods, in contrast to the increase observed for fish fed the other oil types between the corresponding growth periods. The interaction for the ratio of Σ PUFA to Σ SFA may be explained by the significantly greater relative changes in the ratio of Σ PUFA to Σ SFA between growth periods for the pink salmon oil-fed fish compared to the other dietary treatments.

Table 5 The levels of total lipid and selected FA in the edible portion (mg FA per 100 g fillet) of rainbow trout fed different oil sources^{1,2,3,4}

Fatty acid (mg 100 g ⁻¹ fillet)	378g Rainbow trout Commercial diet A	Initial	Week 8					SE	P
		Rangen EXD450 poultry oil diet	Diet 1 Menhaden	Diet 2 Pollock	Diet 3 Pink salmon	Diet 4 Rockfish	Diet 5 Canola		
Total lipid	3150 ± 340	2970 ± 420	3910	5360	4100	4650	2970	540	0.135
18:2 ω 6 cis	100.1 ± 2.7	327.7 ± 31.2 ^{abc}	205.5 ^c	245.5 ^{bc}	215.0 ^{bc}	238.6 ^{bc}	410.6 ^{ab}	40.3	<0.001
18:3 ω 3	18.6 ± 0.7	27.7 ± 5.5 ^b	35.0 ^b	33.9 ^b	34.8 ^b	32.2 ^b	99.8 ^a	7.1	<0.001
20:4 ω 6	26.8 ± 0.2	30.5 ± 2.9 ^{ab}	37.3 ^{ab}	30.2 ^{ab}	25.2 ^{ab}	29.1 ^{ab}	25.1 ^{ab}	3.7	0.029
20:5 ω 3	198.5 ± 5.3	60.4 ± 21.3 ^c	200.9 ^{ab}	300.2 ^a	184.3 ^{abc}	205.3 ^{ab}	72.6 ^{bc}	27.6	<0.001
22:6 ω 3	380.0 ± 13.0	248.0 ± 38.19 ^b	453.0 ^{ab}	526.0 ^a	527.0 ^a	518.5 ^a	296.9 ^{ab}	49.2	<0.001
Σ EPA + DHA	578.6 ± 8.6	308.4 ± 58.6 ^c	653.9 ^{abc}	826.2 ^a	711.3 ^{ab}	723.8 ^{ab}	369.5 ^{bc}	75.6	<0.001
$\Sigma\omega$ 3	626.6 ± 7.2	367.0 ± 68.7 ^c	754.2 ^{abc}	927.0 ^a	822.9 ^{ab}	820.2 ^{ab}	502.7 ^{abc}	88.7	0.001
$\Sigma\omega$ 6	127.6 ± 2.9	400.5 ± 37.3 ^{abc}	276.2 ^{bc}	306.7 ^{abc}	270.6 ^{bc}	300.1 ^{abc}	488.1 ^{ab}	48.2	0.002
$\Sigma\omega$ 3/ $\Sigma\omega$ 6	4.9 ± 0.2	0.9 ± 0.1 ^e	2.7 ^{abc}	3.0 ^a	3.1 ^a	2.8 ^{abc}	1.0 ^e	0.1	<0.001
Σ SFA	711.3 ± 9.6	700.7 ± 105.9 ^{ab}	1013.4 ^{ab}	1339.7 ^a	929.7 ^{ab}	1062.7 ^{ab}	657.1 ^{ab}	136.7	0.024
Σ MUFA	623.1 ±	868.4 ± 138.9	869.5	1548.9	1209.0	1438.6	1355.8	179.3	0.060
Σ PUFA	782.6 ± 5.0	784.1 ± 106.7	1091.2	1278.1	1111.5	1144.9	1006.4	137.7	0.306
Σ PUFA/ Σ SFA	1.1 ± 0.0	1.1 ± 0.0 ^{cd}	1.1 ^{cd}	0.9 ^d	1.2 ^c	1.1 ^{cd}	1.5 ^a	0.04	<0.001

FA, fatty acid; Σ SFA, sum of saturated FA; Σ PUFA, sum of polyunsaturated FA; Σ MUFA, sum of monounsaturated FA; EPA, eicosapentaenoic acid; DHA, decosahexaenoic acid.

¹ Means (\pm pooled standard error) within the same row that share the same superscript are not significantly different (One-factor ANOVA, Unequal N HSD test, $P < 0.05$).

² ND, not detected or NA, not available.

³ Wild rainbow trout data ($n = 10$) adapted from Blanchet *et al.* (2005) and are not included in statistical analysis.

⁴ Commercial diet A rainbow trout data ($n = 10$) are not included in statistical analysis.

Table 6 Relative changes (%) in fillet fatty acid levels (mg fatty acid per 100 g fillet) of rainbow trout fed diets containing different fish oils for 8 weeks and between the beginning of the study to week 4 and weeks 4–8^{1,2}

Fatty acid	Dietary oil type (a)					SE	P	Week (b)				Interaction P (a × b)
	Menhaden	Pollock	Pink salmon	Rockfish	Canola			1–4	4–8	SE	P	
18:2 ω 6 cis	-20.8 ^b	-9.1 ^b	-13.1 ^b	-14.3 ^b	34.7 ^a	11.83	0.024	-17.8 ^A	8.7	7.48	0.021	0.194
18:3 ω 3	12.8 ^b	14.8 ^b	12.9 ^b	7.8 ^b	158.1 ^a	20.19	<0.001	55.9	26.6	12.77	0.120	0.001
20:4 ω 6	11.9	5.6	-5.9	-1.5	-24.4	10.99	0.217	-12.3	6.5	6.95	0.070	0.015
20:5 ω 3	104.5 ^a	131.1 ^a	76.9 ^a	95.5 ^a	-78.0 ^b	36.24	0.005	129.2 ^A	2.8	22.92	0.001	0.797
22:6 ω 3	40.3 ^a	45.7 ^a	46.3 ^a	47.7 ^a	-13.8 ^b	13.89	0.022	53.7 ^A	12.8	8.78	0.004	0.354
$\sum\omega$ 3	49.9	58.9	51.3	51.8	-5.2	16.37	0.069	65.6	17.1	10.35	0.003	0.500
$\sum\omega$ 6	-16.9 ^b	-8.2 ^b	-12.2 ^b	-13.1 ^b	30.0 ^a	11.35	0.048	-16.9 ^A	8.8	7.18	0.020	0.159
$\sum\omega$ 3/ $\sum\omega$ 6	82.6 ^a	91.7 ^a	106.4 ^a	79.5 ^a	-64.1 ^b	19.93	<0.001	124.4 ^A	-6.0	12.61	<0.001	0.516
\sum SFA	22.5	39.5	18.0	23.3	-22.1	15.32	0.101	16.4	16.1	9.69	0.982	0.149
\sum MUFA	0.3	33.9	20.8	29.5	40.2	15.43	0.426	24.0	25.9	9.76	0.895	0.350
\sum PUFA	19.7	29.0	19.3	21.0	11.2	12.82	0.911	23.0	17.1	8.11	0.609	0.227
\sum PUFA/ \sum SFA	-1.9 ^{bc}	-7.3 ^c	5.0 ^b	-1.9 ^{bc}	28.3 ^a	3.77	<0.001	8.60 ^A	3.0	2.38	0.023	0.014

FA, fatty acid; \sum SFA, sum of saturated FA; \sum PUFA, sum of polyunsaturated FA; \sum MUFA, sum of monounsaturated FA.

¹ Relative changes (%) in fillet FA levels (mg FA 100 g⁻¹ edible fillet) for each 4-week period were calculated using the following formula: (final FA content – initial FA content)/(initial FA content) × 100.

² Means that share the same superscripts (lower case for dietary oil type; upper case for week) are not significantly different (\pm pooled standard error) within the same factor (Two-factor ANOVA, $P < 0.05$).

Discussion

We investigated fillet FA deposition and the potential for altering the ω -3 to ω -6 FA ratio and the EPA and DHA fillet tissue levels in ~400 g rainbow trout, the low end of the weight range of trout produced for USA markets. The trout were phase-fed diets containing poultry oil up to 187 g and then switched to diets containing menhaden oil, canola oil and three fish oils produced from Alaskan seafood processing by-products. Growth rates and FCRs for fish fed all diets were comparable to those routinely achieved at commercial freshwater rainbow trout production facilities (Hardy 2002). The growth performance of the fish fed canola oil indicated that sufficient dietary levels of essential ω -3 FA were provided or that there were sufficient body reserves carried over from the first phase of feeding.

There were large differences in the relative changes of fillet FA levels over the first 4 weeks of the study and the 4- to 8-week period that support the concept of a dilution effect of FA deposition and retention in fish tissues (Jobling 2003). The majority of the changes occurred in the first 4 weeks, and as fish increased in size, the relative changes decreased, consistent with the model proposed by Robin *et al.* (2003). Although rainbow trout exhibit indeterminate growth throughout their lives (Simpson *et al.* 2004), the reduction in relative change in fillet FA composition is consistent with the phenomenon that as fish become larger, their physiological potential to grow decreases (Busacker *et al.* 1990). This phenomenon has implications on the relative change in fillet

FA composition and also on the development of feeding strategies adopted for use on larger fish approaching market size (Turchini *et al.* 2009). Replacing fish oil with poultry oil in feed used during a portion of the production cycle in this study reduced fish oil use over the course of the cycle by 25% compared to using feeds containing fish oil throughout the production cycle. Further reductions could be achieved by increasing the portion of production during which feeds not containing added fish oil are fed.

The total lipid content of fillets has a direct influence on the quantity of individual FA in fillets, and therefore, the quantity present in typical fillet servings. The rainbow trout in this study had 3.0–5.5 times the total fillet lipid content of wild rainbow trout (Blanchet *et al.* 2005). For comparative purposes, it was assumed that the targeted end point for FA levels found in 100 g of skinned edible fillets in experimental fish would be based on FA levels reported for wild rainbow trout by Blanchet *et al.* (2005) who reported linoleic acid, linolenic acid, arachidonic acid, EPA and DHA levels of approximately 25.2, 10.2, 32.4, 48.6 and 193 mg FA per 100 g skinned fillet, respectively, and an ω 3/ ω 6 ratio of 4.8 (Table 5).

EPA and DHA levels in fillets of poultry oil-fed fish increased when fish were switched to fish oil diets, particular pollock oil, during the last 4–8 weeks of feeding. As a proportion of total FA, the levels of EPA in the fillets of all fish oil treatments were progressively and significantly increased over the 4 and 8 weeks of feeding compared to EPA levels in fillets of initial fish or those fed the canola oil diet, similar to results found in Atlantic salmon fed diets containing linseed

oil or vegetable oil blends (Bell *et al.* 2004; Torstensen *et al.* 2005). In contrast, the levels of DHA for the dietary treatment groups remained relatively constant. On an edible portion basis, changes in EPA and DHA were far more variable, and hence, values increased numerically. These changes would result in considerable differences in the consumption of EPA and DHA.

The intakes of dietary ω -3 FA, especially EPA and DHA, are reported to have beneficial effects in reducing the incidence of coronary heart disease (Wang *et al.* 2006). For primary prevention of coronary heart disease, the International Society for the Study of Fatty Acids and Lipids recommends daily consumption of 500 mg of EPA + DHA (Blanchet *et al.* 2005). Based on EPA + DHA data reported by Blanchet *et al.* (2005) for wild rainbow trout of 242 mg 100 g⁻¹ fillet or 48% of the recommended daily intake, a consumer would need to eat 202 g of fillets to meet the recommended daily intake level. In contrast, the recommended daily intake level of EPA + DHA could be met by the consumption of 77 g of fillet from menhaden oil-fed fish or 61 g of fillet from the pollock oil-fed fish. There was a relative improvement of 26.2% for the amount of EPA + DHA consumed for a given portion of pollock oil-fed trout compared to the menhaden oil-fed trout.

The ω 3/ ω 6 FA ratio

Both fish and humans lack the required enzymes (Δ 12 and Δ 15 (ω 3) desaturases) to form the ω -3 or ω -6 FAs, α -linolenic or linoleic acid, from oleic acid (Tocher 2003). Therefore, both ω -3 and ω -6 FA are essential dietary nutrients in fish and humans (NRC 1993; Simopoulos 2000). DHA and arachidonic acid are the main end products of desaturation and elongation of 18:3 ω 3 and 18:2 ω 6, respectively (Tocher 2003). In humans, both ω -3 and ω -6 FA compete for the same metabolic enzymes, thus an excess of one class can significantly influence the ratio of the ensuing eicosanoids (Simopoulos 2000). The metabolic enzymes responsible for chain elongation and desaturation of the ω -3 and ω -6 FA in fish are similar to humans and also compete for the same substrates. However, unlike in humans, the affinity of these enzymes, especially the desaturases, are greater for the ω -3 FA (Tocher 2003).

The dietary ratio of ω 3/ ω 6 FA is reported to exert a profound effect on the production of the ensuing eicosanoids (hormones) and hence influence metabolism (Simopoulos 2000). For human nutrition, the ideal ratio of ω 3/ ω 6 FA has been reported to range from 1 : 3 to 1 : 5 (Simopoulos 2000, 2003; Okuyama 2001). The ω 3/ ω 6 FA ratios of fillets from

fish fed the menhaden and Alaskan fish oils ranged from 2.73 to 3.06 and compared favourably to corresponding values of 4.4 and 4.8 reported for wild and menhaden oil-fed rainbow trout, respectively (Blanchet *et al.* 2005).

Conclusions

EPA and DHA levels were significantly increased, and the ratio of ω 3/ ω 6 FA in fillets of rainbow trout improved by phase-feeding diets containing Alaskan fish oils or menhaden oil for 4 and 8 weeks to fish previously fed diets containing poultry oil. Fish oil use was reduced by 25% over the production cycle by substituting poultry oil for fish oil in feeds used during the middle segment of production. Of the fish oils used in this study, pollock oil resulted in the highest levels of ω -3 HUFAs in the rainbow trout fillets, although all fish oils increased ω -3 HUFA contents (mg kg⁻¹) of fillets to healthful levels. Higher recovery of fish oils from Alaska seafood processing by-products could supply the aquafeed industry with high-quality fish oil suitable for use in phase-feeding programmes for trout and salmon.

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