Ecotoxicology and Environmental Safety 180 (2019) 53–62

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

journal homepage: www.elsevier.com/locate/ecoenv

Growth and metabolism of adult polar cod (*Boreogadus saida*) in response to dietary crude oil

Jasmine Nahrgang[a,*], Morgan L. Bender[a], Sonnich Meier[b], Jordan Nechev[a], Jørgen Berge[a,c,d], Marianne Frantzen[e]

[a] Department of Arctic and Marine Biology, University of Tromsø, 9037, Tromsø, Norway
[b] Institute of Marine Research, 5817, Bergen, Norway
[c] University Centre in Svalbard, 9171, Longyearbyen, Norway
[d] Centre for Autonomous Underwater Operations, Norwegian University for Science and Technology, 7491, Trondheim, Norway
[e] Akvaplan-niva, Fram Centre, 9296, Tromsø, Norway

ARTICLE INFO

Keywords:
Polar cod
Crude oil
Growth
Metabolic rate
Reproductive status
Dietary exposure

ABSTRACT

The increasing human presence in the Arctic shelf seas, with the expansion of oil and gas industries and maritime shipping, poses a risk for Arctic marine organisms such as the key species polar cod (*Boreogadus saida*). The impact of dietary crude oil on growth and metabolism of polar cod was investigated in the early spring (March–April) when individuals are expected to be in a vulnerable physiological state with poor energy stores. Adult polar cod were exposed dietarily to three doses of Kobbe crude oil during an eight weeks period and followed by two weeks of depuration. Significant dose-responses in exposure biomarkers (hepatic ethoxyresorufine-O-deethylase [EROD] activity and 1-OH phenanthrene metabolites in bile) indicated that polycyclic aromatic hydrocarbons (PAHs) were bioavailable. Condition indices (i.e. Fulton's condition factor, hepatosomatic index), growth, whole body respiration, and total lipid content in the liver were monitored over the course of the experiment. The majority of females were immature, while a few had spawned during the season and showed low hepatic lipid content during the experiment. In contrast, males were all, except for one immature individual, in a post-spawning stage and had larger hepatic energy stores than females. Most specimens, independent of sex, showed a loss in weight, that was exacerbated by exposure to crude oil and low hepatic liver lipids. Furthermore, females exposed to crude oil showed a significant elevation of oxygen consumption compared to controls, although not dose-dependent. This study highlights the importance of the energy status of individuals for their response to a crude oil exposure.

1. Introduction

Climate variability and global warming have changed and will continue to change the Arctic, most notably seen in the abrupt decline in Arctic sea ice extent and thickness (Barber et al., 2015). In parallel with these changes, anthropogenic activities including oil and gas exploration, maritime shipping, and tourism are all predicted to increase (Smith and Stephenson, 2013), posing a risk to arctic marine organisms.

The sensitivity of polar cod (*Boreogadus saida*), a key fish species in the Arctic marine ecosystem (reviewed by Mueter et al., 2016), to petroleum related compounds, has been investigated intensively in the past two decades (Christiansen and George, 1995, Nahrgang et al., 2010a, 2010b, 2010c, Geraudie et al., 2014, Andersen et al., 2015, 2015b, Bender et al., 2016, Vieweg et al., 2018, Bender et al., 2018). Early life stages have shown a high sensitivity to very low levels of a crude oil water-soluble fraction (WSF) (Nahrgang et al., 2016), while adult specimens are considered more robust when exposed to low environmentally relevant concentrations of dietary crude oil (Bender et al., 2016; Vieweg et al., 2018). Thus far, only few studies have investigated the effects of crude oil on energy homeostasis and associated physiological processes in polar cod (Christiansen et al., 2010; Vieweg et al., 2018, Bender et al., 2018). Crude oil and related contaminants, such as polycyclic aromatic hydrocarbons (PAHs) have been shown to affect growth (e.g. Gravato and Guilhermino, 2009; Kerambrun et al., 2012; Claireaux et al., 2013; Sandrini-Neto et al., 2016) and metabolism (Davoodi and Claireaux, 2007; Christiansen et al., 2010; Klinger et al., 2015) in fish. The mechanisms behind these effects can be multiple, including increased energy costs from detoxification metabolism

* Corresponding author.
E-mail address: jasmine.m.nahrgang@uit.no (J. Nahrgang).

https://doi.org/10.1016/j.ecoenv.2019.04.082
Received 17 December 2018; Received in revised form 11 April 2019; Accepted 27 April 2019
Available online 06 May 2019

and toxicity (Klinger et al., 2015), behavioral changes leading to reduced nutrient assimilation (Moles and Rice, 1983; Christiansen and George, 1995), and toxicant induced alterations in nutrient assimilation (Saborido-Rey et al., 2007). Adult polar cod have previously been shown to exhibit altered growth performance when exposed to dietary crude oil (Christiansen and George, 1995) and a depression in routine metabolism following an exposure to the WSF of crude oil (Christiansen et al., 2010).

The Arctic is characterized by a strong seasonality in light availability, profoundly affecting biological activity and basic physiological processes in arctic marine ecosystems (Berge et al., 2015). The vast majority of experimental studies on adult polar cod have dealt with specimens during the late summer/fall concurrent with gonadal maturation (Hop et al., 1995, Hop and Graham, 1995, Christiansen and George, 1995, Nahrgang et al., 2010b, 2010c, Christiansen et al., 2010, Bender et al., 2018). Therefore a marked need exists to determine the physiological trade-offs and sensitivity to contaminant exposure during the late winter/spring season, which also coincides to a post-spawning stage for mature individuals. Polar cod invest important amounts of energy into reproduction (Hop et al., 1995) and may be highly susceptible to post-spawning mortality. Exposure to crude oil related compounds may have consequences for post-spawning survival and be directly relevant to population level effects. The present study aimed therefore at investigating the effects of dietary crude oil exposure on growth, lipid class composition, and routine metabolic rate in adult specimens in the early spring. At this time, energy levels in polar cod are expected to be significantly reduced after reproduction and following a period of low food availability during the dark winter months. The primary hypothesis of the present study was that the exposure to crude oil might lead to a reallocation of energy from somatic growth towards detoxification, and lead to an increase in oxygen consumption. The dietary route of exposure was chosen as it allows for accurate control of the dose of contaminant given to the test organism. Furthermore, although it is in general less studied for petroleum products, it may constitute an important pathway for long-term toxicity (Agersted et al., 2018).

2. Materials and methods

2.1. Sampling and acclimation period

Polar cod were caught in Rijpfjorden (Svalbard) with a Campelen bottom trawl attached to a fish-lift (Holst and McDonald 2000), onboard R/V *Helmer Hanssen* and were transferred to the experimental facilities at the University Centre in Svalbard (Norway) in mid January 2012. Upon arrival, polar cod were kept in acclimation until early March in two 700L tanks under running 25 µm filtered seawater and constant darkness. Temperature loggers (HOBO onset) recorded continuously (19/01/2012–25/05-2012) air temperature (4.1 ± 0.2 °C), water temperature (6.9 ± 1.0 °C), and salinity (28.6 ± 1.3 psµ) in the acclimation tanks. During acclimation, polar cod were fed every 3 days with aquaculture feed AgloNorse TROFI AS, Tromsø, Norway (protein 59%; fat 18–20%; ash 10%; fibres 1%; moisture 8–9%; PUFA n-3 2.4%; PUFA n-6 2.6%). During acclimation, feeding was done by giving food in excess to the tanks. One week before exposure start, fishes (n = 36 per treatment) were randomly transferred to exposure tanks (200L) placed in the same room as the acclimation tanks and containing 5 µm filtrated seawater. During transfer, each fish was anesthetized with metacain (1 mg/L seawater), tagged (Floy Fish Dangler Tags), and total length and body weight were recorded to the nearest 0.1 mm and 0.1 g.

2.2. Preparation of the food

The treatments consisted of aquaculture feed pellets hydrated with 0.77 g water per g dry pellets, and blended with 0.1, 1, and 5 mg Kobbe crude oil per gram food wet weight, for the low, medium, and high treatments, respectively. For the control group, the feed pellets were hydrated but crude oil was not added. Individually tagged syringes were prepared in advance with food mixture corresponding to 4% body wet weight of each specific fish and stored at −80 °C. The choice of the crude oil doses was selected based on literature review of similar experiments that employed dietary crude oil exposure or PAH mixture exposure and that showed alterations at physiological levels. In particular the study by Christiansen and George (1995) showed alterations in growth performances. Our levels correspond to a range one order of magnitude lower to one order of magnitude higher than those used in Christiansen and George (1995).

2.3. Experimental design

The experiment started in March and consisted of four treatments (4 tanks, n = 34 per tank) with fish exposed once a week to crude oil contaminated feed (control, low, medium, and high doses) during eight weeks and followed by two weeks (one feeding) of recovery. During the recovery, all specimens received the same uncontaminated feed as that of the control group during the exposure period. Once a week, on the day of feeding, a batch of syringes were thawed and fish were force fed 4% body weight using 1 ml Luer-lokk syringes (BD Plastipak™). The feeding took maximum 20 s per fish. Force feeding was chosen to control crude oil dose and avoid confounding effects of differential feeding behavior on growth response (Christiansen and George, 1995; Saborido-Rey et al., 2007). Upon force-feeding, fish were transferred to new tanks containing fresh seawater (5 µm filtered) that had been equilibrating to room temperature during 24 h. In addition, 80% of the water of the experimental tanks was changed every second day. Water temperature (5.9 ± 0.7 °C) and pH (7.9 ± 0.1) in the semi-static experimental tanks were monitored daily over the course of the experiment using a handheld WTW multimeter.

Polar cod were sampled at exposure start (holding tanks, n = 14), and after one and after eight weeks of exposure (experimental tanks, n = 12 per treatment per timepoint). A final sampling point for recovery consisted in 10 additional specimens sampled per treatment (ten weeks). Total length, total weight (TW), gonad weight (GW) and liver weight (LW) were recorded. The liver samples were snap frozen in liquid nitrogen, and stored at −80 °C for further analyses. At the start (week zero) and end (week eight) of the exposure period, a portion of gonad tissue was fixed in 4% neutral buffered formaldehyde for histological analysis. Otoliths were collected for age analysis.

Hepato- and gonadosomatic indices (HSI and GSI, respectively) were determined using the following equations:

$$GSI\,(\%) = \frac{GW}{(\mathrm{TW} - (\mathrm{GW} + \mathrm{LW}))} \times 100$$

$$HSI\,(\%) = \frac{LW}{(\mathrm{TW} - (\mathrm{GW} + \mathrm{LW}))} \times 100$$

The specific growth rate (SGR, % per d) was based on records of initial (i, at tagging) and final (f, at sampling) TW records, using the following equation:

$$SGR\ (\%\ per\ d) = \frac{(\ln \mathrm{TW_f} - \ln \mathrm{TW_i})}{\text{Time in days}} \times 100$$

2.4. Respirometry

Whole body respiration was measured on polar cod after two, four, six, eight, and ten weeks (n = 8 per treatments) using an automated intermittent flow through respirometer equipped with eight chambers (volume of 573 ml) (Loligo® Systems, Denmark). The oxygen consumption was measured using a polymer optical fiber dipping probe. Measurement were always performed on the day prior to feeding, i.e. six days after the previous feeding, in order to limit the effects of

specific dynamic action (SDA). The chambers were placed in individual tanks containing filtered seawater equilibrated to room temperature (5.9 ± 0.7 °C). When possible, the same individuals, identified by tags, were used each time; however, due to some mortality, different fish were used at the end of the experiment. Fish were weighed and placed in individual chambers. The automated respiration consisted in 7-min cycles of closed respirometry and flushing. Prior to the experiment, eight fish from the holding tank were placed in the chambers and oxygen consumption was recorded during 24 h to evaluate the time necessary to reach the routine metabolism (Fig. S1). The oxygen consumption decreased typically exponentially over the course of the first 3 h and the average oxygen consumption between 2.5 h and 3 h was used for the data analysis for the experimental fish.

2.5. Age estimation

Polar cod age (years) was based on otolith readings: for small transparent otoliths, white winter rings were counted in sub-surface light with a Leica M205 C stereo microscope and a Planapo 1.0 × objective lens (Gjøsæter and Ajiad, 1994); for all larger otoliths, cross sectioning with a scalpel blade and counting the rings under polarised light was necessary.

2.6. EROD activity

Liver samples were homogenized in a phosphate buffer (0.1M, pH 7.4) using a precellys bead-beater and centrifuged 9000 g during 30 min (S9 fraction). EROD activity was measured according to Eggens and Galgani (1992). The reaction mix consisted of 10 µl microsomal fraction in 100 mM of Tris-phosphate buffer (pH 7.4), ethoxyresorufin 46 µM as substrate in a final volume of 230 µl. Reaction started by adding 0.25 mM NADPH in the microwells. The resorufin production was measured in four replicates during 20 min at room temperature with a Biosynergy H1 plate reader at 544/584 nm excitation/emission wavelengths, respectively. A resorufin standard curve (0–2 µM) was used for determination of the reaction rates in pmol of resorufin produced $min^{-1}mg^{-1}$ of total protein (S9 fraction).

2.7. Histology

The fixed gonad samples were routinely processed by dehydration and embedded in paraffin wax in a Shandon Citadel 1000 (Micron AS, Moss, Norway). Embedded tissues were sectioned at 5 µm thickness in a Leitz RM 2255 microtome, stained with hematoxylin/eosin, and examined under a Leica Wild M10 dissecting scope with a Leica DFC295 camera for maturity status and indications of previous spawning. For each fish, six replicate slices were prepared and viewed under 40 × and 80 × magnification. Characterization of the gonadal development was based on Brown-Peterson et al. (2011) with 5 categories (immature, developing, spawning capable, regressing, regenerating) for females (N = 27), and for males (N = 34). The presence of late vitellogenic (Vtg3) atretic residual oocytes was interpreted as evidence that specimens had spawned in the present season.

2.8. Lipid analysis

Lipids composition was analyzed on liver of 10 individuals per treatment after eight weeks of exposure. The lipids of the liver samples were extracted and the different lipid classes were separated by Solid Phase Extraction (SPE) prior to analysis of fatty acids by gas chromatography. The total lipids of liver samples were extracted by a modified Folch method with chloroform/methanol (2:1 v/v) (Folch et al., 1957).

The lipid extract was separated into major lipid classes by a SPE procedure adapted from the Kaluzny et al. (1985), using aminopropyl bonded phase columns to separate lipid mixtures into individual classes. Briefly, 0.5 ml of lipid extract (approximately 8 mg lipid) was loaded in a 500 mg aminopropyl modified silica minicolumn (Macherey-nagel gmbh & co. Germany), which had been previously activated with 4 ml of hexane. Neutral lipid (Triacylglycerol's and cholesterol, NL), free fatty acid (FFA), and phosphatidylcholine/phosphatidylethanolamine (PC/PE) were sequentially eluted with 7 ml of chloroform/isopropanol (2:1 v/v), 5 ml of 2% acetic acid in diethyl ether, and 10 ml of methanol. The eluates were collected in 15 ml thick-walled glass tubes with Teflon lined screw caps, which contained nonadecanoic acid (19:0) as internal standard. The phosphatidylserine/phosphatidylinositol (PS/PI) fraction was obtained by opening the column and collecting all of the stationary phase directly to the test tubes. All the eluates were dried by nitrogen gas and the fatty acids were analyzed by gas chromatography with a flame ionization detector (GC-FID). Prior to analysis on GC-FID, all SPE fractions from the liver samples were methylated with 2.5 M dry HCl in methanol (HPLC-grade, Merck in Oslo, Norway) to obtain fatty acid methyl esters (FAME) that was analyzed on gas chromatograph according to Meier et al. (2006).

2.9. PAH analyses in feed

Analyses of PAHs in the fish feed were carried out by Akvaplan-niva (accredited for the methods). Three replicate feed samples per dose were analyzed. Each sample was thoroughly grounded and homogenized prior to analyses. Samples were weighed and a potassium hydroxide-methanol solution and an internal standard-mix of deuterated PAHs were added. The solution was boiled with reflux for 4 h (saponification), before filtration and extraction with pentane. Samples were purified using gel permeation chromatography (GPC), with dichloromethane as a mobile phase. Samples were filtrated and further purified by solid phase extraction (SPE). Analyses were performed using a GC-MSD (Agilent 7890 GC with split/splitless injector, Aglient 7683 and Agilent 5975C, mass spectrometer with EI ion source). Blind samples were run in parallel to all samples, and proficiency test samples (Quasimeme, Netherlands) were used as control samples. The limit of detection (LOD) was determined from analyses of a series of blank samples, processed along with real samples, and calculated as: LOD = (blank average) + 3 × (blank standard deviation). For the calculation of sum PAHs, values below detection limit were not considered.

2.10. Biliary 1-OH phenanthrene metabolite

1-OH phenanthrene was analyzed according to Nechev et al. (unpublished) on bile samples from the experimental fish collected at week zero, one and eight weeks of exposure. Briefly, 1-OH phenanthrene was extracted from bile samples through enzymatic hydrolysis. Bile samples were freeze dried overnight and 40 µl of water was added to each sample. Samples were incubated for 1 h at 37 °C with β-Glucuronidase/aryl sulfatase (5 µl) and an internal standard (5 µL triphenylamin in methanol, 160 ng/ml) was added. After incubation, 750 µl of methanol were added and centrifuged for 10 min at 13000 g and supernatants were collected. Extracts were analyzed using a HPLC Agilent 1200 Series equipped with a fluorescence detector FLD Agilent 1200 Series G1321A. Separation of the compounds was performed in a C18 column (Eclipse XDB-C18, 150 × 4.6 mm; 5 µm particle size; Agilent, USA) heated to 35 °C. The injected volume was 25 µl. The initial composition of the mobile phase was 40:60 acetonitrile:water (vv) and a linear gradient to 100% acetonitrile was programmed in 30 min, with a final hold of 5 min. Initial conditions were reached in 1 min and maintained for 2 min before the next run. The total run time was 38 min with a flow rate of 1 ml/min 1-OH phenanthrene was detected at its optimal excitation/emission wavelength pair 256/378 nm (1-OH-phenanthrene). Samples of bile in the medium group at eight weeks exposure were lost during extraction and are thus not analyzed.

2.11. Statistical analyses

All statistical analyses were conducted with R 3.1.1 (R Core Team 2014). As our data fell outside a normal distribution, non-parametric Kruskal-Wallis tests by ranks were employed to investigate differences between the sexes and crude oil treatments at each time point on the continuous factors of age, morphometrics, EROD activity, PAH bile metabolite concentrations, SGR, and oxygen consumption. Length and sex were tested as covariates of response variables to account for initial difference between treatment groups at tagging and inherent differences in physiology between sexes. When significant results were encountered, a post hoc pairwise Dunn's test using rank sums was performed between the control and crude oil treatments. These tests were done in conjunction with a Benjamini-Hochberg adjustment on p-values to account for potential errors arising from multiple comparisons (Benjamini and Hochberg, 1995). Correlation tests were performed using the Spearman method for PAH levels, HSI, SGR, and liver lipid levels. Linear models were used to explore the relationship between SGR and HSI in relation to crude oil treatment, sex, and length for fish after one week of exposure. Comparisons were considered significantly different than the control when $p \leq 0.05$ level. Values are reported as mean ± standard deviation (SD).

3. Results

3.1. Dietary doses of PAHs, levels of 1-OH phenanthrene in the bile and EROD activity

Polar cod from the low, medium, and high treatment were exposed weekly to 4, 40, and 200 µg crude oil/g fish, respectively (Table 1). This weekly dietary dose corresponded to a sum 26 PAHs (Σ26PAHs) in the feed of 0.004, 0.06, 0.4, and 2.4 µg 26 PAHs/g fish/week in the control, low, medium, and high treatments, respectively. The levels of PAHs measured in the feed were significantly correlated to the nominal crude oil doses ($R^2 = 0.97$, $p < 0.001$), indicating that the crude oil was homogenously mixed in the feed. Typical for crude oil, the most abundant PAHs in the feed were the low molecular weight naphthalenes with predominance of substituted compounds in the order C3 > C2 > C1, followed by substituted phenanthrenes (Table 2). All 26 PAHs analyzed in the feed were above detection limit in the highest exposed feed, except for indeno(1,2,3cd)pyrene (Table 2).

Levels of 1-OH-phenanthrene in polar cod bile (Fig. 1A), and EROD activity (Fig. 1B) increased in a dose-dependent manner after one week of exposure and remained at similar levels after eight weeks of exposure regardless of fish sex or length.

3.2. Fish morphometrics, gonadal maturation stages and mortality during the exposure

Although polar cod were collected and randomly distributed to the experimental tanks, at tagging the average fork length and total weight from the fish in the "low" group were significantly higher compared to medium and control groups ($p = 0.03$ and 0.05 for length and weight, respectively) (Table S1). At subsequent sampling times, however, the fork length and total weight were no longer significantly different among treatments and sexes. Overall, the sex ratio was biased towards males in the medium and high treatments, unfortunately affecting the sex balance in the high treatment at eight weeks exposure (n = 1 female). Sex and length were included as covariate in response analysis to account for potential bias by the initial conditions. Specimens were between two and four years old.

The sexual maturity status of polar cod varied between gender and sampling time, but not with oil treatment. Female specimens showed low GSI (1–3%) throughout the experiment, and the majority (n = 19 out of 27 analyzed) were immature, i.e. they had never spawned (Fig. 2 and Table S2). Specimens categorized as "regressing" (n = 6) showed late vitellogenic (Vtg3) atretic residual oocytes that suggested spawning during the season. Two of these regressing females showed residual oocytes at more advanced atretic stages, a potential indication of spawning that occurred during the previous season. Thus, these two specimens may have belonged to the regenerating category. Finally, two females were in a regenerating stage with late-stage atretic residual oocytes (i.e. had skipped the present reproductive cycle). Regressing females were not significantly different in length or total weight compared to immature or regenerating females, however and although not significant, they showed a slightly reduced HSI ($p = 0.15$) and reduced lipid concentration in the liver ($p = 0.09$, Table S2).

Males showed significantly higher GSI (11–17%) than females at week zero ($p = 0.01$) and week one ($p < 0.001$) and compared to GSI in males sampled after eight and ten weeks ($p < 0.01$). Histological analysis at week zero indicated specimens in an early post-spawning stage (regressing) at exposure start (Fig. 2) with discontinuous germinal epithelium throughout the testis, no active spermatogenesis, and residual spermatozoa in lobule lumens and sperm ducts. After eight weeks of exposure, the GSI of males had decreased to levels similar to that of females (below 2%, Table S2). Except for one immature specimen in the medium treatment, all males were in a late regressing or regenerating stage (Fig. 2).

During the experiment, some mortality occurred in the low (n = 2 at three weeks) and high (n = 1 after three days, and n = 4 at three weeks) treatments. Furthermore, one individual was removed from the high treatment in the sixth week due to the appearance of finrot (disintegration of caudal fin). Mortality occurred only in males. Except for two specimens of the high treatment (death at three weeks), all mortalities occurred among the specimens used in respirometry experiments, although several days after the respirometry handling. The number of polar cod left for the last sampling time (respiration individuals at ten weeks) was reduced to eight, nine and five in the low, medium, and high treatments, respectively.

3.3. Lipid class composition in the liver

Total liver lipid content and lipid class composition was studied on ten of the twelve specimens sampled from each treatment after 8 weeks of exposure to dietary crude oil. The total lipid content of the liver was correlated to the HSI ($R^2 = 0.62$, $p < 0.001$). Furthermore, males had significantly higher liver lipid content (329 ± 17 mg/g liver wwt) than females (212 ± 32 mg/g liver wwt, $p = 0.002$, Table 3) with little

Table 1
Crude oil nominal concentrations, and measured concentrations of sum of 26 PAHs in the feed (µg/g feed wwt) and as weekly doses in the fish (µg/g fish/week or µg/fish/week). Data represent mean ± standard deviation.

Treatments	Crude oil nominal doses		Sum 26 PAHs		
	Feed mg/g wwt	Fish dose µg/g fish/week	Measured concentration in feed, µg/g wwt	Fish dose µg/g fish/week	Fish dose µg/fish/week
Control	0	0	0.08 ± 0.01	0.003	0.05 ± 0.01
Low	0.1	4	1.6 ± 0.04	0.06	1.1 ± 0.4
Medium	1	40	11.7 ± 0.5	0.5	7.0 ± 2.1
High	5	200	64.4 ± 3.8	2.6	41.4 ± 8.0

Table 2
Concentration of 26 PAHs (µg/kg wet weight) and their sum (µg/g wwt) in the diet fed polar cod (*Boreogadus saida*) in the control, low (0.1 mg crude oil/g feed), medium (1 mg crude oil/g feed) and high (5 mg crude oil/g feed) treatments. For the determination of the sum PAHs, values below the limit of detection (LOD) were not considered. Data represent mean ± standard deviation.

	Control	Low	Medium	High
Naphthalene	< 5.8	85.7 ± 4.0	674.2 ± 27.5	3673.3 ± 163.8
C1-Naphthalene	< 10	208.2 ± 12.1	1684.5 ± 92.2	9325.3 ± 723.3
C2-Naphthalene	< 13	295.6 ± 11.7	2428.9 ± 107.4	13367.7 ± 634.0
C3-Naphthalene	78.4 ± 13.7	701.9 ± 20.7	4819.5 ± 214.9	26505.0 ± 1650.4
Acenaphthylene	0.8 ± 0.1	0.7 ± 0.01	1.3 ± 0.2	4.2 ± 0.5
Acenaphthene	< 1.1	3.1 ± 0.4	23.8 ± 1.7	135.6 ± 11.5
Fluorene	< 0.8	9.0 ± 1.0	67.5 ± 1.9	369.2 ± 31.1
Dibenzothiophene	< 0.5	3.6 ± 0.2	27.1 ± 1.1	151.4 ± 2.5
C1-Dibenzothiophene	< 1.5	8.6 ± 0.2	61.8 ± 5.7	361.0 ± 35.9
C2-dibenzothiophene	< 4.5	16.8 ± 0.6	125.6 ± 6.6	656.0 ± 39.3
C3-dibenzothiophene	< 4.1	17.5 ± 0.6	136.8 ± 5.6	716.2 ± 30.7
Antracene	< 0.3	0.4 ± 0.1	0.5 ± 0.1	2.9 ± 0.3
Phenanthrene	< 3.0	21.6 ± 0.5	183.1 ± 5.5	996.5 ± 28.5
C1-Anthr/Phenanthrene	< 8.6	45.5 ± 1.6	343.9 ± 25.6	1959.6 ± 85.7
C2-Anthr/Phenanthrene	< 7.4	73.4 ± 2.1	602.4 ± 19.2	3305.6 ± 178.8
C3-Anthr/Phenanthrene	< 4.7	62.1 ± 7.0	473.3 ± 26.8	2692.7 ± 282.2
FLuoranthene	< 2.0	< 2.0	3.2 ± 0.5	17.6 ± 9.1
Pyrene	< 3.3	< 3.3	6.7 ± 3.1	34.5 ± 9.5
Benzo(a)anthracene	< 0.5	< 0.5	2.3 ± 0.3	16.5 ± 5.2
Chrysene	< 0.6	0.8 ± 0.02	6.9 ± 0.2	44.1 ± 3.3
Benzo(b)fluoranthene	< 0.7	< 0.7	1.2 ± 0.4	10.4 ± 9.7
Benzo(k)fluoranthene	< 0.2	< 0.2	< 0.2	3.7 ± 3.1
Benzo(a)pyrene	< 0.3	< 0.3	0.6 ± 0.2	6.8 ± 6.1
Indeno(1,2,3-cd)pyrene	< 0.7	< 0.7	< 0.7	< 0.7
Benzo(ghi)perylene	< 0.6	< 0.6	< 0.6	5.7 ± 4.8
Dibenzo(a,h)anthracene	< 0.26	< 0.26	< 0.26	1.60 ± 1.5
SUM 26 PAHs, µg/g	0.08 ± 0.01	1.6 ± 0.04	11.7 ± 0.5	64.4 ± 3.8

variation correlated with length ($p = 0.52$). For both sexes, the neutral lipids (NL) accounted usually for more than 90% of the lipid classes. The NL were totally dominated by storage lipids, triacylglycerols. The polar membrane lipids contributed with less than 7% (PC/PE [3–5%], PS/PI [2%]) of the total lipids, and FFA with 1.5% of the total lipids. In females, there was generally a high variability in liver lipid content, with some specimens (n = 3) showing extreme low values (41–61 mg/g liver wwt). In general, females in a regressing stage showed lower lipid content than specimens in an immature or regenerating stage (Table S2). Unfortunately, two specimens with extreme low values were represented in the control group, which resulted in lower average lipid levels in the control group (average of 120 ± 40 mg/g liver wet weight) compared to the other groups (> 243 ± 54 mg/g liver wet weight), and thus erroneously suggesting an increasing trend in lipid content with crude oil dose. This also led to differences in lipid classes distribution (e.g. average of 70% NL) in the control group compared to the other treatments (> 90% NL). In males, there were no significant differences between treatments.

3.4. Specific growth rates (SGR)

Males and female polar cod showed no significant differences in

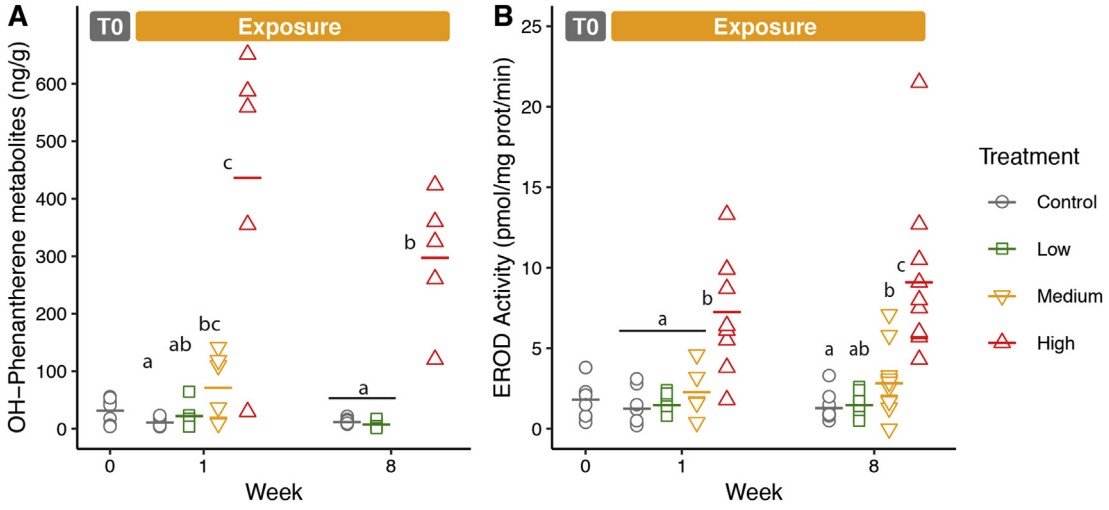

Fig. 1. (A) 1-OH phenanthrene metabolites (ng/g bile dw) in polar cod bile, and (B) EROD activity (pmol/min/mg protein) in polar cod liver, at exposure start (zero weeks), and after one and eight weeks of exposure. Bile metabolite samples in the medium group at eight weeks were not available (NA). Plots show individual data points distinguished by shape and color for each treatment group, treatment group means are represented with a dash (−). Different letters (a, b, c) indicate significant differences (Kruskal Wallis test, $p < 0.01$) among treatments for each time point. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

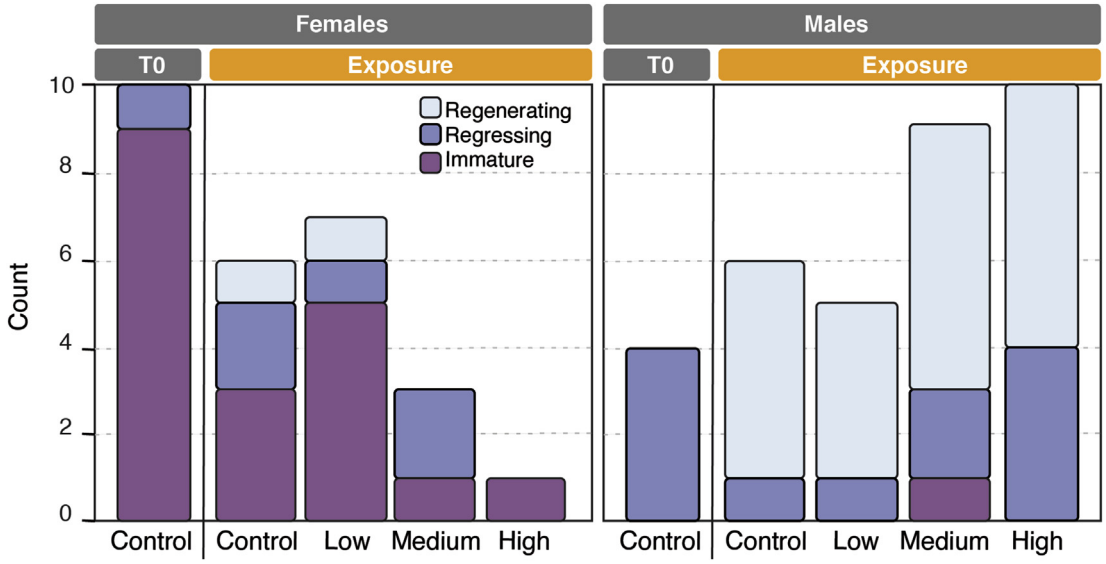

Fig. 2. Sexual maturity of polar cod at exposure start (T0) and after eight weeks of exposure, based on histological examination of gonads. Only three maturity stages were identified (immature, regressing, and regenerating). Bars are representing counts.

SGR over the course of the experiment and with regard to dose. Following one week of exposure, also corresponding to the first dietary dose, a significant decrease in SGR was observed with increasing oil exposure (Kruskal-Wallis, p = 0.03). Interestingly, SGR was lowest in individuals that presented a reduced HSI (Fig. 3). This relationship increased in strength with increasing dose (R^2 = 0.2, p = 0.23 in the low treatment and increased to R^2 = 0.63, p < 0.001 in the high treatment). The negative interaction between crude oil treatment and HSI on SGR was strongest in the high oil treatment group (p = 0.017) regardless of fish sex (p = 0.81) or length (p = 0.38).

After eight weeks of exposure, the SGR was no longer dose-dependent (Fig. 4). Specimens sampled after ten weeks i.e. eight weeks of exposure and two weeks of recovery, showed a negative SGR, and females also exhibited a tendency to a dose-dependent reduction in SGR, although not significant (p = 0.44). These specimens were also those used for respirometry every second week, thus subjected to additional handling stress over the course of the experiment.

3.5. Whole body oxygen consumption

Oxygen consumption was, in general, elevated in oil-exposed females (min-max range 72.5–202.3 mg O_2/kg fish/hr) compared to controls (min-max range 61.8–102.9 mg O_2/kg fish/hr) after four weeks of exposure (Fig. S2). This increased oxygen consumption was however not dose-dependent. In males, oxygen consumption was elevated in the medium group (min-max range 112.5–226.2 mg O_2/kg fish/hr) compared to the other treatments (min-max range 43.1–131.5 mg O_2/kg fish/hr). Although not significant, this group was characterized by the smallest average total weight, condition factor, and GSI.

4. Discussion

4.1. Uptake and bioavailability of dietary crude oil

The determination of 1-OH-phenantrene metabolites in the bile and EROD activity were used as biomarkers of exposure to PAHs. As indicated by the presence of 1-OH-phenantrene metabolites in the bile and the levels of EROD activity, metabolism of PAHs was already taking place following a single dose of crude oil (first week of exposure) in both females and males. Furthermore, the dietary exposure remained dose-dependent throughout the exposure period. Dietary oil compounds ingested weekly during eight weeks in the present study were

Table 3
Lipid content (mg/g liver wet weight) and lipid class distribution (% distribution of the fatty acids in the different lipid classes) in polar cod liver following eight weeks of exposure. Out of the four control group females, two had atretic vitellogenic oocytes and extreme low levels (< 61 mg/g liver wet weight) of liver lipids. Males and females showed significant differences in total lipid levels (Kruskal-Wallis test, p = 0.002). NL; neutral lipid, PC/PE; phosphatidylcholine/phosphatidylethanolamine, PS/PI; phosphatidylserine/phosphatidylinositol, FFA; free fatty acid.

	Control			Low			Medium			High		
Females	(n = 4)			(n = 6)			(n = 3)			(n = 1)		
Lipid (mg/g)	120	±	40	244	±	58	243	±	54	292		
Lipid class distribution (%)												
NL	70.2	±	17.0	91.6	±	2.5	92.1	±	2.7	93.6		
PC/PE	19.9	±	11.3	5.2	±	1.5	4.4	±	2.0	3.8		
PS/PI	7.1	±	4.6	2.1	±	0.8	1.9	±	0.5	0.9		
FFA	2.8	±	1.2	1.2	±	0.3	1.7	±	0.3	1.6		
Males	(n = 5)			(n = 4)			(n = 7)			(n = 9)		
Lipid (mg/g)	363	±	21	345	±	78	322	±	25	308	±	28
Lipid class distribution (%)												
NL	95.7	±	0.2	93.6	±	2.0	94.9	±	0.5	94.4	±	0.5
PC/PE	2.3	±	0.1	3.9	±	1.5	2.4	±	0.3	3.4	±	0.4
PS/PI	0.5	±	0.1	1.2	±	0.5	1.1	±	0.2	1.0	±	0.2
FFA	1.5	±	0.1	1.3	±	0.2	1.6	±	0.1	1.2	±	0.2

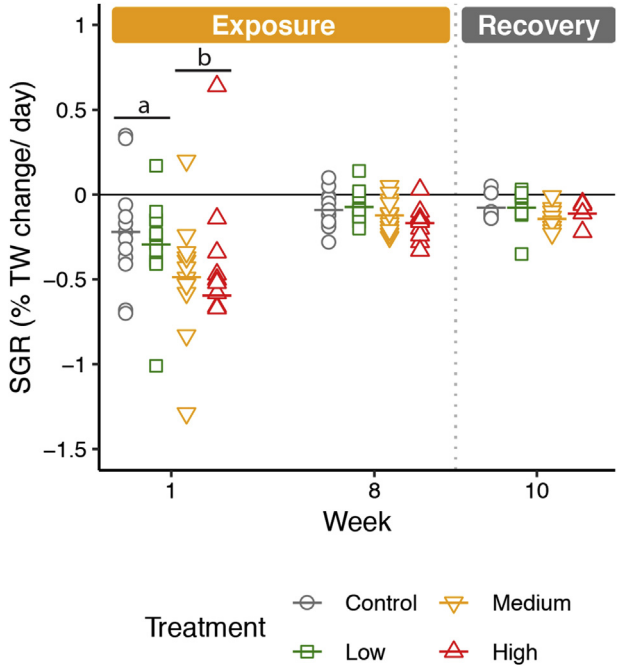

Fig. 3. The interaction of HSI (%) and treatment on the total weight specific growth rate (% TW per day) of mixed sex fish in the first week of exposure. Results from linear models and 95% confidence intervals are plotted for each treatment group with data points representing individual fish.

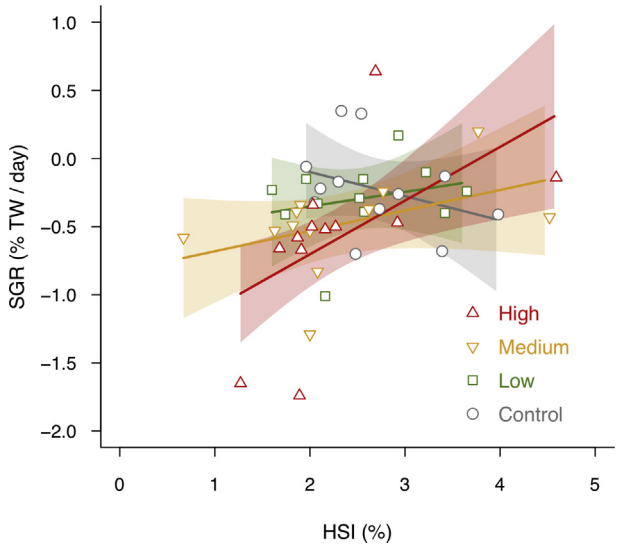

Fig. 4. Specific growth rate (SGR, % TW per day) of mixed females and males between the period from tagging to one, eight and ten weeks. Plots show individual data points distinguished by shape and color for each treatment group, treatment group means are represented with a dash (−). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

most likely bioavailable for the entire experimental period (ten weeks), including the last two weeks of depuration where polar cod were force-fed uncontaminated feed. For instance, Bakke et al. (2016) showed that a single dietary dose of phenanthrene and benzo(a)pyrene (0.40 ± 0.12 µg/g and 1.15 ± 0.36 µg/g fish for phenanthrene and benzo(a)pyrene, respectively) was retained in the tissues for at least 30 days, even for not covalently bound metabolites.

It is important to note that the responses observed in exposed polar cod of the present study cannot be solely attributed to the PAH fraction but rather a complex mixture of several thousands of unidentified petroleum compounds from the unresolved complex mixture (UCM). The UCM contains highly bioaccumulative and potentially toxic substances, and for which the toxicokinetics and toxicodynamics are largely unknown (Scarlett et al., 2007; Melbye et al., 2009; Petersen et al., 2017).

The crude oil doses used in the present study (4–200 µg crude oil/g fish/week) were in the same range as previous dietary studies on polar cod (George et al., 1995; Bender et al., 2016; Vieweg et al., 2018) that also showed the induction of hepatic EROD activity at their highest doses (George et al., 1995; Vieweg et al., 2018). In comparison with dietary studies on different fish species, our doses were similar to those of Bratberg et al. (2013) for cod (*Gadus morhua*) and were considered environmentally relevant. It is however important to highlight that the exposure method is not reflecting realistic environmental exposure, that would have required exposure of live feed to dispersed oil. The dietary crude oil taken-up by polar cod in this experiment was thus not represented by a realistic fraction composed of potential metabolites produced by living prey items. Furthermore, all compounds present in the whole crude oil were ingested by polar cod including fractions that may not have been bioavailable to the fish through exposure to live feed in the natural environment.

4.2. Baseline physiological status, SGR, and routine metabolic rate in control specimens

The study design suffered from an unexpected strong divergence in the physiological state of females and males that forced a sex-specific data analysis for certain parameters such as lipid composition. Accounting for these initial conditions by including physiological covariates such as sex and length allowed for a thorough investigation of possible effects of crude oil exposure on physiological endpoints. Even though some of the parameters did not show significant effects ($p > 0.05$), pronounced trends are discussed hereafter.

The majority of the female polar cod in the present study were immature and had thus never spawned before. By contrast, the histological analysis of the male gonads suggested that males had been spawning capable and most likely spawned earlier in the season, and advanced from a post-spawning (regressing) stage at the exposure start towards a resting (regenerating) stage at the end of the ten week experimental period concurrent with a significant decrease in GSI. This was further supported by the GSI at the exposure start that were lower than values known for ripe males in January (> 30% in e.g. Hop et al., 1995; Nahrgang et al., 2014), and in the known spawning timeframe (January–March) of polar cod populations of the Barents Sea (Hop and Gjøsæter, 2013). The disparity in maturity stage between sexes may be explained by males reaching sexual maturity at a younger age than females (Hop and Gjøsæter, 2013; Nahrgang et al., 2014). However, this hypothesis was not verified based on the otolith readings in the present study. In general, the very low HSI (75th percentile = 3.4% all treatments combined) indicated that the specimens were in a weak physiological state. No previous studies have shown such low HSI levels in this species for any season (Nahrgang et al. 2010a, 2014, Bender et al., 2016; Vieweg et al., 2018). The hepatic lipid levels in our post-spawning males were half those reported in males in the fall and early winter (Hop et al., 1995, 1997), suggesting an important allocation to reproduction. Females in the present study showed even lower levels of hepatic lipid content than males. In particular, the few females that were in a post-spawning stage had less than half the total lipid levels observed in males, and storage lipids (NL) represented as little as 20% of the total lipid class composition.

Specific growth rates were in general lower than rates reported in the same species elsewhere (Hop et al., 1997; Laurel et al., 2016, 2017). Although comparison to other studies may be difficult due to different factors (e.g. feed type, age, size range, temperature, and handling stress), SGR in polar cod fed to satiation have been shown to range between 0.5% and 1.5% wwt/day depending on size (Hop et al., 1995;

Laurel et al., 2016). In the present study, SGR levels were negative in most individuals. Our weekly feed rations (4% body wwt/week) were similar to maintenance levels reported by Hop et al. (1997). However, our study was conducted at higher temperatures than in Hop et al. (1997) (ca 6 °C instead of 0 °C), and our metabolic rates in control specimens (e.g. 92.0 ± 12.1 mg O_2/kg fish/hr for mean ± SE at ten weeks) were elevated compared to levels (51.03 ± 6.27 mg O_2/kg fish/hr) reported in Hop and Graham (1995). Given the elevated metabolic costs at increased temperatures, the rations given in the present study were insufficient to reach a positive growth in weight. The weight loss could be further rationalized by the particular weak physiological state of our specimens in early spring, as indicated by the reduced hepatic lipid levels. Finally, the weekly force-feeding most likely represented an additional handling stress that affected growth performance (e.g. McCormick et al., 1998; Barton, 2002; Jentoft et al., 2005). The specimens in the present study were therefore under sub-optimal conditions for growth including elevated temperatures, reduced feed ration, and low energy reserves.

4.3. Effect of crude oil on total wet weight alterations, and routine metabolic rate

The deleterious effect of crude oil or petroleum related compounds on fish growth has been shown previously in polar cod (Christiansen and George, 1995, Bender et al., 2018), as well as in other fish species (Al-Yakoob et al., 1996; Moles and Norcross, 1998; Kerambrun et al., 2012; Claireaux et al., 2013; Sandrini-Neto et al., 2016). In sexually developing polar cod, Christiansen and George (1995) found a reduction in weight gain when exposed to crude oil contaminated feed at levels (ca 2.1–2.6 µg crude oil/g fish/day) in the lower range of this study (0.6–28 µg crude oil/g fish/day). In the present study, there was a seemingly rapid (following the first dietary dose) and dose-dependent loss in weight, especially in individuals with an initial low condition (see section 4.2., and Fig. 3), suggesting an increased energy trade-off between somatic growth, and potential detoxification metabolism in individuals with reduced energy stores. Handling stress from the force-feeding may as well have been an aggravating factor on growth performance (McCormick et al., 1998). Indeed, fish were fed by hand during the acclimation period, and the first force-feeding event corresponded to the start of the exposure, one week following transfer to experimental tanks and tagging.

Another hypothesis that cannot be ruled out is the alteration of feed assimilation and/or conversion, in crude oil exposed groups, leading to a decrease in energy intake. A reduction in digestive function from crude oil exposure was suggested for river otters (*Lontra canadensis*) (Ormseth and Ben-David, 2000), and juvenile turbot (*Scophthalmus maximus*) (Saborido-Rey et al., 2007). It is not possible to discriminate the mechanisms leading to an accelerated loss in weight, but the effects in the high oil treatment are likely due to a combination of several factors such as an increased energy demand due to handling stress and detoxification metabolism, and alteration in digestive function.

The dose-dependent increase in weight loss after one week of exposure seemed to be offset over the eight week exposure period in all oil treatments. Similarly, Bender et al. (2018) found a transient depression in growth in polar cod acutely exposed to dispersed oil, followed by a period of increased growth in exposed individuals compared to controls. While the mechanisms could not be explained, a temporary reduction in feeding activity in exposed fish or potentially compensatory mechanisms for growth were suggested. In the present study, force feeding allowed for control of the feed intake by each individual. Thus, changes in feeding regime or appetite (Christiansen and George, 1995) could not explain the accelerated weight loss in oil exposed individuals, nor the following reduction in weight loss. Ali et al. (2003) suggested that behavioral adjustments (e.g. reduction in locomotion and metabolic costs) and changes in growth efficiency may play a role in growth compensation. Also, an habituation to the force-feeding over the following seven weeks may also have attenuated the combined effects of the exposure and stress on growth observed during the first sampling point (McCormick et al., 1998). Fish that were monitored for growth following the final two weeks of depuration (tenth experimental week) had also been used in respirometry measurements every second week during the entire experimental period, and had thus undergone additional handling stress. The worsening effect of handling stress was again marked on the health of these individuals with the increased incidence of mortality in males from the oil treatments and the trend to a dose-dependent reduction in weight loss in females.

The consistency in oxygen consumption levels found from week to week in both sexes suggested that these specimens had reached a steady state, and had adjusted their routine metabolic rate within the first weeks of exposures. Females exposed to crude oil showed a dose-independent, but elevated oxygen consumption, suggesting a threshold response to an elevated energy demand. This elevated oxygen consumption may correspond to the so-called “resistance” phase in the conceptual model of the general adaptation syndrome developed by Selye (1973). At equal feed intake and considering the increased trend in weight loss with dose, it can be hypothesized that females of the high treatment may have had a more important energy trade-off compared to the low and medium treatment females. On the contrary, Christiansen et al. (2010) showed a decrease in routine metabolic rate in polar cod exposed to the crude oil WSF both acutely and for the following four weeks. In this case, the depression in oxygen consumption from acutely exposed specimens was mostly attributed to an immediate response associated with behavioral changes (e.g. immobility). The depression of long-term (four weeks) exposed individuals could not be explained, but was suggested to be related to a crude oil induced alteration in digestion or assimilation by Klinger et al. (2015), resulting in decreased SDA and associated metabolic rates relative to controls.

Male polar cod showed in general no significant alterations of neither weight loss nor routine metabolic rate with dose. The elevated metabolic rate found in males from the medium group at all time points studied, could be explained by a lower body mass (mean 13 ± 2 g wwt) compared to the other groups (mean 14 ± 4 g wwt) (Table S1). Mass specific oxygen consumption increases with decreasing body weight in fish, thus suggesting that the increased routine metabolic rate in the medium group was a size artefact rather than the effect of the crude oil exposure. Although, males seemed more robust to the exposure than females, exposure may alter active metabolic rate and thus the metabolic scope for activity, even though their minimum energy demands were maintained. Such effects were shown in common sole (*Solea solea*) exposed to fuel oil (Davoodi and Claireaux, 2007). Furthermore, mortality during the experiment was solely observed in male specimens thus suggesting a sex-specific sensitivity.

Post-spawning survival is believed to be linked to remaining energy reserves and the capability of polar cod to resume feeding (Hop et al., 1995). This feature is highly important, especially in females for which fecundity is limited by body size, and are thus dependent on growing larger and reproducing over several winters to maximize fecundity (Nahrgang et al., 2014). Polar cod shows a high-energy investment in reproduction, compared to other gadids, with a total body weight loss of 30–50% through gonadal development and spawning (Hop et al., 1995). Post-spawning survival is thus dependent on optimal conditions to resume feeding and acquiring new energy stores. The additional stress from exposure to petroleum may thus divert already low energy reserves to detoxification metabolism and away from growth, potentially leading to a significant reduction in condition or even death. While previous studies have investigated the sensitivity of polar cod to low exposure doses during gonadal maturation and concluded with a certain robustness (Bender et al., 2016, 2018), the low-energy status of females in spring, potentially related to spawning, may be a more critical time period during the year, where initial low conditions of these specimens could have important consequences on their capacity to cope with additional stress factors such as pollutants. Females were also

suggested to be more at risk due to their indiscriminate feeding behavior when offered both contaminated and uncontaminated feed (Christiansen and George, 1995). The present study, does not allow drawing firm conclusions on the true risk implied in this hypothesis, and requires future work.

The two weeks of recovery where fish were fed clean feed did not show any changes in SGR compared to specimens exposed during eight weeks. The two weeks window may have been too short to highlight any significant physiological changes in the organisms or the endpoints measured were simply not sensitive enough to highlight any recovery. For instance, restoration of baseline levels within two weeks following crude oil exposure has been previously found in the same species but for molecular and cellular biomarkers (Nahrgang et al., 2010c; Andersen et al., 2015.

5. Conclusion

The present study revealed a negative impact of crude oil exposure on growth performance on adult polar cod with low condition in the early spring. The differential physiological states of both sexes in terms of liver lipid content and maturity status, influenced their response to crude oil exposure, with females increasing their routine metabolic rate, and mortality only observed in males. The present study suggests that hepatic storage lipids are a critical factor for growth of adult polar cod, especially when exposed to additional stressors such as dietary crude oil. Dietary levels of crude oil as low as 4 µg crude oil per g fish per fish led to reduced SGR in specimens with low HSI and this effect increased with increasing crude oil dose. The present study further stresses the importance of investigating the sensitivity to oil exposure of specimens in a post-spawning state. It also calls for caution in study designs that involve a significant amount of animal handling, as this can have important consequences on data quality and conclusions drawn.

Ethical statement

All work was performed according to and within the regulations enforced by the Norwegian Animal welfare authorities. The R/V Helmer Hanssen is owned by the University of Tromsø, which has all the necessary authorization from the Norwegian Fisheries Directorate to use a bottom trawl to collect fish for scientific purposes. Permission to carry out this experiment was granted by the Norwegian Animal Welfare Authority in 2012 (ID 4377).

Acknowledgement

This work was supported by the Norwegian Research Council [grant numbers 214184 and 195160] and the Fram Centre flagship Hazardous substances in Tromsø. We thank Eni Norge for providing Akvaplan-niva with the Kobbe crude oil used in this study. The authors declare no conflict of interest. Additional sampling help from Ingeborg Hallanger was greatly appreciated. Authors acknowledge contribution from Prof. Jørgen Schou Christiansen for reviewing of the manuscript and Prof. Michael Greenacre for reviewing the manuscript and help in statistical data analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoenv.2019.04.082.

References

Agersted, M.D., Møller, E.F., Gustavson, K., 2018. Bioaccumulation of oil compounds in the high-Arctic copepod *Calanus hyperboreus*. Aquat. Toxicol. 195, 8–14. http://doi.org/10.1016/j.aquatox.2017.12.001.

Al-Yakoob, S.N., Gundersen, D., Curtis, L., 1996. Effects of the water-soluble fraction of partially combusted crude oil from Kuwait's oil fires (from Desert Storm) on survival and growth of the marine fish *Menidia beryllina*. Ecotoxicol. Environ. Saf. 35, 142–149. http://doi.org/10.1006/eesa.1996.0093.

Ali, M., Nicieza, A., Wootton, R.J., 2003. Compensatory growth in fishes: a response to growth depression. Fish Fish. 4, 147–190. http://doi.org/10.1046/j.1467-2979.2003.00120.x.

Andersen, Ø., Frantzen, M., Rosland, M., Timmerhaus, G., Skugor, A., Krasnov, A., 2015. Effects of crude oil exposure and elevated temperature on the liver transcriptome of polar cod (*Boreogadus saida*). Aquat. Toxicol. 165, 9–18. http://doi.org/10.1016/j.aquatox.2015.04.023.

Bakke, M.J., Nahrgang, J., Ingebrigtsen, K., 2016. Comparative absorption and tissue distribution of ^{14}C-benzo(a)pyrene and ^{14}C-phenanthrene in the polar cod (*Boreogadus saida*) following oral administration. Polar Biol. 39, 1165–1173. http://doi.org/10.1007/s00300-015-1816-7.

Barber, D.G., Hop, H., Mundy, C.J., Else, B., Dmitrenko, I.A., Tremblay, J.-E., et al., 2015. Selected physical, biological and biogeochemical implications of a rapidly changing Arctic Marginal Ice Zone. Prog. Oceanogr. 139 (C), 122–150. http://doi.org/10.1016/j.pocean.2015.09.003.

Barton, B.A., 2002. Stress in fishes: a diversity of responses with particular reference to changes in circulating corticosteroids. Integr. Comp. Biol. 42, 517–525. http://doi.org/10.1093/icb/42.3.517.

Bender, M.L., Frantzen, M., Camus, L., Le Floch, S., Palerud, J., Nahrgang, J., 2018. Effects of acute exposure to dispersed oil and burned oil residue on long-term survival, growth, and reproductive development in polar cod (Boreogadus saida). Mar. Environ. Res. 140, 468–477. https://doi.org/10.1016/j.marenvres.2018.09.005.

Bender, M.L., Frantzen, M., Vieweg, I., Falk-Petersen, I.B., Johnsen, H.K., Rudolfsen, G., et al., 2016. Effects of chronic dietary petroleum exposure on reproductive development in polar cod (*Boreogadus saida*). Aquat. Toxicol. 180, 196–208. http://doi.org/10.1016/j.aquatox.2016.10.005.

Benjamini, Y., Hochberg, Y., 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. J. R. Stat. Soc. Ser. B 57, 289–300.

Berge, J., Renaud, P.E., Darnis, G., Cottier, F., Last, K., Gabrielsen, T.M., et al., 2015. In the dark: a review of ecosystem processes during the Arctic polar night. Prog. Oceanogr. 139, 258–271. http://doi.org/10.1016/j.pocean.2015.08.005.

Bratberg, M., Olsvik, P.A., Edvardsen, R.B., Brekken, H.K., Vadla, R., Meier, S., 2013. Effects of oil pollution and persistent organic pollutants (POPs) on glycerophospholipids in liver and brain of male Atlantic cod (*Gadus morhua*). Chemosphere 90, 2157–2171. http://doi.org/10.1016/j.chemosphere.2012.11.026.

Brown-Peterson, N.J., Wyanski, D.M., Saborido-Rey, F., Macewicz, B.J., Lowerre-Barbieri, S.K., 2011. A standardized terminology for describing reproductive development in fishes. Marine and Coastal Fisheries 3, 52–70. http://doi.org/10.1080/19425120.2011.555724.

Christiansen, J.S., George, S.G., 1995. Contamination of food by crude oil affects food selection and growth performance, but not appetite, in an Arctic fish, the polar cod (*Boreogadus saida*). Polar Biol. 15, 277–281. http://doi.org/10.1007/BF00239848.

Christiansen, J.S., Karamushko, L.I., Nahrgang, J., 2010. Sub-lethal levels of waterborne petroleum may depress routine metabolism in polar cod *Boreogadus saida* (Lepechin, 1774). Polar Biol. 33, 1049–1055. http://doi.org/10.1007/s00300-010-0783-2.

Claireaux, G., Theron, M., Prineau, M., Dussauze, M., Merlin, F.-X., Le Floch, S., 2013. Effects of oil exposure and dispersant use upon environmental adaptation performance and fitness in the European sea bass, *Dicentrarchus labrax*. Aquat. Toxicol. 130–131, 160–170. http://doi.org/10.1016/j.aquatox.2013.01.004.

Davoodi, F., Claireaux, G., 2007. Effects of exposure to petroleum hydrocarbons upon the metabolism of the common sole *Solea solea*. Mar. Pollut. Bull. 54, 928–934. http://doi.org/10.1016/j.marpolbul.2007.03.004.

Eggens, M.L., Galgani, F., 1992. Ethoxyresorufin-O-deethylase (EROD) activity in flatfish: fast determination with a fluorescence plate-reader. Mar. Environ. Res. 33 (3), 213–221. http://doi.org/10.1016/0141-1136(92)90149-G.

Folch, J., Lees, M., Stanley, S.G.H., 1957. A simple method for the isolation and purification of totals lipids from animal tissues. J. Biol. Chem. 226, 497–509.

George, S.G., Christiansen, J.S., Killie, B., Wright, J., 1995. Dietary crude oil exposure during sexual maturation induces hepatic mixed function oxygenase (CYP1A) activity at very low environmental temperatures in Polar cod *Boreogadus saida*. Mar. Ecol. Prog. Ser. 122, 307–312. http://doi.org/10.3354/meps122307.

Geraudie, P., Nahrgang, J., Forget-Leray, J., Minier, C., Camus, L., 2014. *In vivo* effects of environmental concentrations of produced water on the reproductive function of polar cod (*Boreogadus saida*). J. Toxicol. Environ. Health, Part A 77, 557–573. http://doi.org/10.1080/15287394.2014.887420.

Gjøsæter, H., Ajiad, A.M., 1994. Growth of polar cod, *Boreogadus saida* (lepechin), in the Barents Sea. ICES (Int. Counc. Explor. Sea) J. Mar. Sci.: Journal Du Conseil 51, 115–120.

Gravato, C., Guilhermino, L., 2009. Effects of benzo(a)pyrene on seabass (*Dicentrarchus labrax L.*): biomarkers, growth and behavior. Hum. Ecol. Risk Assess. Int. J. 15, 121–137. http://doi.org/10.1080/10807030802615659.

Holst, J.C., McDonald, A., 2000. FISH-LIFT: a device for sampling live fish with trawls. Fisher. Res. 48, 87–91. https://doi.org/10.1016/s0165-7836(00)00116-8.

Hop, H., Gjøsæter, H., 2013. Polar cod (*Boreogadus saida*) and capelin (*Mallotus villosus*) as key species in marine food webs of the Arctic and the Barents Sea. Mar. Biol. Res. 9, 878–894. http://doi.org/10.1080/17451000.2013.775458.

Hop, H., Graham, M., 1995. Respiration of juvenile Arctic cod (*Boreogadus saida*): effects of acclimation, temperature, and food intake. Polar Biol. 15, 359–367.

Hop, H., Tonn, W.M., Welch, H.E., 1997. Bioenergetics of Arctic cod (*Boreogadus saida*) at low temperatures. Can. J. Fish. Aquat. Sci. 54, 1772–1784.

Hop, H., Trudeau, V.L., Graham, M., 1995. Spawning energetics of Arctic cod (*Boreogadus saida*) in relation to seasonal development of the ovary and plasma sex steroid levels. Can. J. Fish. Aquat. Sci. 52, 541–550.

Jentoft, S., Aastveit, A.H., Torjesen, P.A., Andersen, Ø., 2005. Effects of stress on growth, cortisol and glucose levels in non-domesticated Eurasian perch (*Perca fluviatilis*) and domesticated rainbow trout (*Oncorhynchus mykiss*). Comp. Biochem. Physiol. Mol. Integr. Physiol. 141, 353–358. http://doi.org/10.1016/j.cbpb.2005.06.006.

Kaluzny, M.A., Duncan, L.A., Merritt, M.V., Epps, D.E., 1985. Rapid separation of lipid classes in high yield and purity using bonded phase columns. J. Lipid Res. 26, 135–140.

Kerambrun, E., Henry, F., Courcot, L., Gevaert, F., Amara, R., 2012. Biological responses of caged juvenile sea bass (*Dicentrarchus labrax*) and turbot (*Scophtalmus maximus*) in a polluted harbour. Ecol. Indicat. 19, 161–171. http://doi.org/10.1016/j.ecolind.2011.06.035.

Klinger, D.H., Dale, J.J., Machado, B.E., Incardona, J.P., Farwell, C.J., Block, B.A., 2015. Exposure to Deepwater Horizon weathered crude oil increases routine metabolic demand in chub mackerel, *Scomber japonicus*. Mar. Pollut. Bull. 98, 259–266. http://doi.org/10.1016/j.marpolbul.2015.06.039.

Laurel, B.J., Copeman, L.A., Spencer, M., Iseri, P., 2017. Temperature-dependent growth as a function of size and age in juvenile Arctic cod (*Boreogadus saida*). ICES (Int. Counc. Explor. Sea) J. Mar. Sci.: Journal Du Conseil 74, 1614–1621. http://doi.org/10.1093/icesjms/fsx028.

Laurel, B.J., Spencer, M., Iseri, P., Copeman, L.A., 2016. Temperature-dependent growth and behavior of juvenile Arctic cod (*Boreogadus saida*) and co-occurring North Pacific gadids. Polar Biol. 39, 1127–1135. http://doi.org/10.1007/s00300-015-1761-5.

McCormick, S.D., Shrimpton, J.M., Carey, J.B., O'Dea, M.F., Sloan, K.E., Moriyama, S., Björnsson, B.T., 1998. Repeated acute stress reduces growth rate of Atlantic salmon parr and alters plasma levels of growth hormone, insulin-like growth factor I and cortisol. Aquaculture 168, 221–235. http://doi.org/10.1016/S0044-8486(98)00351-2.

Meier, S., Mjøs, S.A., Joensen, H., Grahl-Nielsen, O., 2006. Validation of a one-step extraction/methylation method for determination of fatty acids and cholesterol in marine tissues. J. Chromatogr. A 1104, 291–298. http://doi.org/10.1016/j.chroma.2005.11.045.

Melbye, A.G., Brakstad, O.G., Hokstad, J.N., 2009. Chemical and toxicological characterization of an unresolved complex mixture-rich biodegraded crude oil. Environ. Toxicol. Chem. 28, 1815–1824.

Moles, A., Norcross, B.L., 1998. Effects of oil-laden sediments on growth and health of juvenile flatfishes. Can. J. Fish. Aquat. Sci. 55, 605–610. http://doi.org/10.1139/f97-278.

Moles, A., Rice, S.D., 1983. Effects of crude oil and naphthalene on growth, caloric content, and fat content of pink salmon juveniles in seawater. Trans. Am. Fish. Soc. 112, 205–211. http://doi.org/10.1577/1548-8659(1983)112<205:EOCOAN>2.0.CO;2.

Mueter, F.J., Nahrgang, J., Nelson, R.J., Berge, J., 2016. The ecology of gadid fishes in the circumpolar Arctic with a special emphasis on the polar cod (*Boreogadus saida*). Polar Biol. 39, 961–967. http://doi.org/10.1007/s00300-016-1965-3.

Nahrgang, J., Camus, L., Broms, F., Christiansen, J.S., Hop, H., 2010a. Seasonal baseline levels of physiological and biochemical parameters in polar cod (*Boreogadus saida*): implications for environmental monitoring. Mar. Pollut. Bull. 60, 1336–1345. http://doi.org/10.1016/j.marpolbul.2010.03.004.

Nahrgang, J., Camus, L., Carls, M.G., Gonzalez, P., Jönsson, M., Taban, I.C., et al., 2010b. Biomarker responses in polar cod (*Boreogadus saida*) exposed to the water soluble fraction of crude oil. Aquat. Toxicol. (Amst.) 97, 234–242. http://doi.org/10.1016/j.aquatox.2009.11.003.

Nahrgang, J., Camus, L., Gonzalez, P., Jönsson, M., Christiansen, J.S., Hop, H., 2010c. Biomarker responses in polar cod (*Boreogadus saida*) exposed to dietary crude oil. Aquat. Toxicol. 96, 77–83. http://doi.org/10.1016/j.aquatox.2009.09.018.

Nahrgang, J., Varpe, Ø., Korshunova, E., Murzina, S., Hallanger, I.G., Vieweg, I., Berge, J., 2014. Gender specific reproductive strategies of an arctic key species (*Boreogadus saida*) and implications of climate change. PLoS One 9, e98452. http://doi.org/10.1371/journal.pone.0098452.s008.

Nahrgang, J., Dubourg, P., Frantzen, M., Storch, D., Dahlke, F., Meador, J.P., 2016. Early life stages of an arctic keystone species (*Boreogadus saida*) show high sensitivity to a water-soluble fraction of crude oil. Environ. Pollut. 218, 605–614. http://doi.org/10.1016/j.envpol.2016.07.044.

Ormseth, O.A., Ben-David, M., 2000. Ingestion of crude oil: effects on digesta retention times and nutrient uptake in captive river otters. J. Comp. Physiol. B Biochem. Syst. Environ. Physiol. 170, 419–428. http://doi.org/10.1007/s003600000119.

Petersen, K., Hultman, M.T., Rowland, S.J., Tollefsen, K.-E., 2017. Toxicity of organic compounds from unresolved complex mixtures (UCMs) to primary fish hepatocytes. Aquat. Toxicol. 190, 150–161. http://doi.org/10.1016/j.aquatox.2017.06.007.

R Development Core Team, 2014. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Saborido-Rey, F., Domínguez-Petit, R., Tomás, J., Morales-Nin, B., Alonso-Fernandez, A., 2007. Growth of juvenile turbot in response to food pellets contaminated by fuel oil from the tanker Prestige. Mar. Ecol. Prog. Ser. 345, 271–279. http://doi.org/10.3354/meps06961.

Sandrini-Neto, L., Pereira, L., Martins, C.C., de Assis, H.C.S., Camus, L., Lana, P.C., 2016. Antioxidant responses in estuarine invertebrates exposed to repeated oil spills: effects of frequency and dosage in a field manipulative experiment. Aquat. Toxicol. 177, 237–249. http://doi.org/10.1016/j.aquatox.2016.05.028.

Scarlett, A., Galloway, T.S., Rowland, S.J., 2007. Chronic toxicity of unresolved complex mixtures (UCM) of hydrocarbons in marine sediments. J. Soils Sediments 7, 200–206. http://doi.org/10.1065/jss2007.06.232.

Selye, H., 1973. The evolution of the stress concept. Am. Sci. 61 (6), 692–699.

Smith, L.C., Stephenson, S.R., 2013. New Trans-Arctic shipping routes navigable by mid-century. Proc. Natl. Acad. Sci. U.S.A. 110, E1191–E1195. http://doi.org/10.1073/pnas.1214212110.

Vieweg, I., Bilbao, E., Meador, J.P., Cancio, I., Bender, M.L., Cajaraville, M.P., Nahrgang, J., 2018. Effects of dietary crude oil exposure on molecular and physiological parameters related to lipid homeostasis in polar cod (*Boreogadus saida*). Comp. Biochem. Physiol., C 206–207, 54–64. http://doi.org/10.1016/j.cbpc.2018.03.003.