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Impact of deep-water fish farms on benthic macrofauna communities under different hydrodynamic conditions

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ABSTRACT

In this study the environmental impacts of two fish farms located over deep water (180–190 m) were compared. MC-Farm was located at a site with slightly higher water currents (mean current speed 3–5 cm s^{-1}) than LC-farm (<2 cm s^{-1}). Macrofauna composition, bioirrigation and benthic fluxes (CO_2 and NH_4^+) were quantified at different stages of the production cycle, revealing very different impact of the two farms. Macrofauna abundance and bioirrigation were stimulated compared to a non-impacted reference site at MC-farm, while macrofauna diversity was only moderately reduced. In contrast, macrofauna communities and related parameters were severely impoverished at LC-Farm. This study suggests that deep-water fish farms should not be sited in low current areas (<2 cm s^{-1}), since this will hamper waste dispersal and aggravate environmental impacts. On the other hand, fish farming at slightly more dynamic sites can lead to stimulated benthic macrofauna communities and only moderate environmental impacts.

1. Introduction

Finfish aquaculture is increasing worldwide, accounting for an increasing percentage of global fish consumption (e.g., in 2012 production was 67 million metric tons y^{-1} corresponding to 42% of total capture fisheries; FAO, 2014). Research to increase sustainable management of the fish farming industry is therefore more relevant now than ever. Aquaculture in Norway has followed global trends and total production of finfish (primarily salmonids) has tripled since 1999 to 1.3 billion kg y^{-1} in 2012 (Taranger et al., 2015). During the same time, the number of fish farms has decreased, while the size of individual fish farms has increased, and hence, the total organic waste emission of individual farms has also increased. Fish farms are therefore moved to deeper and more exposed sites in the deep Norwegian fjords, in order to facilitate greater dispersal of organic waste and mitigate negative environmental impacts (Gullestad et al., 2011). Nevertheless there is a lack of studies documenting the environmental impact of deep-water fish farms, supporting or dismissing this practice as a management tool.

One of the main environmental issues with fish farms at both shallow and deep farming locations is the emissions of large quantities of labile organic waste consisting of excess feed and faecal matter. The organic waste settles on the seafloor, stimulates sediment associated microbial communities and leads to progressively stimulated sediment O_2 consumption and microbial sulfate reduction (Holmer and Kristensen, 1992; Valdemarsen et al., 2010) over a wide range of sedimentation rates (Findlay and Watling, 1997). Above a certain sedimentation threshold sediments turn completely anoxic and hydrogen sulfide – a by-product of microbial sulfate reduction – accumulates to toxic levels (Valdemarsen et al., 2009, 2010). Benthic fauna is highly sensitive to hypoxia and hydrogen sulfide, and fish farming is therefore frequently associated with negative impacts on benthic fauna. Sensitive species are affected at relatively low levels of organic enrichment, whereas a few pollution tolerant opportunists may survive even extreme levels of organic enrichment (Pearson and Rosenberg, 1978; Hargrave, 2010).

Benthic macrofauna is critical for the assimilative capacity and functioning of benthic ecosystems. Macrofauna stimulate the capacity for organic matter degradation either directly through ingestion/assimilation or indirectly through bioturbation activities and related stimulation of microbial degradation processes (Kristensen et al., 2012). Bioturbation includes sediment reworking, whereby particles (e.g., organic waste) are re-distributed vertically within the sediment matrix (Gilbert et al., 2007; Quintana et al., 2007; Wendelboe et al., 2013), and bioirrigation, which is enhanced advective porewater flow induced by macrofauna ventilating their burrows (Martin and Banta, 1992; Heilskov et al., 2006). The relative intensity of these two processes is strongly dependent on species composition and is intrinsically linked to important ecosystem functions such as nutrient cycling and organic matter degradation rates (Valdemarsen et al., 2010; Quintana et al., 2013;

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Kristensen et al., 2014). The impact of fish farms and organic enrichment on benthic macrofauna community composition (diversity, richness etc.) is relatively well described (e.g., Pearson and Rosenberg, 1978; Hyland et al., 2005; Hargrave, 2010), whereas there are only few studies concerning the ecological implications of impoverished macrofauna beneath fish farms.

Particulate fish farm waste settles with rates of 4–10 cm s^{-1} (Cromey et al., 2002; Chen et al., 2003) and horizontal dispersion at deep-water farming locations should be enhanced several-fold when compared to shallow water farming locations, due to the longer settling time (Findlay et al., 1995; Mayor et al., 2010; Nordi et al., 2011). Reduction of area specific organic matter loadings is therefore an important argument for moving fish farms to deeper and more exposed locations. One of the few available studies of deep-water fish farms shows that only moderate water currents (<20 cm s^{-1}) are needed to facilitate far field dispersal (>250 m) of particulate waste (Kutti et al., 2007a). The enhanced dispersal lowers the area specific environmental impact to a level where impacted but diverse benthic fauna communities can persist despite high waste emissions from the farm above (Kutti et al., 2007b; Bannister et al., 2014). Fish farms located at deep water are not always associated with minor environmental impact, however, as documented in Valdemarsen et al. (2012), who found severely deteriorated sediment conditions under a highly productive fish farm located at 190 m depth. The severity of environmental impacts beneath deep-water fish farms thus appears to be delicately controlled by hydrodynamics, as water current regimes did not differ much between study sites in the aforementioned studies (Kutti et al., 2007a; Valdemarsen et al., 2012; Bannister et al., 2014).

In this study we explore the benthic impact of two deep-water fish farms with similar fish production/waste emission but located under slightly different hydrodynamic conditions. Benthic impacts were measured at different stages of the production cycle and temporal developments in benthic communities were evaluated. Changes in benthic macrofauna was partly described by conventional parameters (abundance, diversity, richness), but also by measurement of whole community bioirrigation as a proxy for ecological functioning. This comparative approach allowed us to evaluate the importance of hydrodynamics for the environmental impact of deep-water fish farms.

2. Materials and methods

2.1. Study sites and sampling strategy

The two Atlantic salmon (*Salmo salar*) farms compared in this study were located in Hardanger Fjorden, on the west coast of Norway (Husa et al., 2014; Fig. 1). The farms were sampled over an 18 months production cycle in 2010–2011 as part of a larger project aiming to elucidate ecosystem responses to aquaculture at deep water locations. The impact of these individual farms on sediment biogeochemistry was described previously in Valdemarsen et al. (2012) and Bannister et al. (2014) and some of the data from these publications (e.g., sedimentation rates, water currents and benthic fluxes) are included as supporting data here. The two farms are denoted LC-Farm (low current farm) and MC-Farm (moderate current farm), respectively. LC-Farm was located at 190 m water depth at a location where water currents 10 m above the bottom rarely exceeded 2 cm s^{-1}. MC-Farm was located in a more exposed location at 180 m water depth were mean bottom water currents were 3–5 cm s^{-1}, with intermittent periods of >20 cm s^{-1}. The farms were similar with respect to fish production, feed consumption and waste production (Table 1). The LC and MC farms had been in operation in the same positions 8 and 7 years prior to this investigation, respectively. Reference stations (LC-Ref and MC-Ref, respectively) were located 600–700 m from each farm and were similar to farm sites with respect to water depth and currents. Bottom water temperatures were stable at 8–9 °C at all sites, irrespective of season. For more detailed descriptions of the fish farms and details on water current measurements consult Valdemarsen et al. (2012) and Bannister et al. (2014).

Norwegian fish farms have an 18 month farming period followed by a fallowing period of at least 2 months (Hansen et al., 2001). During the 18 months of fish production there is an almost exponential increase in food consumption and waste production. Integrated environmental impacts are therefore strongly dependent on time relative to the production cycle of individual farms. The farm and reference stations were sampled in March, June and September 2010 corresponding to month 7, 9 and 12 of the production cycle at LC-Farm and month 11, 14 and 17 at MC-Farm.

2.2. Sampling procedures

On every sampling occasion six undisturbed box cores (surface area 30 × 35 cm) were collected from every station. At the fish farms, box cores were taken at the edge of the fish cages at the same GPS position during the different samplings. One 10 cm deep sediment core was sampled with an acrylic core liner (30 and 10 cm length and diameter, respectively) from every box core. Every sediment core was closed at the bottom with a rubber stopper and the core-headspace was gently filled with bottom water collected 10 m above the bottom with a Niskin water sampler. Cores were sealed at the top with rubber stoppers and placed in insulated cooler boxes containing bottom water with in situ

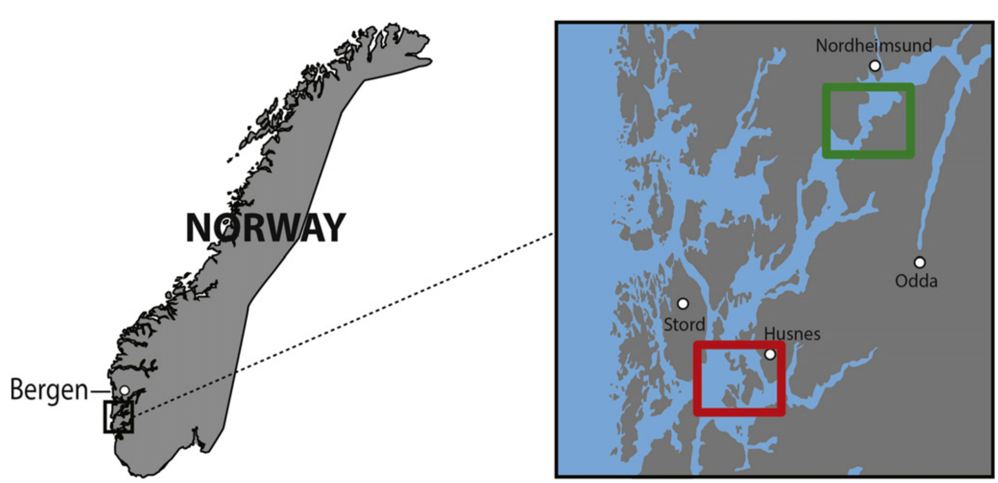

Fig. 1. Maps showing the location of the Hardanger Fjord (left panel) and the specific areas where the two fish farms were located (right panel). Green and red rectangles indicate the locations of the low current sites (LC-Ref and LC-Farm) and moderate current sites (HC-Ref and HC-Farm). For reasons of disclosure the exact position of the two fish farms are not provided.