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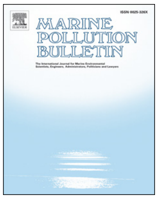

Investigation of broad scale implementation of integrated multitrophic aquaculture using a 3D model of an estuary

Scott Hadley[a,*], Karen Wild-Allen[b], Craig Johnson[a], Catriona Macleod[a]

[a] Institute for Marine and Antarctic Studies, University of Tasmania, Private Bag 129, Hobart, Tasmania 7001, Australia
[b] CSIRO Oceans & Atmosphere, GPO Box1538, Hobart, Tasmania 7001, Australia

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ABSTRACT

A 3D ecosystem model was used to quantify changes in water quality brought about by salmon aquaculture in the D'Entrecasteaux Channel and Huon Estuary in southeast Tasmania. Macroalgae-based integrated multi-trophic aquaculture (IMTA) was simulated and showed that IMTA is capable of reducing the increased chlorophyll concentration attributable to fish farming by up to 10–15% in large areas of the region, during the season of highest production. Kelp farms (*Macrocystis pyrifera*) recovered between 6 and 11% of the dissolved inorganic nitrogen (DIN) input by salmon aquaculture over a nine month period, with DIN remediation increasing linearly with farm size. Under a ten-fold increase in aquaculture to very high loads, a much lower remediation effect was found for both chlorophyll and DIN. Model results indicate that IMTA could have an important impact on reducing negative effects of finfish aquaculture on water quality providing that stocking rates are not too high.

1. Introduction

Nutrient enrichment of coastal water by waste output from finfish aquaculture can lead to ecosystem changes (Buschmann et al., 2009; Jiang et al., 2010; Price et al., 2015; Wild-Allen et al., 2010). Aquaculture is a growing industry with global production in 2012 of 66 million tonnes of food fish, including a contribution from Australia of 80 thousand tonnes (FAO, 2014). Coastal finfish aquaculture uses open cages as they are easily assembled and allow waste dispersal into surrounding water, thus reducing costs (Bostock et al., 2010). However, inshore aquaculture operations are often sited in sheltered waterways and estuaries with restricted water movement relative to the open coastline, and in areas of high biological diversity. Cloern (2001) highlighted the variability in the responses of coastal ecosystems to nutrification, where biological and chemical 'filters', flow regimes, bathymetry, light conditions, and optical properties of the water column interact to determine system responses to nutrification from anthropogenic inputs. Without knowledge of the system response it is particularly difficult to manage industries that introduce bio-reactive nutrient-rich waste as a byproduct. For dissolved nutrients subject to advection and diffusion, the system wide effects can be particularly difficult to quantify without the use of longitudinal studies from purpose designed monitoring systems. Several studies have recommended further research is needed to determine the risk of adverse interactions between finfish aquaculture farms and the environment and to identify potential management responses (Buschmann et al., 2009; Creighton et al., 2016; Eng et al., 1989; Price et al., 2015; Wu, 1995). From the perspective of the aquaculture operators, the failure to undertake such research could lead to stagnation of an industry, as seen in Europe, due to social conflict arising partly through lack of understanding of impacts and/or poor capacity to manage them (Ertor and Ortega-Cerda, 2015).

While it makes good economic sense for farmers to minimize waste feed output, finfish respire ammonium and excrete faeces and so in an open cage system waste output into the surrounding water is unavoidable. Consequently, the ability of an ecosystem to assimilate wastes will be the primary determinant of the carrying capacity of a water body. Models for waste output of dissolved inorganic nitrogen (DIN) (Islam, 2005; Wang et al., 2012) suggest that as much as 65% of total feed derived nitrogen can be returned to the water column, with up to 85% of this quantity in dissolved form. For this reason, integrated multitrophic aquaculture (IMTA) has been proposed as a means to remediate the effects of the dissolved nutrients released into ecosystems from fish farming (Troell et al., 2009; Buschmann et al., 2009).

In IMTA, extractive species (e.g. macroalgae to take up DIN waste) are grown next to the 'fed' species (e.g. finfish). In addition to mitigating nutrification there is potential for economic benefit through selling the 'new' secondary product. Field studies have shown the benefit of growing macroalgae near fish farms for both algal growth and nutrient removal (Abreu et al., 2009; Buschmann et al., 2008;

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[*] Corresponding author.
E-mail address: s_hadley@utas.edu.au (S. Hadley).

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Sanderson et al., 2008; Westermeier et al., 2011; Wu et al., 2015). Much of the current focus for modelling macroalgal based IMTA has been focused on optimizing the production ratios of the fed species to other extractive species, with the approach combining empirical data with process models to establish a realistic DIN sequestering potential for selected species of algae (Lamprianidou et al., 2015; Ren et al., 2012). The FAO (2009) have highlighted the need for research into the technical implementation of integrated mariculture at the farm level. However, an equally important consideration is to determine how the spatial distribution of finfish aquaculture within an estuary affects the impact of waste DIN, as this can inform the implementation of IMTA. Annual phytoplankton primary production within estuaries can vary up to 10-fold spatially and 5-fold from year to year due to sinking, advection, growth and mortality processes (Cloern et al., 2014). Modelling at the regional level is therefore essential to realistically assess and optimise IMTA.

IMTA is currently being investigated for its potential in Tasmanian waters. One of the three main salmon farming companies in Tasmania is currently exploring IMTA as a serious option to support industry expansion. Exploratory leases have been established in 3 regions and research is being undertaken to clarify the optimal species and locations for production (based on both market opportunities, ability to manage/reduce nutrients and culture potential). Consistent commercial scale production has been achieved, and the research is now moving beyond the proof of concept and into the commercial development stage. However, there is still considerable scope (and interest) in utilising modelling to fine tune farming locations and optimise both production and the broad scale benefits of IMTA.

Wild-Allen et al. (2010) used a fully coupled hydrodynamic, sediment and biogeochemical model to examine the effects of salmon aquaculture on a temperate estuary in southeast Tasmania. Their results suggested that a proposed increase in salmonid aquaculture would result in large areas of the estuary shifting from oligotrophic to mesotrophic in terms of mean chlorophyll concentration. In a separate study, Hadley et al. (2015) used an IMTA process model to compare the bioremediation capacity of three functionally different species of macroalgae, and identified that the giant kelp *Macrocystis pyrifera* clearly showed greater potential than the other candidate species (*Ulva lactuca* and *Porphyra umbilicalis*). In the present study we bring these two elements together, using a simulation of the southeast Tasmanian estuary studied by Wild-Allen et al. (2010) and described in Wild-Allen and Andrewartha (2016) to quantify the bioremediation potential of *Macrocystis pyrifera* in this area. Primary phytoplankton production in the estuary is investigated under the aquaculture-derived nitrogen loads used in Wild-Allen et al.'s (2010) study and under the scenario of a tenfold increase in those loads, with and without farming *Macrocystis pyrifera* adjacent to the fish pens, to quantify the magnitude of the IMTA effect.

2. Methods

2.1. Model location

Although the model domain used in this study includes the Derwent Estuary we only consider results in the D'Entrecasteaux Channel and Huon Estuary, which contain finfish aquaculture in southeast Tasmania. The D'Entrecasteaux Channel and Huon Estuary (DCHE) form a connected water body (Fig. 1), characterized by a cool temperate maritime climate dominated by zonal westerly winds with seasonally driven rainfall. The Huon Estuary is a drowned river valley with a strongly stratified (salt wedge) water column at the head, partially mixed at the mouth, and is intermediate between wave- and tide-dominated (Butler, 2006). The D'Entrecasteaux Channel lies between Bruny Island to the east and the main island of Tasmania, with the mouth of the Huon Estuary bisecting it. The ‘Channel’ connects to the Derwent Estuary through a narrow passage in the north section and opens to the Tasman Sea in the south. The region supports a thriving salmon aquaculture industry, has a relatively low human population and shows relatively minor impacts from anthropogenic sources (Parsons, 2012).

2.2. Model description

The coupled hydrodynamic, sediment and biogeochemical model applied on the Derwent Huon D'Entrecasteaux (DHD) grid has evolved through a series of case studies in the area including the Derwent Estuary Ecological Risk Assessment (Parslow et al., 2001), the Aquafin CRC study of the D'Entrecasteaux Channel (Wild-Allen et al., 2005), the Huon Estuary study (CSIRO Huon Estuary Study Team, 2000), and the Derwent Estuary modelling study (Herzfeld et al., 2005; Margvelashvili et al., 2005; Wild-Allen et al., 2013; Skerratt et al., 2013). Each study has addressed specific environments and ecological questions resulting in the development, implementation and testing of a diverse range of model components, which have been synthesised into the CSIRO environmental modelling suite (EMS). The DHD model used in this study is presented in detail by Wild-Allen and Andrewartha (2016), so we present only a brief outline here.

2.2.1. Hydrodynamic model

The 3D finite difference hydrodynamic model SHOC (Sparse Hydrodynamic Ocean Code; Herzfeld, 2006) advects and diffuses physical tracers (e.g. temperature and salinity) through cells in the model grid. The horizontal coordinates are provided using an orthogonal curvilinear grid with resolution ranging from < 100 m in the upper Derwent and Huon estuaries and coastal cells to a maximum of ~ 1 km in the deeper waters at the ocean boundaries. The vertical grid was comprised of 25 z coordinates (layers) plus the surface (air-water) and epibenthic (sediment-water) layers which vary dynamically in thickness (-60.0 -50.0 -40.0 -30.0 -25.0 -21.0 -17.0 -14.0 -12.0 -10.2 -9.0 -8.0 -7.1 -6.3 -5.6 -5.0 -4.5 -4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0) (m). Inputs to SHOC include the meteorological forcing for wind speed and direction, cloud cover, pressure and humidity, which were provided from the Bureau of Meteorology operational meteorological product ACCESS-A (http://www.bom.gov.au/nwp/doc/access/NWPData.shtml ACCESS, 2014).

The hydrodynamic model was nested within regional and intermediate scale ocean models using a one-way nested approach, which provide temperature, salinity, sea level, tide and velocity conditions to the local model at the open boundaries (shown in Fig. 1). Specifically, a large-scale regional model was implemented to supply the initial and open-boundary conditions for an intermediate scale model, which in turn supplied boundary forcing to the local-scale grid of the region of interest (for further details see Herzfeld et al., 2010). There was forcing for flow from the Huon, Derwent and 3 smaller rivers (Jordan, North-West Bay, and Esperance). The local hydrodynamic model was integrated with an adaptive 3D time step of 30 s and 2D time step of 3.75 s (small time steps are necessary for numerical stability in high-resolution parts of the grid). The vertical transport processes for the water column and sediment, including advection, diffusion, re-suspension and sinking, are resolved using the sediment model MECOSED (Margvelashvili, 2008.) The model runtime ratio in fully coupled mode was approximately 60:1 (i.e. 60 simulated days achieved in 1 day of simulation), which permits simulation of a seasonal hindcast. The hydrodynamic model is able to simulate the observed regional hydrodynamics with sufficient skill to host the biogeochemical model, as evidenced by the model agreement with observed temperature and salinity (Wild-Allen and Andrewartha, 2016).

2.2.2. Biogeochemical model

Carbon, nitrogen, phosphorous, and oxygen are cycled through both inorganic and organic phases comprising plankton, detritus, macrophytes and dissolved nutrients (Fig. 2). Dissolved inorganic nitrogen (DIN) is available for autotrophic uptake and is modeled as ammonium,