Incorporation of salmon fish feed and feces components in mussels (Mytilus edulis): Implications for integrated multi-trophic aquaculture in cool-temperate North Atlantic waters

Aleksander Handå, Anders Ranheim, Anders Johny Olsen, Dag Altin, Kjell Inge Reitan, Yngvar Olsen, Helge Reinertsen

A R T I C L E   I N F O

Article history:
Received 21 November 2011
Received in revised form 18 September 2012
Accepted 20 September 2012
Available online 5 October 2012

Keywords:
Mytilus edulis
Salmon fish feed
Fatty acids
Bivalve growth
Integrated multi-trophic aquaculture

A B S T R A C T

The incorporation of salmon fish feed and feces components in the digestive gland, mantle, and gill tissue of blue mussels (Mytilus edulis), and associated growth in shell length and soft tissue dry weight, were studied in a 28 day laboratory experiment. Mussels were fed mixed rations of either salmon fish feed and Rhodomonas baltica, salmon feces and R. baltica or mono rations of either a full or half ration of R. baltica. Feed rations were designed to supply a particulate organic carbon ration equal to ~5% of soft tissue carbon content ind−1 day−1. Significant changes in the fatty acid composition, which appointed that of the food profiles, were evident in the digestive gland and gill tissue (p < 0.05), whereas no changes were found in mantle tissue. For digestive gland data, a principal component analysis particularly identified the contribution of 18:1 (n−9), 18:3 (n−3), 18:2 (n−6) and 20:1 (n−9) and as being the single fatty acids most responsible for the difference between the various diets. A significant growth in length was found for mussels fed fish feed and R. baltica (p < 0.05), but not for mussels fed feces and R. baltica. The dry weight was significantly higher for mussels fed the full diet with R. baltica compared to the other diets, and significantly lower for mussels fed feces and R. baltica than fish feed and R. baltica at the end of the experiment (p < 0.05). A more pronounced incorporation of salmon feed compared to salmon feces components in mussel tissues suggested that mussels will utilize fish feed more efficiently than feces particles in an integrated aquaculture with salmon.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

Global salmonid production increased by ~60% from 1999 to 2009 (1.26 to 2.17 million tons) (FAO, 2011), and further growth is expected. Atlantic salmon (Salmo salar) cage aquaculture accounts for the majority of the production (1.44 million tons in 2009, FAO, 2011), and it is estimated that 67–84% of the nutrients (carbon, nitrogen and phosphorus) from the feed input are released into the surrounding waters as respiratory products (dissolved nutrients), feces and uneaten feed particles (Hail et al., 1990, 1992; Holby and Hall, 1991; Troell et al., 2003 and references therein, Norø et al., 2011). Feed wastage is typically in the range of 3−5% (Cromey et al., 2002) and a feed loss of e.g. 3% will constitute about 12% of the total solid wastes from a salmon farm (Reid et al., 2008). There is an increasing concern with regard to the negative environmental impacts associated with this nutrient load (Amberg and Hall, 2008; Braaten, 2007; Tett, 2008), with one of the major challenges for the sustainable development of salmonid mariculture therefore being to minimize waste discharges that can potentially lead to deterioration of the local marine environment (Cheshuk et al., 2003).

As a measure to reduce this organic loading it has been suggested to cultivate inorganic and organic extractive species at lower trophic levels in close vicinity to the fish farms in an integrated multi-trophic aquaculture (IMTA) system. IMTA has two non-conflicting overall objectives: 1) Increased biomass production and added value based on the feed investments, and 2) mitigating potentially negative environmental impacts of waste nutrients. In this way, IMTA may contribute to a more sustainable aquaculture production (Chopin et al., 2001, 2008; Neori, 2008; Neori et al., 2004a, 2004b; Troell et al., 2003, 2009). In a properly designed IMTA system, the dissolved nutrient wastes can be taken up by inorganic extractive species such as seaweed (Buschmann et al.,...
2. Material and methods

Rhodomonas baltica microalgae in shell length and soft tissue dry weight as mussels fed the particulate waste concentrations relative to microalgae densities. The hypothesis was that mussels would incorporate salmon particulate waste from fish cage aquaculture. There is therefore a need to further investigate the potential of bivalve filter feeders to perform bioremediative services in IMTA, little is known about the ability of particulate wastes originating from salmon farming to promote shellfish growth (MacDonald et al., 2011).

Several studies have indicated better growth for mussels grown adjacent to cage fish farms (Lander et al., 2004; Peharda et al., 2007; Sarà et al., 2009; Stirling and Okumus, 1995; Wallace, 1980), while others have failed to demonstrate this (Navarrete-Mier et al., 2010; Taylor et al., 1992), suggesting that the distance from the farms does not substantially influence food availability and growth. In any case, conflicting results bring some uncertainty to whether the combined cultivation of fish and blue mussels can reduce the organic load from fish cage aquaculture. There is therefore a need to further explore the incorporation of components of salmon fish feed and feces and associated mussel growth.

This study aimed to examine food incorporation and the growth of blue mussels fed salmon fish feed and feces particles. For that purpose, a 28 day experiment was carried out with continuous feeding under controlled laboratory conditions in order to eliminate temporal and spatial variations in feed and feces fluxes and to enable high particulate waste concentrations relative to microalgae densities. The hypothesis was that mussels would incorporate salmon fish feed and feces particles and exhibit the same growth performance in shell length and soft tissue dry weight as mussels fed the microalgae Rhodomonas baltica.

2.1. Experimental design

Blue mussels (Mytilus edulis) were fed salmon fish feed, feces and the microalgae R. baltica for 28 days in June 2009 according to Table 1. Mussels were offered two mixed rations consisting of either salmon fish feed and R. baltica (FD + RB), salmon feces and R. baltica (FC + RB) or a full (RB) or half ration (1/2RB) of R. baltica. The particulate organic carbon (POC) content of experimental diets corresponded to ~5% day\(^{-1}\) of the carbon content of soft tissue dry weight of the individual mussels, which was ~40% (n = 10).

Feed pellets were of the OptiTime 2500 type (Skretting Ltd). Salmon (3–6 kg) were anesthetized with benzozik prior to squeezing for feces, which were then frozen in thin plates at −80 °C. R. baltica (Clone NIVA 5/91, d = 6–10 μm, ~41.4 pg C cell\(^{-1}\), ~7.4 pg N cell\(^{-1}\)) was cultivated semi-continuously at 20 ± 2 °C and maintained at 50% of their maximum growth rate by daily dilution. The cultures were enclosed in 160 and 200 l polycarbonate tubes (40 cm in diameter) with natural seawater at ambient salinity (33–34 psu) and enriched with a Conway medium (Walne, 1974). The algae were kept in suspension by aeration from the bottom by compressed air-added CO\(_2\) to keep the pH in the cultures in the range of 7.5–8.5. All diets were homogenized and freeze-dried for 24 h prior to analyses of the carbon content on a Carlo Erba CHN model 1106 elemental analyzer. The carbon and nitrogen contents of salmon fish feed and feces were 50% and 6.5% and 30% and 2.6%, respectively, of dry weight (n = 3).

Each day during the experiment, feed pellets and frozen feces were weighed (Mettler Toledo UMX2) and crushed for 10 s in 500 ml 1 μm-filtered seawater using a kitchen blender (Electrolux ASB 2600) before the pastes and R. baltica were transferred to cleaned 90 l feeding tanks with a cone bottom filtered with 2 μm filtered, aerated seawater to maintain a uniform feed distribution.

Mussels (38–42 mm) were collected from a suspended longline farm at Marholmen in Åfjorden in Central Norway (63° 56' N, 10° 11' E), and transferred to laboratory facilities at the Norwegian University of Science and Technology (NTNU) for acclimatization in flow-through raceways (40 × 20 × 400 cm, 320 l volume, 6.0 l min\(^{-1}\) exchange rate) at 10 °C for 14 days prior to the experiment. Sand-filtered and UV-treated seawater (35 ppt) from 70 m depth in the Trondheimsfjord was temperature-regulated in aerated reservoirs before impurities were successively removed by two serially coupled CUNO AquaPure filters with nominal retention of particles >50 μm and >2 μm, respectively. R. baltica was continuously added in the front of the raceway with peristaltic pumps (Watson-Marlow 505U), keeping the inflow concentration at ~1000–2000 cells ml\(^{-1}\). To avoid spawning in mature mussels during the experiment, the temperature was increased to 16 °C for 2 h prior to the experiment in order to induce spawning. Only minor spawning incidents were observed and the mussels that spawned were not used in the experiment.

After acclimatization, the mussels were placed on horizontal grid plates (25 × 0.4 × 50 cm) 2 cm above the bottom in rectangular plastic trays (40 × 15 × 70 cm, 30 l volume) with flowing seawater (Fig. 1). A perforated plastic plate (2 mm holes) was installed vertically in the water stream in front of the horizontal plate to avoid strong turbulence and to create a uniform feed distribution. Food was continuously added to the mixing zone in front of the perforated plate with peristaltic pumps (Watson-Marlow 505U). The water level was regulated by a vertical circular discharge pipe (height over tray bottom 14 cm) at the

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Abb.</th>
<th>Feed ration (mg carbon)</th>
<th>mg C ind(^{-1}) day(^{-1})</th>
<th>Trays (ind tray(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish feed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish feed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R. baltica</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed and R. baltica</td>
<td>FD + RB</td>
<td>3.3</td>
<td>3.3</td>
<td>6.6</td>
</tr>
<tr>
<td>Feces and R. baltica</td>
<td>FC + RB</td>
<td>–</td>
<td>3.3</td>
<td>–</td>
</tr>
<tr>
<td>R. baltica</td>
<td>RB</td>
<td>–</td>
<td>6.6</td>
<td>–</td>
</tr>
<tr>
<td>R. baltica</td>
<td>1/2RB</td>
<td>–</td>
<td>3.3</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 1

Experimental treatments showing food supply corresponding to 5% of soft tissue carbon content per mussel and day based on the food carbon content of salmon feed, salmon feces and the microalgae Rhodomonas baltica.
“distal” end of the tray. The water exchange (new water) was 6 l h⁻¹ (20% of the volume), which should theoretically be sufficient to maintain the oxygen saturation above 70% based on a maximum oxygen consumption rate of 0.5 ml O₂ ind⁻¹ h⁻¹ (Handá et al., 2012). To minimize sedimentation and maintain a uniform distribution of food particles in the trays, the water was constantly pumped from the distal end of the tray to the mixing zone in front of the perforated plate at a rate of 3 l min⁻¹ by an external aquarium pump (New-Jet 1), leaving the water volume in the trays to be pumped 6 times h⁻¹. During the experiment, water samples (20 ml, n = 3) were taken in front of the perforated plate and at the outlet five times between days 7 and 28 to measure particle concentrations with a Beckman Coulter-Counter Multisizer 3 (BCCM3).

2.2. Clearance rates

Clearance rates (CR) were measured for salmon fish feed, feces and R. baltica prior to the experiment by placing single mussels (n = 7 for each food type) in circular glass containers filled with 2 l of 1 µm-filtered and aerated seawater-added salmon fish feed, feces or R. baltica particles, respectively. Water samples (20 ml) were taken every 30 min for 2 h to calculate the CR based on particle counts according to Widdows and Staff (1997).

2.3. Fatty acid analysis

Samples of R. baltica, salmon fish feed, feces (n = 6) and mussel digestive gland, mantle and gill tissue (n = 5) were flushed with nitrogen to avoid oxidation and maintain the original polyunsaturated fatty acids, and stored at −80 °C until analysis. The total lipids were extracted according to Bligh and Dyer (1959), followed by analysis of fatty acids after treating the samples according to Metcalfe et al. (1966). 0.8 ml of distilled water, 2 ml of methanol and 1 ml of chloroform with C19:0 as an internal standard (Nu-Chek Prep, Japan) were added to the freeze-dried and weighed samples before being vortexed (1 min) and added 1 ml of chloroform. The tubes (kimax) were then vortexed (20 s), added 1 ml of distilled water and re-vortexed (20 s), followed by centrifugation (4000 rpm, 10 min, 4 °C) (Hettich universal 32R). 0.5–1 ml of the chloroform phase was then transferred to kimax tubes from which the chloroform was steamed off. 1 ml of 0.5 N NaOH–methanol was then added and the tubes were vortexed and heated (100 °C, 15 min) to release the fatty acids (hydrolysis). The tubes were then cooled on ice, after which 2 ml of 12 BF₃ in methanol was added for esterification. The samples were then again vortexed, heated (5 min, 100 °C) and cooled again. Finally, 1 ml of isooctane was added to the samples, which were vortexed, heated (1 min, 100 °C) and then cooled again before 3 ml of saturated NaCl solution was added. The methyl esters were then extracted with isooctane (3 × 0.5 ml) and centrifuged (4000 rpm, 3 min) before the upper isooctane phase was transferred to vials and analyzed for fatty acids using a gas chromatograph (Perkin Elmer AutoSystem XL) with TotalChrom Version 6.3.1 software.

2.4. Gender determination

Gametes from the mantle tissue were activated by placing a small tissue sample dissected with a scalpel in filtered (1 µm) seawater. A glass pipette was used to transfer the activated gametes to a microscope (Leitz Wetzlar Dialux), where the sperm or eggs were visually identified. Mussel sperm was activated in contact with salt water, while the spherical eggs (68–70 µm diam.) remained passive. Gender was determined in order to reveal any differences between the fatty acid composition in male and female mantle tissue.

2.5. Growth measurements

The shell length and dry weight (DW) of soft tissue were measured prior to-, and at the end of the experiment. The length was measured with a digital caliper (Mitutoyo Absolute Digimatic mod CD-20CPX) with an accuracy of 10 µm, while changes in the soft tissue dry weight (DW) were expressed as a condition index standardized to a certain shell length L′ according to Bayne and Worrall (1980) and Bonardelli and Himmelman (1995). The DW was measured with an electronic weight (Mettler Toledo Precisa 180A) after drying the tissue at 60 °C for 48 h, and the index was then calculated as a standardized dry weight (DW′) by the following equation:

\[
DW' = \frac{DW}{L''^b/L^b}
\]

where DW is the weight in mg, L the length in mm and b the slope of log₁₀ DW plotted as a function of log₁₀ L. DW’ corresponds to the condition index, and was scaled so it equals the DW when L equals L’. L’ was set to 40 mm based on an average shell length of 40.2 ± 1.2 mm (n = 450). The mean initial DW’ before the feeding experiment was

![Fig. 1. Experimental tray with mussels.](image-url)
325 ± 4 mg (n = 60). The specific growth rate (\( \mu \), d\(^{-1}\)) in DW\(^{\prime}\) (SGR\(_{DW}^{\prime}\)) was calculated by the equation:

\[
\mu = \frac{\ln \text{DW}^{\prime}_t - \ln \text{DW}^{\prime}_0}{t}.
\]

The percentage growth per day (P) was calculated by the equation:

\[
P = 100 \times \left( \exp(\mu) - 1 \right).\]

The average rate of length increase (\( \mu_m \), d\(^{-1}\)) (AGR\(_m\)) was calculated by the equation:

\[
\mu_m = \frac{L_t - L_0}{t}
\]

where \( L_0 \) and \( L_t \) are \( L \) at the start and end of each experiment, respectively, and \( t \) is the time in days.

### 2.6 Data analysis

The data for shell length and DW\(^{\prime}\) were pooled for each treatment and tested for normality using the Kolmogorov–Smirnov test and for homogeneity of variance using a Levene’s test. The equality of means for shell length, DW\(^{\prime}\) and relative content of identified fatty acids (% per g wet tissue of digestive gland, mantle and gills) between Day 0 and Day 28 samples, and between the different treatments on Day 28, were tested with one-way ANOVA followed by post hoc comparisons by Tamhane’s T2, not assuming equal variances. The Mann Whitney U test for non-parametric data was used to analyze the equality of mean particle densities and the sum of monounsaturated and polyunsaturated fatty acids. The significance limit was set to 0.05 and the means are given with standard error.

Statistical analyses were performed using SPSS (rel. 17.0, Chicago, SPSS Inc.), while a principal component analysis (PCA) for fatty acid
composition was performed with an Unscrambler version 9.8 2008 (Camo Software LTD). The data was analyzed without weighing, therefore leaving open the chance for the PCA of each tissue to be dominated by the fatty acids that dominated the fatty acid composition.

3. Results

3.1. Particle sizes, clearance rate and food availability

After mixing salmon fish feed pellets and frozen feces with filtered seawater, more than 99% of the salmon fish feed and feces particles were distributed within the size range equivalent to a sphere diameter between 2 and 30 μm. Within this size range, 85% of the fish feed particles were 2–5 μm, 11% were 5–10 μm and 4% were 10–30 μm (Fig. 2A). Salmon feces particles in the range of 2–5 μm comprised 72% of the 2–30 μm size distribution, while 24% were 5–10 μm and 3.6% were 10–30 μm (Fig. 2B). The cell size of Rhodomonas baltica was 6–10 μm.

Prior to the experiment, mussels cleared salmon fish feed, feces and Rhodomonas baltica at similar rates and exhibited a similar pattern of variation for the various food sources. Among the particle concentrations that were obtained within the sample intervals, the highest CR measured 2.4 ± 0.2, 2.9 ± 0.2 and 2.4 ± 0.1 h−1 at -1680 ± 160, -2450 ± 370 and -1080 ± 90 particles ml−1 of salmon fish feed, feces and Rhodomonas baltica, respectively, while a significant lower CR was found for higher and lower particle concentrations with all diets (p < 0.05) (Fig. 2C–E). The CR was significantly higher for Rhodomonas baltica compared to feed and feces at the highest offered particle concentrations, while being low for all types of food with particle densities <500 ml−1. The clearance of feed, feces and Rhodomonas baltica was ceased at 354 ± 30, 433 ± 62 and 235 ± 28 particles ml−1, respectively.

The mean particle concentration was significantly higher in feed + RB (2010 ± 180 ml−1) and FC + RB traps (2100 ± 160 ml−1) than in 1/2RB (975 ± 190 ml−1) and RB traps (1460 ± 150 ml−1) (p < 0.05) (Fig. 3). The concentration in the control-tray (C) without fish feed and salmon feces was signiﬁcantly lower (524 ± 85 particles ml−1). The particle densities were accordingly in the range in which the mussels showed the highest CR.

3.2. Incorporation of food components in mussel tissues

The principal component analysis of fatty acid profiles clearly demonstrated incorporation of nutritional components from salmon fish feed and Rhodomonas baltica in the digestive gland and gill tissue of the mussels, whereas no systematic pattern was revealed for mantle tissue (Fig. 4A–C). For the digestive gland, mantle and gill tissue, the score plots (upper panels) showed that 81, 96 and 83% of the variance in the data was explained by the two first principal components. The fatty acid profile in the digestive gland and gill tissue changed from Day 0 to Day 28, and the changes were more pronounced in the direction of the food signatures for mussels fed FD + RB and RB in comparison to those fed FC + RB. One RB outlier was removed from the PCA analysis.

In the digestive gland samples, the loading plots (lower panels) confirmed the incorporation of 18:1 (n − 9) from salmon fish feed and feces, 20:1 (n − 9) from salmon fish feed, 18:2 (n − 6) from salmon fish feed and Rhodomonas baltica and 18:3 (n − 3) and 18:4 (n − 3) from Rhodomonas baltica, while 20:5 (n − 3) and 22:6 (n − 3) contributed more to the total fatty acid profile in the control mussels at Day 0. The same pattern of variation was found for these fatty acids in the gill tissue, except for the lack of 18:4 (n − 3) and the presence of 18:1 (n − 7), and there was a large contribution of 16:0 to the variance in samples of mussels fed salmon fish feed and feces. In the mantle tissue, the loading plot indicated that there was a larger contribution of DHA in males than in females, and that 16:1 (n − 7) appeared to be higher in females. As was also found for the gill tissue, the low fraction of 16:0 in mussels fed RB contributed strongly to the variance.

The fatty acid content (% of total FA in DW tissue) was significantly higher in the digestive gland of the mussel (6.1 ± 0.5% than in the mantle tissue (3.9 ± 0.6%), and significantly higher in the mantle than in the gill tissue (1.6 ± 0.2%) at the start of the experimental period (p < 0.05) (Fig. 5A). The fatty acid content increased signiﬁcantly in the digestive gland tissue of mussels fed FD + RB during the experimental period, from 6.1 to 9.5% of DW (p < 0.05), whereas no significant changes were seen in the mantle and gill tissues for this treatment or in any tissues in the mussels that were fed FC + RB or RB. The fatty acid content was highest in salmon fish feed (25.4 ± 0.5%) and lower and not significantly different in feces (5.3 ± 0.1%) and Rhodomonas baltica (5.6 ± 0.3%) (Fig. 5B).

The fatty acid composition of the digestive gland, mantle and gill tissue of mussels at Day 0 (control, fed Rhodomonas baltica for 12 days), and for mussels fed RB, FD + RB and FC + RB, is shown in Table 2A–C. Significant changes in the fatty acid composition of tissues in the direction of the composition of salmon fish feed and feces were evident in the digestive gland and gill tissue (p < 0.05), whereas no changes were identiﬁed in the mantle tissue (Fig. 6A–C). The fatty acid composition (% of identiﬁed FAs in dried material of salmon fish feed, salmon feces and Rhodomonas baltica) is shown in Table 3. A lower total fatty acid content and mono- and polyunsaturated FAs, and a higher content of saturated fatty acids in feces than in ﬁsh feed, indicated a poorer nutrient quality for feces.

Out of 22 identiﬁed fatty acids in the digestive gland samples at Day 28, the 18:1 (n − 9) was the only one that had increased more in mussels fed FD + RB and FC + RB than in mussels fed RB (from 1.6% at Day 0 to 7.1, 2.2 and 1.5% at Day 28, respectively) (p < 0.05) (Table 2A). The more pronounced increase of this acid in mussels fed FD + RB compared to FC + RB (p < 0.05) reﬂected the higher content of 18:1 (n − 9) in salmon fish feed (26%) than in salmon feces (11%), while Rhodomonas baltica contained only 2% (Fig. 6D).

There was also a signiﬁcant increase in 20:1 (n − 9) in mussels fed FD + RB (2.2 to 3.3% of total FA) (p < 0.05), while no changes were obtained for mussels fed FC + RB, despite this FA making a larger contribution to the proﬁle in the feces (3.2%) than in the feed (2.5%). 20:1 (n − 9) was not present in Rhodomonas baltica. There were no signiﬁcant contributions of other fatty acids in mussels fed FC + RB that could reﬂect changes in the direction of the feces proﬁle, e.g. 16:0, 18:3 (n − 6) and 22:1 (n − 11).

At Day 28, the four fatty acids 16:0, 18:3 (n − 3), 20:5 (n − 3) (eicosapentaenoic acid, EPA) and 22:6 (n − 3) (docosahexaenoic acid, DHA) contributed to 58.3, 56.8 and 62.2% of the digestive composition.
gland tissue FAs for mussels fed RB, FD + RB and FC + RB, respectively. The relative concentration of 18:3 (n − 3) increased significantly for all treatments from Day 0 (3.3% of total FA) to Day 28, though more in mussels fed RB (11.1% of total FA) and FD + RB (7.3%) than in mussels fed FC + RB (6.2%). The *R. baltica* contained 24.4% 18:3 (n − 3). The same tendency was indicated for 18:2 (n − 6), which increased more in the digestive gland samples of mussels fed FD + RB compared to mussels fed FC + RB (p < 0.05). The increases, however, were not significantly higher than in samples of mussels fed RB, reflecting the high contribution of 18:2 (n − 6) to the profile in both *R. baltica* (15.7%) and salmon fish feed (7.9%). The salmon feces did not contain 18:2 (n − 6).

A significant increase was also evident for 18:4 (n − 3) from Day 0 to Day 28 in the digestive gland samples of mussels fed RB (p < 0.05), thus reflecting the high value in *R. baltica* (15.6%). The fraction of EPA decreased significantly from Day 0 to Day 28 for all treatments (p < 0.05), while no significant differences were identified for DHA despite a decrease from 20.2 to 14.4% of total FA for mussels.

![Graph](image)

**Fig. 4.** Principal component analysis of fatty acid profiles in: A) digestive gland, B) mantle and C) gill tissue of mussels at Day 0 (S) and fed mixed rations of either salmon fish feed and *R. baltica* (FD + RB), salmon feces and *R. baltica* (FC + RB) or a mono ration of *R. baltica* (RB) for 28 days. The upper panels show the score plot, while the lower panels show the loading plots for the corresponding fatty acid contribution to the score plot. Numbers at the x (PC-1) and y-axis (PC-2) are the percentages of variance in fatty acid profiles explained by principal components 1 and 2. Gender is indicated for male (M) and female (F) mantle tissues. The food supply corresponded to ~5%day⁻¹ of the soft tissue carbon content of the individual mussels.
fed the mono ration of *R. baltica*, which was probably due to large variation among samples.

Through the exposure period there was a significant increase in the total amount of monounsaturated fatty acids (MUFAs) in the digestive gland (14.3 to 20.3% of total FA) and gill (5.5 to 13.3% of total FA) samples, in addition to a significant decrease in polyunsaturated fatty acids (PUFAs) in both the digestive gland (62.9 to 58.9% of total FA) and gill (65.2 to 56.7% of total FA) tissues, which reflected the salmon fish feed signature.

The same pattern of variation in fatty acid composition as for digestive gland tissue was seen for gill tissue (Fig. 6C), in which 18:1 (n−9) and 20:1 (n−9) increased from 0.1 to 4.0% and 4.5 to 5.3% in tissue from mussels fed FD+RB and RB, respectively (*p*<0.05). The increase in 18:1 (n−9) was also significant for mussels fed FC+RB, but not different from that of the mussels fed RB. There was also a significant increase in 18:1 (n−7) in the gill tissue of mussels fed FC+RB at Day 28, although the contribution to the total profile was not significantly higher than in mussels fed RB (*p*<0.05).

Although no significant differences in fatty acid composition were identified in mantle tissue, the general trend of change, e.g. for 18:1 (n−9), 20:1 (n−9), 18:2 (n−6) and 18:3 (n−3), was the same as in the digestive gland and gill tissue. In contrast to the digestive gland and gill tissue, the average fraction of DHA, EPA and PUFA...
3.3. Growth in shell length and soft tissue

A significant growth in length was found for mussels fed RB as well as RB + FD (p < 0.05), whereas no significant growth in length was found for mussels fed the 1/2RB or FC + RB (Fig. 7A). The growth rate in length (AGRL) for FD + RB, FC + RB, RB and 1/2RB measured 0.6, 0.4, 0.8 and 0.3 μm day⁻¹, respectively. The DW was significantly higher for mussels fed RB compared to FD + RB, FC + RB and 1/2RB at the end of the experiment (p < 0.05) (Fig. 7B). This resulted in an SGRDW of 0.24% day⁻¹ for the RB treatment and weight maintenance of mussels fed the FD + RB and the 1/2RB ration (SGRDW = 0.0% day⁻¹), whereas mussels fed FC + RB demonstrated a significantly lower and negative SGRDW (−0.8% day⁻¹) (p < 0.05).

4. Discussion

4.1. Clearance rate and food availability

Mussels cleared salmon fish feed, feces particles and R. baltica with a similar efficiency. A maximum clearance rate (CR) could not be identified, as only one measurement point was obtained in the range where peak CR could be expected. A high CR for both salmon fish feed and feces is consistent with recent studies by MacDonald et al. (2011) and Reid et al. (2010). However, the CR was significantly higher for R. baltica compared to salmon fish feed and feces at the
highest particle concentrations. In previous reports, mussels have shown ~100% retention efficiency (RE) for particles between 4 and 40 μm (Møhlenberg and Riisgård, 1979), 80% RE for particle sizes of 2–5 μm (Vahl, 1972) and ~50% RE for particle sizes of 1.6–2 μm (Lucas et al., 1987; Newell and Shumway, 1993). Accordingly, the higher CR for R. baltica was most likely a result of different particle sizes and also possibly the particle’s shape. However, the fact that the clearance of salmon fish feed and feces ceased at almost the same level (~500 particles ml⁻¹) as for R. baltica reveals support for the mussels being able to clear out salmon fish feed and feces particles with high efficiency. Salmon fish feed and feces concentrations were lowered down to mean particle concentrations of ~350 and ~430 ml⁻¹, indicating that this is close to the threshold level for the clearance of these particles in M. edulis, while R. baltica was depleted to a minimum concentration of ~235 cells ml⁻¹ (equivalent to 0.18 μg Chl a l⁻¹, Clausen and Riisgård, 1996). The obtained minimum concentration of R. baltica to sustain filtration activity in M. edulis of 40 mm length was lower than previously reported for this microalgae (~630 cells ml⁻¹) (Riisgard et al., 2003), although the result is consistent with Strohmeier et al. (2009), who demonstrated that M. edulis is capable of clearing particles out of suspension at such and even lower Chl a concentrations (down to 0.01 μg Chl a l⁻¹).

A mussel diet consisting of 50% of R. baltica and 50% particulate organic carbon (POC) from either salmon fish feed or feces has a relatively high non-algal organic content. It has been hypothesized that farm wastes will impact positively only if overall seston concentrations are low (Trolle and Norberg, 1998), e.g. in late autumn and winter in cool temperate North Atlantic waters. It is therefore important to study feed incorporation and growth with relatively low food availability combined with a high content of salmon farm wastes to investigate the possibilities of mussels to perform bioaugmentative services under realistic environmental conditions. Particle densities in the experimental trays were adjusted to the lower range of that which supported the highest CR, leaving mussels with just high enough particle densities to maintain a high CR. However, although particle concentrations appeared to be high enough to sustain active feeding, this was only reflected in the growth of mussels fed R. baltica and salmon fish feed, while in contrast, no response was seen for mussels fed salmon feces.

4.2. Incorporation of food components

For the digestive gland and gill tissue samples, the principal component analysis identified a clearer pattern separating Day 28 from Day 0 samples according to a decrease in the fraction of EPA and DHA in combination with the incorporation of single fatty acids recognizable from the various food sources. For the digestive gland tissue in particular, the loading plot identified the fraction of 18:1 (n-9) and 18:3 (n-3) as being the fatty acids most responsible for the difference between mussels fed salmon feed and R. baltica (FD+RB) and the monodiet of R. baltica (RB). 20:1 (n-9) and 18:2 (n-6) separated Day 28 samples of mussels fed FD+RB from mussels fed salmon feces and R. baltica (FC+RB) and FD+RB and FC+RB samples from Day 0 samples, respectively, indicating some incorporation of R. baltica (18:2 n-6) and salmon feces (20:1 n-9) after 28 days of exposure. The same pattern was found for gill tissue, except that 16:0 was identified as being the primary fatty acid responsible for the difference between mussels fed FD+RB and FC+RB compared to mussels fed RD and to Day 0 samples.

The significant time-related increase in total fatty acid content reflecting the total lipids in the digestive gland tissue of mussels fed FD+RB (6.1 to 9.5%) indicates that salmon fish feed was filtered and assimilated, while in contrast, no significant increases were found for the fatty acid content in the mantle or gill tissue. Incorporation time is related to the metabolic activity (Paulet et al., 2006), and tissues with high turnover rates are likely to accomplish a short-term ration change, whereas tissues with a low turnover rate will better reflect the long-term feeding history in bivalves (Lorrain et al., 2002; Piola et al., 2006). For example, mantle tissue has previously been shown to significantly alter fatty acid content and composition in the direction of the feed source first after more than 90 days of exposure (Fukumori et al., 2008; Post, 2002). The present results support the idea that the digestive gland tissue has a faster turnover rate than the mantle tissue in blue mussels, which is in agreement with Narváez et al. (2008) and Redmond et al. (2010) and similar studies of scallops (Pecten maximus) (Malet et al., 2007), while the missing response in the mantle tissue is in agreement with recently reported results for blue mussels (Redmond et al., 2010) and green mussels (Perna viridis) (Shin et al., 2008). In mussels fed FC+RB or RB, no changes were found in the fatty acid content of any of the three tissues. This was as expected, considering that the fatty acid content in feces (5.7%) and R. baltica (5.8%) was significantly lower than in salmon fish feed (26%).

The more pronounced changes in the mussels’ fatty acid composition in the direction of the salmon fish feed, as compared to the salmon feces profile, suggest that mussels were more capable of accumulating salmon fish feed than salmon feces. However, the fact that 18:1 (n-9) increased in the digestive gland tissue of mussels fed...
both FD + RB and FC + RB (from 1.6 to 7.1% and 2.2%, respectively) nevertheless suggests that the mussels also incorporated some of the salmon feces fraction. The more pronounced increase of 18:1 (n−9) in mussels fed FD + RB compared to FC + RB was most likely caused by a combination of a higher content in salmon fish feed (25.8%) than in salmon feces (11%), in addition to a more efficient incorporation and utilization of salmon fish feed, which was in agreement with the length and DW results.

By contrast, an increase in 20:1 (n−9) was only evident for mussels fed FD + RB, while no changes were found in the direction of the food source for mussels fed FD + RB despite a higher contribution of this fatty acid in feces than in the feed, further indicating that mussels were not able to utilize feces as efficiently as salmon fish feed. Furthermore, no increase was found for 18:2 (n−6) in the direction of the content in feces, although this fatty acid was only found in feces and could therefore be a possible tracer of this food source, or in 22:1 (n−9), which accounted for a larger share of the fatty acid composition in feces than in salmon fish feed.

18:3 (n−3) increased significantly in the digestive gland tissue for all treatments from Day 0 to Day 28. This increase was more pronounced in mussels fed RB and FD + RB than in mussels fed FC + RB, again suggesting a higher feeding activity for mussels fed salmon fish feed than in mussels fed feces. *R. baltica* contained a high percentage of 18:3 (n−3) (24.4% of total FA), while salmon fish feed and feces contained 4% and 1.2%, respectively, meaning that the change in this fatty acid will reflect the feeding activity upon *R. baltica*. The same tendency was seen for 18:2 (n−6), which increased more in the digestive gland samples of mussels fed FC + RB than in mussels fed FC + RB. However, as found for 18:1 (n−9), there was also a significant increase in 18:2 (n−6) in the digestive gland tissue of mussels fed FC + RB, indicating some feeding upon *R. baltica* since the feces did not contain 18:2 (n−6).

The same pattern of variation that was seen for the digestive gland tissue was, surprisingly, since the gill tissue was expected to be more conservative than the mantle tissue, also seen for 18:1 (n−9) and 18:2 (n−6) in the digestive gland tissue of mussels fed FC + RB, which was in agreement with the length and DW results.

### Table 2

<table>
<thead>
<tr>
<th>Total fatty acid content (mg FA g DW−1) and fatty acid composition (% of total FA) of:</th>
<th>A) digestive gland</th>
<th>B) Mantle</th>
<th>C) Gill</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Food</strong></td>
<td><strong>Day 0</strong></td>
<td><strong>Day 28</strong></td>
<td><strong>RA</strong></td>
</tr>
<tr>
<td><strong>Food</strong></td>
<td><strong>RA</strong></td>
<td><strong>FD + RB</strong></td>
<td><strong>FC + RB</strong></td>
</tr>
<tr>
<td><strong>Total FA (mg g DW−1)</strong></td>
<td>53.8 ± 5.7</td>
<td>35.4 ± 4.7</td>
<td>47.2 ± 10.5</td>
</tr>
<tr>
<td><strong>% of total FA</strong></td>
<td>14:0</td>
<td>2.1 ± 0.5</td>
<td>1.8 ± 0.4</td>
</tr>
<tr>
<td>16:0</td>
<td>23.8 ± 1.4</td>
<td>19.5 ± 0.8</td>
<td>22.2 ± 0.7</td>
</tr>
<tr>
<td>18:0</td>
<td>5.3 ± 1</td>
<td>4.9 ± 0.6</td>
<td>5.6 ± 0.9</td>
</tr>
<tr>
<td>ΣSFA</td>
<td>31.3 ± 1.8</td>
<td>26.3 ± 0.6</td>
<td>28.8 ± 1.0</td>
</tr>
<tr>
<td>16:1 (n−7)</td>
<td>6.9 ± 2.1</td>
<td>3.7 ± 1.3</td>
<td>4.7 ± 1.5</td>
</tr>
<tr>
<td>18:1 (n−9)</td>
<td>1.5 ± 0.1b</td>
<td>1.9 ± 0.3b</td>
<td>1.0 ± 0.1a</td>
</tr>
<tr>
<td>20:1 (n−7)</td>
<td>5.0 ± 0.6</td>
<td>5.0 ± 0.5</td>
<td>5.0 ± 0.6</td>
</tr>
<tr>
<td>20:2 (n−6)</td>
<td>1.5 ± 0.1b</td>
<td>1.9 ± 0.3b</td>
<td>1.0 ± 0.1a</td>
</tr>
<tr>
<td>20:3 (n−6)</td>
<td>1.2 ± 0.2</td>
<td>0.2 ± 0.1</td>
<td>2.0 ± 0.2</td>
</tr>
<tr>
<td>20:4 (n−6)</td>
<td>3.5 ± 0.2b</td>
<td>2.9 ± 0.4b</td>
<td>2.7 ± 0.2a</td>
</tr>
<tr>
<td>22:5 (n−6)</td>
<td>0.9 ± 0.1a</td>
<td>0.5 ± 0.2</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>ΣPUFA</td>
<td>62.9 ± 6.0b</td>
<td>62.9 ± 11.9b</td>
<td>58.9 ± 0.8b</td>
</tr>
</tbody>
</table>

*SFA = saturated fatty acids (FA), MUFA = monounsaturated FA and PUFA = polyunsaturated FA.*
The RB diet resulted in an average length increase of ~33 μm for mussels fed FC+RB or for the 1/2RB. The results suggest a poorer food quality compared to mussels fed FC+RB (12 μm day⁻¹) in the coastal areas of Central Norway (Handå et al., 2011). The average growth in length for mussels fed FD+RB (25 μm day⁻¹) was twice as high compared to mussels fed FC + RB (12 μm day⁻¹), supporting the notion that mussels were able to utilize salmon fish feed particles more efficiently for growth than salmon feces.

Plant oils are typically depleted in n-3 PUFA when compared to marine sources (Menoyo et al., 2007), therefore leaving salmon fish feed pellets with a high inclusion of terrestrial oils to accordingly contain high concentrations of MUFA. For example, the content of MUFA and PUFA in the salmon fish feed used in these experiments was 41% and 34% of total FA compared to 5% and 73% in R. baltica. Salmon feces contained 25% MUFA and as little as 10% PUFA, indicating a poor nutrient quality for feces that was reflected in the restricted or absent growth response obtained for this treatment. Mussels fed salmon fish feed and R. baltica increased their total amount of MUFA in the digestive gland (14.3 to 20.3% of total FA) and gill tissue (5.5 to 13.3% of total FA), and a significant decrease was found in PUFA, reflecting the salmon fish feed composition.

**4.3. Growth in length and soft tissue**

Although constituting only a 2% increase and being somewhat lower than expected under the experimental conditions provided, a significant growth in length was found for mussels fed RB and FD + RB, whereas no significant growth was found for mussels fed FC + RB or for the 1/2RB. The results suggest a poorer food quality for mussels fed salmon feces compared to salmon fish feed particles. The RB diet resulted in an average length increase of ~33 μm day⁻¹. By comparison, this is in the lower range compared with previously reported growth for farmed mussels of similar length (~38–65 μm day⁻¹) under natural conditions from March to October in the coastal areas of Central Norway (Handå et al., 2011). The average growth in length for mussels fed FD + RB (25 μm day⁻¹) was twice as high compared to mussels fed FC + RB (12 μm day⁻¹), supporting the notion that mussels were able to utilize salmon fish feed particles more efficiently for growth than salmon feces.

Standardized soft tissue dry weight (DW') increased in mussels fed RB, while a maintenance was evident in mussels fed FD + RB and in mussels fed the 1/2RB, thereby suggesting that the 1/2RB ration given was sufficient to sustain the DW'. Although the growth responses were low, the significant lower growth in length and a decrease in DW' for mussels fed feces while mussels fed salmon feed grew in length and maintained their DW' suggested that mussels fed the FD + RB were more able to utilize the food, at least the RB part as this was equal to the 1/2RB ration which was sufficient to sustain the mussels DW'.

The daily food supply rate set at ~5% of the carbon content of soft tissues was chosen based on an estimated temperature-dependent POC requirement between ~2.9% and ~8.2% of soft tissue carbon content for a 0–0.5% daily growth at 7 °C and 14 °C, respectively, found in mussels from the same population during early summer (June–July) (Handå et al., 2012).

The increase in DW' of 0.8 mg (0.33 mg POC)day⁻¹, accounted for 10% of the food ration POC (6.6 mg ind⁻¹ day⁻¹) and constituted a daily growth rate of 0.24%. Although being somewhat low this is within the expected range with this food ration at 10 °C. The following two priorities were made for the present study: 1) relatively large mussels were chosen to ensure a sufficient tissue mass for fatty acid analysis of the gill and mantle tissues, and 2) a relatively low feed ration was chosen to run a realistic trial concerning the typical low seston environments in cool temperate North Atlantic coastal waters after the spring bloom. Weight maintenance, though no net growth in mussels fed FD + RB, did not indicate any significant utilization of salmon fish feed. Nonetheless, weight maintenance in combination with a significant growth in length suggested that mussels were

![Figure 6. Contribution of selected fatty acids (mean ± se, n = 5) to the total fatty acid content in: A) digestive gland, B) mantle and C) gill tissue of mussels at Day 0 and fed mixed rations of either salmon fish feed and R. baltica (FD+RB), salmon feces and R. baltica (FC+RB) or a mono ration of R. baltica (RB) for 28 days. The food supply corresponded to ~53 day⁻¹ of the soft tissue carbon content of the individual mussels; D) content of selected fatty acids in R. baltica, salmon fish feed and feces (mean ± se, n = 5). Upper and lower case letters and numbers denote significant differences between treatments for each fatty acid and the MUFA's (p < 0.05).](image-url)
more capable of utilizing salmon fish feed than salmon feces particulates for growth.

A growth in L and DW’ was significantly higher for mussels fed RB and FD + RB than in those fed FC + RB despite the high CR for all food types. By comparison, a lower C, N and lipid content in feces compared to salmon fish feed can presumably explain the poor growth responses to feces. Moreover, though feed rations were prepared to supply the same amount of POC for all types of food, it is speculated that the poor growth could be attributed to a lower nutrient value of salmon feces compared to salmon fish feed, as well as possible nutritional limitations in mussels fed FC + RB.

**Table 3**

<table>
<thead>
<tr>
<th>FA</th>
<th>Feeds</th>
<th>FD</th>
<th>FC</th>
<th>RB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total FA (mg g DW')</td>
<td>254.2 ± 4.9</td>
<td>52.9 ± 1.1</td>
<td>56.4 ± 2.8</td>
<td></td>
</tr>
<tr>
<td>% of total FA</td>
<td>14:0</td>
<td>5.9 ± 0</td>
<td>5.6 ± 0</td>
<td>10.4 ± 0.1</td>
</tr>
<tr>
<td>16:0</td>
<td>15.7 ± 0.4</td>
<td>37.6 ± 0.4</td>
<td>10.5 ± 0.8</td>
<td></td>
</tr>
<tr>
<td>18:0</td>
<td>2.7 ± 0.4</td>
<td>20.3 ± 0.4</td>
<td>0.5 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>20:0</td>
<td>0.3 ± 0.1</td>
<td>0.9 ± 0.1</td>
<td>0 ± 0</td>
<td></td>
</tr>
<tr>
<td>22:0</td>
<td>0.1 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>0 ± 0</td>
<td></td>
</tr>
<tr>
<td>∑SFA</td>
<td>24.7 ± 0.8</td>
<td>64.8 ± 0.8</td>
<td>21.3 ± 0.7</td>
<td></td>
</tr>
<tr>
<td>16:1 (n–7)</td>
<td>6.3 ± 0.1</td>
<td>15.1 ± 0.1</td>
<td>0.7 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>18:1 (n–9)</td>
<td>25.8 ± 0.3</td>
<td>11.0 ± 0.3</td>
<td>1.9 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>18:3 (n–7)</td>
<td>3 ± 0.1</td>
<td>15.2 ± 0.1</td>
<td>2.6 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>20:1 (n–9)</td>
<td>2.5 ± 0.2</td>
<td>3.2 ± 0.2</td>
<td>0 ± 0</td>
<td></td>
</tr>
<tr>
<td>22:1 (n–11)</td>
<td>2.7 ± 0.1</td>
<td>5.5 ± 0.1</td>
<td>0 ± 0</td>
<td></td>
</tr>
<tr>
<td>22:1 (n–9)</td>
<td>0.3 ± 0.1</td>
<td>0.8 ± 0.1</td>
<td>0 ± 0</td>
<td></td>
</tr>
<tr>
<td>∑MUFA</td>
<td>40.9 ± 0.4</td>
<td>24.9 ± 0.4</td>
<td>5.1 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>18:3 (n–3)</td>
<td>3.4 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>24.4 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>18:4 (n–3)</td>
<td>1.9 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>15.6 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>20:4 (n–3)</td>
<td>0.5 ± 0.1</td>
<td>0 ± 0</td>
<td>0.4 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>20:5 (n–3)</td>
<td>9.9 ± 0.1</td>
<td>16.1 ± 0.1</td>
<td>7.4 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>22:5 (n–3)</td>
<td>1.3 ± 0.1</td>
<td>0 ± 0</td>
<td>0.2 ± 0.0</td>
<td></td>
</tr>
<tr>
<td>22:6 (n–3)</td>
<td>7.8 ± 0.1</td>
<td>2.5 ± 0.1</td>
<td>7.6 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>18:2 (n–6)</td>
<td>7.9 ± 0.1</td>
<td>0 ± 0</td>
<td>15.7 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>18:3 (n–6)</td>
<td>0 ± 0</td>
<td>4.8 ± 0.1</td>
<td>0 ± 0</td>
<td></td>
</tr>
<tr>
<td>20:2 (n–6)</td>
<td>0.2 ± 0.1</td>
<td>0 ± 0</td>
<td>0.1 ± 0.0</td>
<td></td>
</tr>
<tr>
<td>20:3 (n–6)</td>
<td>0 ± 0</td>
<td>0 ± 0</td>
<td>0.1 ± 0.0</td>
<td></td>
</tr>
<tr>
<td>20:4 (n–6)</td>
<td>0.6 ± 0.1</td>
<td>0 ± 0</td>
<td>1.6 ± 0.0</td>
<td></td>
</tr>
<tr>
<td>22:5 (n–6)</td>
<td>0.2 ± 0.1</td>
<td>0 ± 0</td>
<td>0.3 ± 0.0</td>
<td></td>
</tr>
<tr>
<td>∑PUFA</td>
<td>34.3 ± 0.5</td>
<td>103.2 ± 0.5</td>
<td>73.3 ± 1</td>
<td></td>
</tr>
</tbody>
</table>

SFA = saturated fatty acids (FA), MUFA = monounsaturated FA and PUFA = polyunsaturated FA.

**4.4. Implications for integrated multi-trophic aquaculture in cool-temperate North Atlantic waters**

In cool-temperate North Atlantic coastal waters as in Norway the mussels food availability is scarce most of the year except for a short period when a high concentration of phytoplankton is present during the spring bloom. The identification of incorporation of components of salmon fish feed and/or feces in such low salinity environments is therefore a prerequisite to elucidate the potential for growing bivalves in integration with salmon farming in these waters. In a study by Strohmeier et al. (2009), it was demonstrated that M. edulis is capable of clearing particles out of suspension at Chl a concentrations down to 0.01 μg Chl a L−1, suggesting that mussels can maintain their filtering activity also at low phytoplankton concentrations in winter, thereby also possibly maintaining bioremediative services on fish farm wastes. This assumption is supported by Handå et al. (accepted for publication) who demonstrated a higher soft tissue weight of mussels kept in close proximity to a salmon farm compared to that of control mussels in a Norwegian coastal area 5 months during autumn and winter when ambient food availability was measured as Chl a was low. The results from the present study indicate that mussels are able to utilize components of salmon fish feed particles more efficiently than salmon feces for growth. On a single-farm scale, the bio-remediative capacities of blue mussels must be considered when taking this into account. On a regional scale, mussels can still contribute to remove a part the nutrients supplied to, e.g. a fjord system, by filtering out phytoplankton that has accumulated anthropogenic N from fish farming. In any case one has to also take the seasonality of the mussels nutrient removal and biodeposit rates into account (see Newell 2004 and the references therein). Deposit rates of e.g. nitrogen have been estimated at equal amounts to that of the harvested biomass from mussel farms (Lindahl et al., 2005).

The waste particulate food source for mussels to feed on in IMTA with salmon has been seen as the particulate part of all nutrient wastes. Given that mussels will utilize feed particles more efficiently than feces, and that feed wastes probably account for less than 5% of the feed use in modern cage aquaculture of salmon (Mente et al., 2006), the possibility of using mussels for nutrient regeneration and bio-remediating services in IMTA has to be reconsidered. In contrast, the largest salmon farms are currently producing 12,000 t of fish, with a corresponding feed use of 13,800 t (feed conversion ratio = 1.15) and a theoretical 5% feed loss constituting 690 t of particles or 345 t POC from a single farm as a result of crushing of feed pellets and decomposition of pellets after reaching the water. In addition,
although salmon feces seems to be a poor food source for mussels, there is still a chance that the feces can be filtered out and removed together with other food particles. In any case, too little is known about size distribution and how the fraction of particulate wastes from salmon farms in ambient seston varies with, e.g. season, current velocity, salmon biomass and production cycle, to make any valid estimates of assimilating capacities of mussels in integrated production with salmon. Nonetheless, another aspect well worth investigating is the potential of mussels to feed on particulate organic matter (eroded frond tissue) from seaweed [Duggins and Eckman, 1997; Duggins et al., 1989], which together with salmon fish feed and feces, can make up a major food source for mussels to feed on in IMTA.

5. Conclusions

The results suggested that mussels are more capable of incorporating components of salmon feed than salmon feces particulates into soft tissues. This can be concluded based on the more pronounced changes in mussels’ fatty acid composition in the direction of the salmon fish feed compared to the salmon feces profile, which was accompanied by a better growth in length and soft tissue dry weight response in mussels fed mixed rations of salmon fish feed and R. baltica compared to salmon feces and R. baltica. A similar clearance rate of fish feed and feces, as well as indications that mussels incorporated some of the salmon feces fraction, suggested that mussels can also clear salmon feces from suspension. These results are important considering the potential of blue mussels to perform bioresource services on particulate nutrient wastes from salmon cage aquaculture.

Acknowledgments

The work was part of the Research Council of Norway project no. 173527 (INTEGRATE). We are grateful to Kjersti Rennan at the Norwegian University of Science and Technology (NTNU) for her assistance. Financial support was received from the Norwegian University of Science and Technology (NTNU) for her pension. These results are important considering the potential of blue mussels to incorporate some of the salmon feces and salmon fish feed into their tissues. This can be concluded based on the more pronounced changes in mussels’ fatty acid composition in the direction of the salmon fish feed compared to the salmon feces profile, which was accompanied by a better growth in length and soft tissue dry weight response in mussels fed mixed rations of salmon fish feed and R. baltica compared to salmon feces and R. baltica. A similar clearance rate of fish feed and feces, as well as indications that mussels incorporated some of the salmon feces fraction, suggested that mussels can also clear salmon feces from suspension. These results are important considering the potential of blue mussels to perform bioresource services on particulate nutrient wastes from salmon cage aquaculture.

References

MacDonald, B.A., Robinson, S.M.C., Barrington, K.A., 2011. Feeding activity of mussels (Mytilus edulis) held in a mixed polluted-mussel aquaculture (IMTA) site (Salmo salar) and exposed to fish feed in the laboratory. Aquaculture 314, 244–251.


