Journal of Sea Research 132 (2018) 15–23

Contents lists available at ScienceDirect

Journal of Sea Research

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

Identifying the optimal depth for mussel suspended culture in shallow and turbid environments

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ARTICLE INFO

Keywords:
Mussel
Aquaculture
Resuspension
Advection
Dynamic Energy Budget

ABSTRACT

Bivalve aquaculture is commonly carried out in shallow water systems, which are susceptible to resuspension of benthic particulate matter by natural processes such as tidal currents, winds and wave action, as well as human activity. The resuspended material can alter the availability of food particles for cultured bivalves. The effect of resuspended material on bivalve bioenergetics and growth is a function of the quality and concentration of resuspended particles and background diet in the water column. Given the potential for positive or negative impacts on bivalve growth and consequently on farm productivity, farmers must position the cultured biomass at the appropriate depth to benefit from or mitigate the impact of this resuspended material. A combination of field measurements, a 1-D vertical resuspension model and a bioenergetic model for mussels based on Dynamic Energy Budget (DEB) theory has been carried out for a mussel farm in Skive Fjord, a shallow Danish fjord, with the aim of identifying the optimal depth for culture. Observations at the farm location revealed that horizontal advection is more important than vertical resuspension during periods with predominant Eastern winds. In addition, high background seston in the water column reduces the impact of resuspension on the available food for mussels. The simulation of different scenarios in terms of food availability suggested minimal effects of resuspension on mussel growth. Based on this finding and the fact that phytoplankton concentration, the main food source for mussels, is usually higher in the upper part of the water column, suspended culture in the top ~ 3 m of the water column seems to be the optimal practice to produce mussels in Skive Fjord.

1. Introduction

The filtration capacity of bivalves cultivated at high densities can effectively reduce the concentration of particles suspended in the water column, which in turn can lead to a reduction in mussel growth (Fréchette and Grant, 1991). Suspended culture of bivalves is often carried out in shallow waters, in which natural processes such as tidal currents and wave action as well as human activities such as dredging and trawling can cause resuspension of bottom sediments (Grant et al., 1997) and affect local productivity (Sarà, 2009). Bivalves are effectively omnivorous, feeding on microalgae (Bayne et al., 1987; Page and Hubbard, 1987), zooplankton (Davenport et al., 2000; Maar et al., 2008), bacteria (Langdon and Newell, 1990; Kreeger and Newell, 1996), organic detritus (Grant et al., 1997; Safi et al., 2007) and dissolved matter (Manahan et al., 1982; Jørgensen, 1983). However, phytoplankton is usually considered the main food source of bivalves due to the higher absorption efficiency compared to other food sources (e.g. Navarro et al., 1996; Babarro et al., 2003). In fact, mussel growth in inner Danish waters that are not highly affected by resuspended bottom material has been simulated using phytoplankton biomass as the only carbon source (e.g. Larsen et al., 2014; Maar et al., 2015). However, the resuspension of benthic detritus, which tends to be of poor quality compared to planktonic food (Fréchette and Daigle, 2002), potentially dilutes high quality food sources such as phytoplankton (Cranford, 1995). Resuspension can lead to additional pre-ingestive processing costs through pseudofaeces production (Ellis et al., 2002) or to reduction in absorption efficiency (Navarro et al., 1996). The impact of resuspended material on mussel ecophysiology depends on the characteristics and proportion of this material in relation to pelagic suspended material and could be critical for mussel bioenergetics.

One of the key environmental variables that forces resuspension in shallow waters is wave action caused by wind (Prins et al., 1996; Smaal and Haas, 1997; Sarà, 2009). The processes related to vertical transport are strongly associated with the stability of the water column, which depend on factors that promote stratification such as surface heating and estuarine circulation, and opposing mixing factors that include

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https://doi.org/10.1016/j.seares.2017.11.006
Received 11 May 2017; Received in revised form 18 November 2017; Accepted 24 November 2017
Available online 26 November 2017
1385-1101/

tidal mixing, convection, wind stirring and wave stirring. Our study area in the Limfjorden (Denmark) is characterized by shallow depths and frequent resuspension (Lund-Hansen et al., 1999). Wiles et al. (2006) studied the contribution of various factors to water stability measured as the potential energy anomaly (PEA, Simpson and Bowers, 1981) in the Limfjorden during late May-early June 2003. They concluded that the major process promoting stratification was surface heating, which is opposed by stirring due to wind through wave motions. An empirical relationship between water column stability (~PEA) and wind speed was also observed by Maar et al. (2010) in Skive Fjord, one of the inner sounds of the Limfjorden and the experimental site of the present study. The periodic switch between stratified and mixed conditions has been used to explain benthic-pelagic coupling between mussel beds and phytoplankton populations in the Limfjorden and more generally mussel bed productivity (Møhlenberg, 1999; Wiles et al., 2006; Maar et al., 2010).

Benthic-pelagic coupling in the Limfjorden has been commonly studied in relation to bottom mussel culture production (e.g. Dolmer, 2000; Wiles et al., 2006; Maar et al., 2010; Petersen et al., 2013) but to our knowledge there are no studies in which these processes have been investigated in relation to suspended mussel culture, a new cultivation technique in the Limfjorden. Long-line culture had been suggested as an alternative and more sustainable technique to traditional dredging in Limfjorden (Dolmer and Frandsen, 2002) and the first licenses for suspended culture were approved in late 2004 (Dolmer and Geitner, 2004). In the present study, the potential effects of wind-driven resuspended organic material on mussel bioenergetics cultured at different water heights above the seafloor are evaluated following a Dynamic Energy Budget (DEB) approach with the following aims:

- Quantify the potential contribution of resuspended organic material to bivalve growth, and
- Use modelling to determine the potential optimal positioning in the water column for suspended mussel culture.

This use of individual based models as tools to forecast shellfish performance under different environmental conditions is becoming widely accepted (e.g. Thomas et al., 2011) given the potential to evaluate alternative aquaculture scenarios, and their management implications (Nobre et al., 2010; Filgueira et al., 2015). Accordingly, this numerical study should be considered a scoping exercise to a priori identify optimal farming practices, with a posteriori validation of mussel growth required to strengthen the conclusions.

2. Material and methods

2.1. Study area

Skive Fjord (Fig. 1) is an inner branch of Limfjorden, which is a shallow sound connected to the North Sea on the west coast (32–34 PSU) and to the Kattegat (19–25 PSU) on the East coast. Skive Fjord has a surface area of ~49 km^2 and a mean water depth of 4.7 m. It is a partially mixed estuary with stratification occurring on a scale from days to weeks depending on fresh water input, radiation and wind mixing (Møhlenberg, 1999). This locality is characterized as being highly eutrophic with elevated chlorophyll-a concentrations throughout the bivalve growth period and with seasonal hypoxia occurring in late summer (Maar et al., 2010).

A standard commercial long-line unit approximately 250 × 750 m (18.8 ha) divided into 3 sections was placed on the western coast in the central part of Skive Fjord (Fig. 1) at 5–7 m water depth. Each section contained 30 long-lines, each 200 m long, oriented parallel to the coast. The long-lines were kept approx. 0.5–1 m from the sea surface using buoys and ballast to lift and stabilize the lines.

2.2. Fieldwork

A multidisciplinary research was carried out in Skive Fjord during the first two weeks of May 2011 as part of the MuMiHus project (Production of mussels – mitigation and feed for husbandry). Wind speed and direction were collected using a weather station (HOBO Micro Station Logger) located on a floating platform at the farm (Fig. 1). Although the platform was anchored to the seafloor, waves and gusty winds caused slight rotation, introducing uncertainty in wind direction measurements. Therefore, wind direction is considered to provide a general overview of local winds rather than an accurate measurement. Modeled wind speeds for the same area were provided by Karsten Bolding (personal communication) in order to explore the representativeness of our wind data in relation to annual wind patterns. At the center of the farm, a mooring with two SCUFA fluorometers with turbidimeters (Turner Designs) positioned at 1 and 1.7 m above the seafloor and an acoustic FSI 2D–ACM current meter equipped with CTD at 1 m above the seafloor were deployed from 7 until 12 May. Data collected by the SCUFA at 1.7 m was impossible to retrieve, probably due to a battery malfunction. Discrete water samples for chlorophyll *a* concentration (μg l^{-1}) and particulate matter (mg l^{-1}) were also collected at 1 m and 1.7 m above the seafloor as well as at 1 m from the sea surface on two consecutive days characterized by different wind speed: 9 and 10 May with low and high winds, respectively. These water samples were collected using a series of siphons attached to the mooring in order to guarantee that the height above the seafloor of sample collection was accurate. The siphons consisted of small tubes through which water was pumped at low rates in order to minimize the impact on water column structure (See Fig. 2 in Petersen et al., 2013 for a detailed description).

Regular monitoring was carried out as part of the MuMiHus project, covering June 2010 until June 2011 at weekly/bi-weekly frequency. At a station in the center of the farm, but not surrounded by longlines,

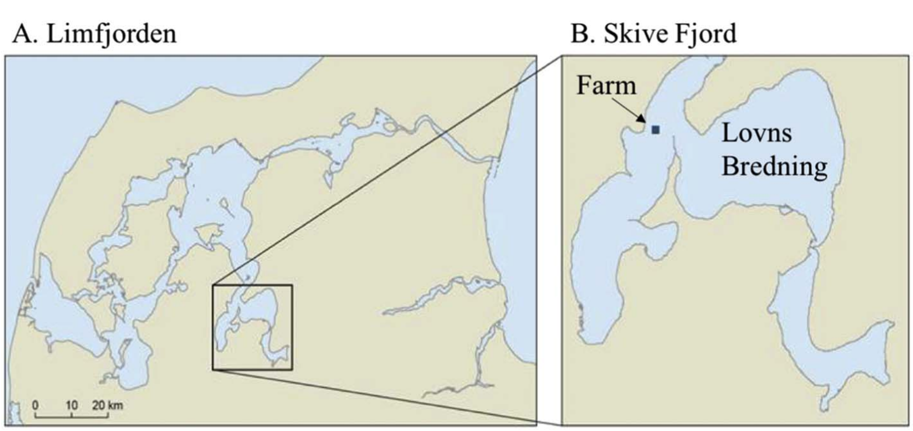

Fig. 1. (A) Position of Skive Fjord within the Limfjorden, and (B) position of the farm within Skive Fjord.