Available online at www.sciencedirect.com
ScienceDirect
Aquaculture 273 (2007) 687–699
Aquaculture
www.elsevier.com/locate/aqua-online

# The effect of dietary lipid and protein source on the swimming performance, recovery ability and oxygen consumption of Atlantic salmon (*Salmo salar*)

C.M. Wilson [a,*], E.N. Friesen [b], D.A. Higgs [c], A.P. Farrell [b,c]

[a] *Faculty of Life Sciences, University of Manchester, Manchester, United Kingdom*
[b] *Faculty of Land and Food Systems, The University of British Columbia, Vancouver, BC, Canada*
[c] *Department of Fisheries and Oceans/University of British Columbia, Centre for Aquaculture and Environmental Research, West Vancouver, BC, Canada*

Received 6 April 2007; received in revised form 2 October 2007; accepted 6 October 2007

**Abstract**

The effect of different dietary lipid sources on the athletic health of five groups of Atlantic salmon (*Salmo salar*) was tested by measuring oxygen consumption rates, prolonged swimming performance, and recovery from exhaustive exercise in a closed circuit respirometer. These groups of fish differed from each other in the source of the supplemental lipid in their diet. The control diet contained 100% anchovy oil, while in the test diets, poultry fat, de-gummed canola oil, or flaxseed oil were used to replace up to 75% fish oil. The composition of the industry diet was a 1:1 blend of anchovy oil and poultry fat, also 50% of the fishmeal protein in this diet was replaced with protein from poultry by-product meal. Despite major differences in dietary lipid and protein composition that altered the lipid composition of the fish, all of our treatment groups performed equally well with respect to their oxygen consumption, swimming performance and recovery ability. Since these swim tests integrated many physiological functions, and collectively represented a sensitive measure of the athletic health of the fish, we concluded that our alternative lipid and protein-based diets represented viable possibilities for salmon farming.


*Keywords:* Atlantic salmon; Swimming performance; Oxygen consumption; Fish oil; Fatty acid; Alternate lipid and protein; Plant oil

## 1. Introduction

Salmon flesh is rich in the physiologically important and essential omega-3 (n-3), long-chain (>3 double bonds >20 carbon atoms long), highly unsaturated fatty acids (HUFAs) including, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which have been shown to reduce the risk of coronary heart disease, arteriosclerosis and many other ailments (Kris-Etherton et al., 2002, 2003). Consequently, with the recommendation for the consumption of fish at least twice a week, and with wild fish stocks in decline, growth of the aquaculture industry continues in an attempt to meet the per capita supply demands of the public for healthy fish products (Kris-Etherton et al., 2003).

Fish feed accounts for over 40% of the total cost of fish farming, and this percentage is rising yearly (Elward

* Corresponding author. Tel.: +44 7817 213 175.
*E-mail address:* chris7_77@hotmail.com (C.M. Wilson).

0044-8486/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.aquaculture.2007.10.027

et al., 2004). The supplemental lipid source in fish feeds is typically based on marine fish oils such as anchovy oil. Although the demand for marine fish oils is increasing for aquafeeds, the forecast is that aquafeeds could utilize all of the global supply of fish oil by 2010, further increasing costs unless suitable cost-effective alternatives are identified (Hardy et al., 2001; New and Wijkström, 2002).

Organohalogen compounds, such as polychlorinated biphenyls (PCBs), polychlorinated dibenzo-*p*-dioxins (PCDDs), polychlorinated dibenzo-*p*-furans (PCDFs) and polybrominated diphenyl ethers, have a ubiquitous distribution in the aquatic ecosystem and they accumulate in the adipose tissue of fish due to their high affinity for lipid (Jacobs et al., 1998, 2002, 2004; Berntssen et al., 2005). Humans accumulate these toxins from many sources, including ingestion via fish oil supplements and fish themselves (Jacobs et al., 1998, 2002). Vegetable oils, and some animal fats, are more abundant and often cheaper than marine fish oils and offer an added advantage of containing fewer organic contaminants (Jacobs et al., 2004; Guruge et al., 2005; Berntssen et al., 2005; Higgs et al., 2006). Thus, there is a desire to partially replace marine oils with alternate lipids of plant and/or animal origin for both economic and contaminant exposure considerations. However, full replacement of marine fish oils is presently not possible because salmonids require the essential fatty acids, especially EPA and DHA, provided by such dietary oils and, in some cases, the production of EPA and DHA from metabolic precursors may be inadequate (Higgs and Dong, 2000; Tocher, 2003). Their essential fatty acid requirement is generally considered to be satisfied when EPA and DHA collectively comprise about 10% of the dietary lipid content (Higgs and Dong, 2000). EPA and DHA, as well as one of the HUFAs of the omega-6 (n-6) family, namely 20:4n-6 (arachidonic acid or AA), are important essential fatty acids since they are precursors of a variety of eicosanoid compounds including prostanoids (prostaglandins and thromboxanes), leukotrienes and lipoxins (Higgs et al., 1995; Higgs and Dong, 2000). The parent acid of the n-3 family of fatty acids, 18:3n-3 (linolenic acid, LNA), in combination with the parent acid of the n-6 family of fatty acids, 18:2n-6 (linoleic acid, LA), can contribute to the essential fatty acid needs of salmonids (salmon, trout and charr) in fresh water (Higgs et al., 1995). However, in salt water, several studies have shown that the conversion of LNA to EPA and DHA is extremely low, and therefore the essential fatty acid needs of the fish are not met (Tocher et al., 2000; Bell et al., 2001, 2003a,b, 2004).

Research to partially replace the supplemental marine fish oil in salmonid diets with animal and plant lipid sources has shown that a 50–80% replacement is possible without any adverse effects on their growth, feed efficiency, and survival provided that their essential fatty acid needs are met (Dosanjh et al., 1984, 1988, 1998; Thomassen and Røsjø, 1989; Torstensen et al., 2000; Bell et al., 2001, 2002, 2003a, 2003b, 2004; Rosenlund et al., 2001; Caballero et al., 2002; Torstensen et al., 2004; Higgs et al., 2006; Jordel et al., 2007, reviews by Higgs and Dong (2000) and Sargent et al. (2002)). The degree to which such replacements might affect the physiology of salmonids has not been investigated extensively. Concerns include non-lethal cardiac myopathy and diminished ability to survive a stress challenge, which Bell et al. (1991) and Bell et al. (1993) observed in post-smolt Atlantic salmon that had ingested excessive levels of n-6 fatty acids in the presence of adequate n-3 fatty acids for growth. Also, ion transport across gill epithelia may be influenced by alterations to fatty acid composition (Higgs et al., 1995). In addition, exercise in salmonids may be preferentially fuelled by 18-carbon unsaturated or long-chain fatty acids (McKenzie et al., 1998; Higgs and Dong, 2000; Richards et al., 2002). Consequently, we reasoned that if the health of salmon were compromised by dietary lipid composition, this could adversely affect swimming performance and recovery ability, as has been shown previously for toxicants and disease exposures when critical speed swimming ($U_{crit}$) and routine oxygen consumption ($MO_{2routine}$), and maximum $MO_2$ at $U_{crit}$ have been measured (for example, Nikl and Farrell, 1993; Jain et al., 1998; Tierney and Farrell, 2004; Wagner et al., 2003; Cheng and Farrell, 2007).

To our knowledge, only three other investigations have similarly examined dietary lipid replacements with non-marine sources in fish (McKenzie et al., 1998; Wagner et al., 2004; Chatelier et al., 2006), but none to the extent attempted here. Estimates of $U_{crit}$ for post-smolt Atlantic salmon were obtained by McKenzie et al. (1998) and Wagner et al. (2004), and for sea bass (*Dicentrarchus labrax*) by Chatelier et al. (2006), but only Wagner et al. (2004) followed the recovery after exercise. While, McKenzie et al. (1998) and Chatelier et al. (2006) reported $MO_{2max}$, Wagner et al. (2004) did not measure $MO_2$.

Therefore, as part of a much larger investigation of the effects of altering the lipid and protein composition of grower diets for post-smolt Atlantic salmon, the present study assessed athletic health by measuring oxygen consumption rates, prolonged swimming