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Temporal variation on environmental variables and pollution indicators in marine sediments under sea Salmon farming cages in protected and exposed zones in the Chilean inland Southern Sea

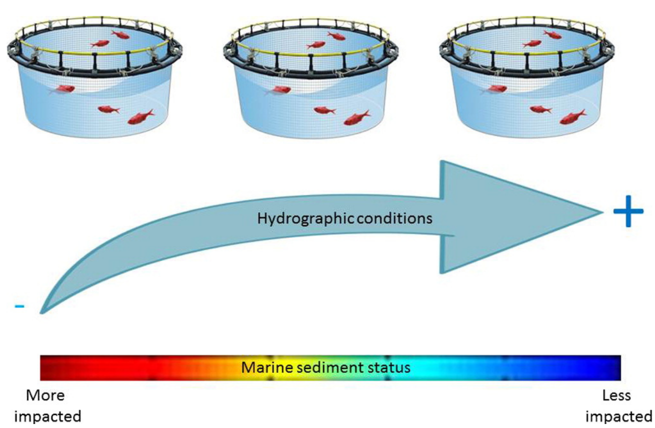
Mauricio A. Urbina

Departamento de Zoología, Facultad de Ciencias Naturales y Oceanográficas, Universidad de Concepción, Concepción, Chile

HIGHLIGHTS

- Salmon farming impacts vary depending on the hydrodynamic characteristics.
- The impacts on the sediments varied in magnitude and temporally between exposed and protected zones.
- Redox potential, sulphurs and phosphorus are the best to reflect the impacts in both protected and exposed zones.
- Organic carbon in the sediments is not an accurate predictor of the salmon farming impacts.
- Oxygen availability in the sediments seems to be a major driver of the impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

The impacts of any activity on marine ecosystems will depend on the characteristics of the receptor medium and its resilience to external pressures. Salmon farming industry develops along a constant gradient of hydrodynamic conditions in the south of Chile. However, the influence of the hydrodynamic characteristics (weak or strong) on the impacts of intensive salmon farming is still poorly understood. This one year study evaluates the impacts of salmon farming on the marine sediments of both protected and exposed marine zones differing in their hydrodynamic characteristics. Six physico-chemical, five biological variables and seven indexes of marine sediments status were evaluated under the salmon farming cages and control sites. Our results identified a few key variables and indexes necessary to accurately evaluate the salmon farming impacts on both protected and exposed zones. Interestingly, the ranking of importance of the variables and the temporality of the observed changes, varied depending on the hydrodynamic characteristics. Biological variables (nematodes abundance) and environmental indexes (Simpson's dominance, Shannon's diversity and Pielou evenness) are the first to reflect detrimental impacts under the salmon farming cages. Then the physico-chemical variables such as redox, sulphurs and phosphorus in both zones also show detrimental impacts. Based on the present results we propose that the hydrodynamic regime is an important driver of the magnitude and temporality of the effects of salmon farming

E-mail address: mauriciourbina@udec.cl.

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on marine sediments. The variables and indexes that best reflect the effects of salmon farming, in both protected and exposed zones, are also described.

1. Introduction

Aquaculture production has constantly increased during the last decade. World aquaculture production reached its maximum of around 60 MT in 2010 with a value of USD 119,000 million (FAO, 2012). Within the American continent Chile is the main aquaculture producer with around 701,062 tons in 2010 representing approximately 27% of the total production of the American continent (FAO, 2012). In 2007, 73% of this production corresponded to salmon farming, which since its beginnings in the 1970′s has experienced an abrupt growth (Buschmann et al., 2009). In 2011 Norway and Chile produced 77% of the farmed Atlantic salmon worldwide with a shared production of 1,324,307 tons of a world total of 1,721,254 tons (FAO, 2013). This is in part due to the exceptionally good water conditions of the deep and protected inland fjords of Chile and Norway (Wilding et al., 2012). In Chile the good water quality, environmental and physical conditions of the southern inland channels and fjords have greatly contributed to the development of salmon farming. In recent years, however, salmon farming zones have become scarce since most of the protected zones are currently in use. This low availability of suitable zones (protected) for salmon farming in the south of Chile has been disadvantageous for the salmon farming industry, forcing companies to move to more exposed zones.

Intensive aquaculture generates diverse effects on the environment, which then relies on ecosystem services such as the recycling of nutrients and maintenance of water quality for mitigation (Folke and Kautsky, 1989; Beveridge, 1996; Soto and Norambuena, 2004; Mulsow et al., 2006). In salmon farming for example, organic matter and nutrients coming from unconsumed food and feces have to be oxidized and recycled in both water column and marine sediments. The production of one ton of salmon generates around 33 kg of nitrogen (N) and 7 kg of phosphorus (P) pollutants in marine sediment (Buschmann and Pizarro, 2001). For example, an average salmon farm producing about 3000 tons over a period of 17 months (2118 tons per year) generates about 186 tons of organic matter, ~70 tons of N and ~15 tons of P per year. According to Folke et al. (1994), this is equivalent to the nitrogenous waste produced by 9000 people and the phosphorous waste produced annually by 27,000 people in developing countries. Therefore, one of the main negative environmental effects caused by salmon farming is a change in the structure of marine sediments, impacting benthic communities (Pereira et al., 2004; Tomassetti and Porrello, 2005; Edgar et al., 2010).

The magnitude and the consequences of the environmental impacts caused by intensive salmon farming depends on several productive characteristics such as the level of production and time under production, but it also depends on environmental conditions. These include salinity, pluviosity, wind, waves, tidal influence, hydrodynamic characteristics, depth, nutrient availability and the capacity of the sediments to recycle them (Brooks and Mahnken, 2003). Therefore, among these factors salmon farming impacts may differ between zones with different oceanographic conditions. These conditions will ultimately determine the potential accumulation of unconsumed food and feces and their degradation (Cromey et al., 2002; Hevia et al., 1996). In fact, it has been shown that the sediments below salmon farms located in zones with high speed currents are better able to recycle the nutrients than sediments below salmon farms located in low speed currents areas (Findlay and Watling, 1997). However, the opposite pattern has also been documented (Mayor et al., 2010), and even a recent study have reported no effect of the hydrodynamic regime (Sweetman et al., 2014). Therefore, while the importance of evaluating how the hydrodynamic regime modulates the effects of salmon farming on the sediments has been recognized (Sweetman et al., 2014), only a handful of studies have explored this.

Marine sediments are temporally more stable than the water column, in part due to the biotic component such as microbes, algae, and fungal biofilm living on it (Amos et al., 2004; Friend et al., 2003). Therefore, marine sediments may show the impacts of salmon farming for longer. Under aquaculture production, however, the regular input of organic matter and nutrients disturbs the bio stabilized natural sediments leading to erosion (instability) and the formation of colonies of new organisms (Droppo et al., 2007; Karthikeyan et al., 1999). Marine sediments have been described to be negatively impacted by the degradation of salmon farming waste products, leading to a reduction in the concentration of oxygen (Dissolved oxygen, DO) as a result of the aerobic oxidation of organic matter. When oxygen is no longer available (anoxia), the organic matter is oxidized by anaerobic pathways producing ammonium and sulphide by-products (Hargrave et al., 1993; Wildish et al., 2001).

Impacts on marine sediment involve changes in physico-chemical variables in turn leading to biological changes. Evaluating the communities that inhabit marine sediments is insightful since their dynamic may integrate the effects of pollutants and disturbances over relatively long time periods (months to years). Furthermore, since different taxa have differing sensitivity to pollutants, their abundance, species richness and dominance allow for a precise evaluation of the effects of salmon farming on impacted sites (Warwick, 1986). Environmental impacts can also be evaluated through the use of indexes (Madec, 2003), which provide useful information about the environmental status before, during and after an event or intervention. Since bias often exists in relation to the use of a particular index, it has been recommended to simultaneously use several indexes to describe the impacts on the marine environments (UICN, 2009). This challenge could be addressed using a multivariate approach and therefore combining several environmental variables into simple indexes (Hartwell, 1998).

Given the current importance and extent of fish farming worldwide and its expected growth in the next years, the present study aims to evaluate the effectiveness of using environmental indexes and variables as indicators of salmon farming impacts between zones differing in hydrodynamic characteristics. This is crucial not only to develop a sustainable industry, but also to enhance food security globally. We selected two marine farming zones with differing hydrodynamic characteristics. The exposed zone presented strong hydrodynamic characteristics facilitating the degradation and dilution of contaminants, while the protected zone presented weak hydrodynamic conditions and therefore not facilitating nutrient degradation and their dilution. Physico-chemical, biological variables (environmental variables) and diversity indexes were quantified and calculated for sediments of control and farming cages sites identifying the ones best describing salmon farming impacts and their temporal variability over a one year period. For both zones, ecological status was assessed and potential relationships between variables and indexes were evaluated. We hypothesized that sediments below salmon farms located in exposed zones (high speed currents) will show less impact than sediments below salmon farms located in protected zones (low speed currents). We also hypothesized that the effects of salmon farming in the sediments of exposed zones will take longer to develop, and they will recover quicker than in the protected zones.