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# Environmental performance of copper-alloy Net-pens: Life cycle assessment of Atlantic salmon grow-out in copper-alloy and nylon net-pens

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ABSTRACT

The environmental impacts of culturing Atlantic salmon in copper-alloy mesh (CAM) net-pens were studied using infrastructure and operating data from a pilot study in Chile in 2012. The analysis included a comparative assessment of culturing fish in CAM net-pens relative to industry-average Chilean nylon net-pen systems in 2012, and an environmental hot-spot analysis of the CAM net-pen supply chain. Life cycle assessment (LCA) was used to quantify the environmental performance of both systems in compliance with the ISO 14040 and 14044 standards for LCA, including sensitivity analysis and uncertainty analysis to test the robustness of the methodology and key assumptions. Results of the study indicated that use of the CAM resulted in improvements in several key performance characteristics, including reductions in feed inputs, on-site energy use, application of antibiotics, and labor hours. These operating performance improvements resulted in reductions in life cycle impacts relative to conventional nylon net-pen systems for nearly all environmental indicators considered, including climate change, acidification, marine ecotoxicity, metal depletion, and cumulative energy demand. The reduced impacts for marine ecotoxicity and metal depletion were a result of lower copper leach rates for the CAM netting relative to nylon netting coated in antifouling paint, as well as the high recyclability of the CAM net material. The recyclability of the CAM nets could result in a more cyclical and sustainable use of copper in the aquaculture industry relative to the one-time use and permanent loss of copper used in anti-fouling paints for nylon nets. The International Copper Association (ICA) is continuing to collect life cycle inventory (LCI) data to further characterize the environmental performance of CAM net-pen systems in an effort to provide further quantitative evidence of the benefits of this emerging alternative to nylon net-pen systems.

*Statement of relevance*

Manuscript presents potential benefits of a novel aquaculture technology.


## 1. Introduction

Global demand for seafood products has continued to increase in recent years, while most marine capture fisheries are being harvested at or beyond sustainable levels (FAO, 2014). Conversely, aquaculture is among the fastest-growing animal food-producing sectors in the world, accounting for nearly half of all fish produced for human consumption in 2012 and expected to account for over 60% of supply by 2030 (FAO, 2014). The global aquaculture industry produces a wide range of finfish, shellfish and aquatic plants that are cultured in various marine and freshwater production systems. There is increasing interest in understanding the environmental impacts of aquaculture production, and these impacts may vary widely depending on the type and intensity of the production system and the culture requirements of the species being produced.

Atlantic salmon (*Salmo salar*) are an increasingly popular species in the global seafood market (FAO, 2014). Global production of salmon nearly doubled between 2003 and 2013, contributing nearly 2.1 million tonnes to the market in 2013 (FAO, 2015). Although this accounted for a relatively small percentage of the over 90 million tonnes of seafood produced globally in 2013 (FAO, 2014), the culture of salmonids in marine aquaculture facilities has received substantial scrutiny for its potential environmental impacts, including: negative impacts to marine organisms and human health due to chemical applications (Hastein, 1995; Ernst et al., 2001); concentration and magnification of diseases and

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parasites and related impacts on wild fish populations (Krkosek et al., 2005; Krkosek et al., 2006); potential competition and interbreeding of escaped farmed salmon with wild fish populations (Hindar et al., 1991; Gausen and Moen, 1991; McGinnity et al., 2003); eutrophication of the ocean bottom beneath net-pens (Folke et al., 1994; Merceron et al., 2002); and depletion of pelagic fish stocks for salmon feed production (Naylor et al., 2000; Tacon, 2005; Tacon and Metian, 2015). The continued growth of net-pen salmon aquaculture coupled with concern over its environmental impacts led the World Wildlife Fund (WWF) to initiate the Salmon Aquaculture Dialogues (SAD) in 2004. These dialogs included stakeholders from industry, government, and non-governmental organizations (NGOs) committed to developing standards that would drive improvements in salmon farming practices to reduce the associated environmental impacts (worldwildlife.org).

In addition to SAD and other stakeholder initiatives, a number of innovations have also been proposed to reduce the environmental impacts of salmon farming, including efforts to reduce fishmeal and fish oil content in salmon feeds (Torstensen et al., 2008; Naylor et al., 2009; Burr et al., 2012; Tacon and Metian, 2015) and the development of various closed-containment technologies to enable management of fish wastes and to prevent escapes and interactions between farmed salmon and wild fish (Ayer and Tyedmers, 2009; Price et al., 2011; Summerfelt and Christianson, 2014; McGrath et al., 2015). The International Copper Association (ICA) and several industry partners have developed an alternative to conventional net-pens in which copper-alloy mesh (CAM) nets are used to contain the farmed fish as opposed to the conventional nylon (or other polymer) mesh nets. The use of CAM nets is intended to improve culture conditions by potentially improving water flow and oxygen levels and increasing the structural integrity of the net-pen in order to reduce maintenance and reduce predator interactions and risks of escapes (ICA, 2012). These improvements in culture conditions could in-turn promote improved fish health and growth rates (ICA, 2012; Gonzalez et al., 2013). Furthermore, these improvements in operating conditions and growth rates could potentially yield indirect environmental benefits due to efficiencies gained with respect to feed inputs and material and energy inputs to the system. These indirect environmental benefits have yet to be quantified, and the primary objective of this study was to explore these indirect benefits more fully using data collected from grow-out trials of CAM nets in Chile in 2012.

### 1.1. Copper-alloy mesh net-pens

One of the operational challenges for net-pen salmon farming is that nylon nets are subject to biofouling, and over time biofouling inhibits water circulation through the nets, which can gradually degrade culture conditions by decreasing the availability of fresh water and dissolved oxygen (Braithwaite et al., 2007; Fitridge et al., 2012). Biofouling can contribute to direct and indirect impacts on fish health and growth due to the restriction of water exchange, increased risk of disease, and cage deformation (Fitridge et al., 2012). Mortalities due to anoxia have been recorded in heavily-fouled nets, and decreased oxygen concentrations can impact negatively on feeding, fish growth, and respiration (Fitridge et al., 2012). Ultimately these negative impacts on fish health and growth rates can lead to higher feed conversion ratios, and may also force producers to increase the use of chemicals and chemotherapeutants to improve fish health and restore desired growth rates.

Due to the detrimental effects of biofouling, salmon farm operators must undertake regular prevention and maintenance practices, including the application of copper-based antifouling coatings to protect the nets, deployment of divers to clean the nets, and periodic removal and cleaning of the nets (Braithwaite et al., 2007; Fitridge et al., 2012). These maintenance activities also have the potential to interfere with salmon growth rates due to increased disturbance of the fish (Fitridge et al., 2012). Nylon nets are also subject to mechanical fatigue and tearing as a result of tidal action (which is enhanced by the added weight of biofouling) and attempts by marine predators to hunt fish contained in the nets (Jackson et al., 2015). Rips in net-pens lead to escapes of farmed salmon which can potentially lead to local ecological and genetic impacts of on native wild fish species and economic losses for the fish farmer.

The proposed advantage of CAM nets is that in marine applications they resist corrosion, ripping, and degradation and require less cleaning and diver maintenance (ICA, 2012; Gonzalez et al., 2013). The copper alloy materials naturally stay clean, which prevents the nets from clogging with organic matter and provides improved water circulation. These attributes could result in several operating performance improvements relative to nylon mesh nets (Table 1).

The manufacturing and deployment of CAM net-pens is in its early stages and the ICA and its partner organizations currently have CAM net-pens in pilot-scale and full production grow-outs in over thirteen countries in various regions of the globe to collect data on their operating performance. In addition to measuring and verifying potential improvements in operating performance, there are also potential indirect environmental benefits that could result from these performance improvements, including reduced feed inputs, reduced material and energy inputs on-site and in infrastructure production and maintenance, reduced material sent to landfill, and reduced demand for virgin copper (Table 1). In an effort to quantify these potential environmental benefits, ICA has adopted the life cycle assessment (LCA) methodology and is using operating data from these ongoing grow-out trials to assess the life cycle environmental performance of this emerging technology relative to conventional nylon net-pens. LCA is an internationally-accepted and standardized tool (ISO 14040, 2006; ISO 14044, 2006) that can be used to quantify environmental impacts related to many of the impact categories identified by the WWF SAD stakeholders. Results of this LCA work are being used to inform future design decisions and to quantify potential environmental benefits associated with this technology that could be communicated to the aquaculture industry, regulators, NGOs (like the WWF), and consumers.

As a first step in this life cycle environmental management approach, we have conducted a life cycle assessment comparing the relative impacts of culturing Atlantic salmon (*S. salar*) in CAM net-pen systems in Chile to average Chilean nylon net-pen production in 2012. The objectives of this initial study were to utilize production data from grow-out trials in Chile to: 1) provide an initial comparative assessment of the life cycle environmental impacts of culturing Atlantic salmon in

**Table 1**
Summary of potential performance improvements for copper-alloy mesh (CAM) relative to nylon net-pen systems.

| Performance characteristic | Potential performance benefits of CAM[a] |
|---|---|
| Improved culture environment | •Improved water circulation<br>•Increased dissolved oxygen levels<br>•Reduced crowding and stress on fish<br>•Increased growth rates and reduced feed inputs[a] |
| Reduced predator interactions | •Resistant to ripping from predator interactions<br>•Less anti-predator infrastructure[a]<br>•Reduced stress on fish |
| Reduced escapes | •Resistance to ripping from tidal action and predators<br>•Reduced ecological impacts on local wild fish<br>•Reduced FCR[a] |
| Reduced maintenance | •Reduced repair and cleaning labor<br>•Reduced material and energy inputs on-site[a]<br>•Reduced fish stress |
| Longer service life | •Reduced material and energy inputs to infrastructure[a]<br>•Less material sent to final disposal (landfill, etc.)[a] |
| Recyclability and recycled content | •Reduced demand for virgin copper[a]<br>•Less material sent to final disposal (landfill, etc.) |

[a] These performance improvements may result in reduced life cycle environmental impacts as a result of decreases in material and energy demands.