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Waste feed from coastal fish farms: A trophic subsidy with compositional side-effects for wild gadoids

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ABSTRACT

Aquaculture of carnivorous fish species in sea-cages typically uses artificial feeds, with a proportion of these feeds lost to the surrounding environment. This lost resource may provide a trophic subsidy to wild fish in the vicinity of fish farms, yet the physiological consequences of the consumption of waste feed by wild fish remain unclear. In two regions in Norway with intensive aquaculture, we tested whether wild saithe (*Pollachius virens*) and Atlantic cod (*Gadus morhua*) associated with fish farms (F_{assoc}), where waste feed is readily available, had modified diets, condition and fatty acid (FA) compositions in their muscle and liver tissues compared to fish unassociated (UA) with farms. Stomach content analyses revealed that both cod and saithe consumed waste feed in the vicinity of farms (6–96% of their diet was composed of food pellets). This translated into elevated body and liver condition compared to fish caught distant from farms for cod at both locations and elevated body condition for saithe at one of the locations. As a consequence of a modified diet, we detected significantly increased concentrations of terrestrial-derived fatty acids (FAs) such as linoleic (18:2ω6) and oleic (18:1ω9) acids and decreased concentrations of DHA (22:6ω3) in the muscle and/or liver of F_{assoc} cod and saithe when compared with UA fish. In addition, the ω3:ω6 ratio clearly differed between F_{assoc} and UA fish. Linear discriminant analysis (LDA) correctly classified 97% of fish into F_{assoc} or UA origin for both cod and saithe based on the FA composition of liver tissues, and 89% of cod and 86% of saithe into F_{assoc} or UA origin based on the FA composition of muscle. Thus, LDA appears a useful tool for detecting the influence of fish farms on the FA composition of wild fish. Ready availability of waste feed with high protein and fat content provides a clear trophic subsidy to wild fish in coastal waters, yet whether the accompanying side-effect of altered fatty acid compositions affects physiological performance or reproductive potential requires further research.

1. Introduction

Anthropogenic changes to natural habitats have precipitated shifts in the abundance of many vertebrate populations (e.g. Gill et al., 1996; Wang et al., 2001). When changes have resulted in increased abundance of food for wild animals, super-abundance has sometimes resulted (Garrott et al., 1993). In terrestrial habitats, waste dumps in particular have directly increased populations of birds (Ramos et al., 2009) and bears (Eberhardt and Knight, 1996), which utilize these areas as feeding habitats. Increases in the populations of such species have been attributed to their gregarious nature and their flexible, opportunistic feeding behaviors, which makes them highly adapted to utilising new feed resources. In the marine environment, coastal sea-cage fish farms may represent an analogous scenario; an increased abundance of food is constantly available in their vicinity due to the loss of waste feed and wild fish aggregate in their vicinity in great biomass (Dempster et al., 2002, 2009; Fernandez-Jover et al., 2008) to feed upon this resource (Tuya

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et al., 2006; Fernandez-Jover et al., 2008). Wild fish may benefit from this feed resource (Fernandez-Jover et al., 2007; Sanchez-Jerez et al., 2008; Dempster et al., in press), which could act as a trophic subsidy. However, whether they are exposed to physiological changes as a result of consuming large amounts of waste feed has not been thoroughly explored.

In coastal Norway, 1142 concessions for salmonid farming were active in 2008 and used 1.2 million tons of fish food to produce 827 000 t of fish (Kjønhaug, 2009; Norwegian Fisheries Directorate, 2009). The amount of food that goes uneaten by salmon during production and falls through the sea-cages as waste varies, but estimates of up to 5% (Otterå et al., 2009) indicate that >50 000 tons of waste feed is directly available to wild fish in the vicinity of farms each year. Wild carnivorous gadoid fish, such as Atlantic cod (*Gadus morhua*), saithe (*Pollachius virens*) and haddock (*Melanogrammus aeglefinus*), are the main fish present around Norwegian fish farms (Dempster et al., in press, 2010). Aggregations sizes of gadoids have been estimated to be over 10 tons in the summer months within the typically less than 1 ha of sea surface area that salmon farms occupy (Dempster et al., 2009).

These wild gadoids consume large amounts of waste feed in the vicinity of farms, which results in a significant shift away from their natural diets (Dempster et al., in press). Marine fish, especially carnivores, have a natural diet rich in polyunsaturated ω3 fatty acids (PUFA), and as a consequence, ω3 PUFAs occur in higher concentrations in marine fish muscle (Ackman, 1967). Fish meal and fish oil are added into commercial fish feeds to supply the requirements of reared carnivorous fish. However, as the demand for and the cost of these fish feed components is high, the fish feed industry has developed feeds that contain substantial amounts of vegetable-derived oils and meals of terrestrial origin that consist mainly of ω6 PUFAs rather than ω3 PUFAs. This fundamentally changes the fatty acid profile of feeds. Sunflower, soya bean, palm or rapeseed oils are used extensively in fish feed production and result in high concentrations of oleic acid (18:1ω9) and linoleic acid (18:2ω6), reducing the concentration of ω3 PUFAs (Pickova and Mørkøre, 2007; Turchini et al., 2009). If wild fish feed extensively on lost waste pellets from coastal fish farms, their total fat content and fatty acid composition may change in the same way as occurs with reared fish (e.g. Bell et al., 2006; Fernandez-Jover et al., 2007; Jobling et al., 2008). A previous study carried out at a single farm showed that wild saithe that were captured nearby had a different muscle fatty acid composition than saithe caught distant from the farm (Skog et al., 2003).

As a first step towards determining whether the modified diets available to wild fish around Atlantic salmon (*Salmo salar*) farms have physiological or ecological consequences for wild fish, we tested whether the diets of cod (*Gadus morhua*) and saithe (*Pollachius virens*) differ when they are aggregated around fish farms compared to natural control locations. Further, we tested whether differences we detected in diets translated into differences in traditional measures of condition, including Fulton's condition index and the hepato-somatic index, and fatty acid concentrations in body tissues. In doing so, we tested the fatty acid compositions of muscle and liver tissue, liver being the main fat storage organ in gadoid fish (Dos Santos et al., 1993).

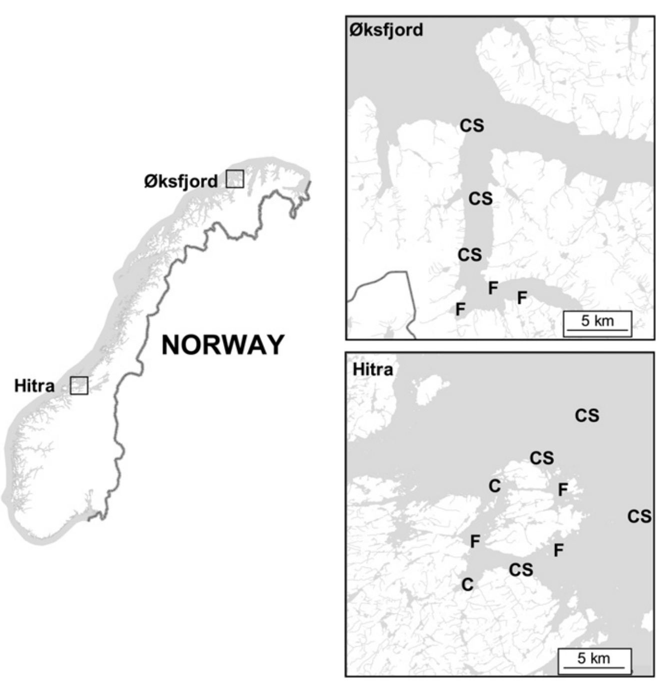

Fig. 1. Map of the Hitra and Øksfjord salmon farming areas in Norway showing the sampling locations for farm-associated (F) saithe *Pollachius virens* and Atlantic cod *Gadus morhua* and farm-unassociated sampling locations for saithe (S) and cod (C).

2. Materials and methods

2.1. Study locations and fish sampled

Saithe and cod were sampled from two salmon farming areas (Fig. 1): Hitra within the South-Trondelag region (63°N; 94 farms; 82,000 t) and Øksfjord within the Troms region (70°N; 123 farms; 72,000 t; Norwegian Fisheries Directorate, 2009). Farm-associated (hereafter F_{assoc}) fish were defined as those captured within 5 m of sea-cages containing Atlantic salmon. Both cod and saithe were sampled from within 5 m of the sea-cages at 3 farms at both Hitra and Øksfjord. These were the same farms used to assess aggregation sizes by Dempster et al. (2009). Farm-unassociated fish (hereafter UA) were defined as those captured 4–20 km distant from the nearest salmon farms (Fig. 1) to limit the possibility of sampling fish at non-farm locations that had interacted recently with a farm. Depending on the species and farming area, UA fish were sampled from 3 to 6 locations. The 4 km minimum limit was based on telemetry-derived observations of the predominant movements of wild cod and wild saithe (Uglem et al., 2008, 2009, 2010) in the vicinity of fish farms. UA areas were of similar depth and bottom habitat as those of the salmon farms. All fishes were captured between June–August 2007 with standardized hook and line fishing gear. Due to the low number of fish obtained at some UA and F_{assoc} sampling locations, samples were pooled for diet, condition and fatty acid analyses at the level of the farming area (i.e. Hitra F_{assoc}, Hitra UA, Øksfjord F_{assoc}, and Øksfjord UA; Table 1).

In addition to the fish samples, dry food pellets were directly collected from the feed bags at each of the studied farms in Hitra and Øksfjord. 4 pellet types were collected at Hitra and 3 at Øksfjord. Pellets from the various farms were pooled for Hitra and Øksfjord for later analysis of their FA profiles.

2.2. Diet and condition indices

Upon capture, fish were immediately placed on ice before transfer to the laboratory where they were measured (fork length: FL) and weighed. Livers were then dissected and weighed and stomach contents from the foregut were dissected. We calculated two condition indices: Fulton's Condition Index (FCI = $[100 \times W]/L^3$, where W = weight in g (after withdrawing stomach content weight) and L = length in cm), and the Hepato-Somatic Index (HSI = $100 \times$ [liver weight/total weight]). FCI is widely used to