Atlantic Salmon, *Salmo salar* Linnaeus, 1758

Owner: FAO/FIRA - Aquaculture Service (FIRA), FAO Fisheries and Aquaculture Department, FAO, Rome

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Species name
Salmo salar Linnaeus, 1758
Family Salmonidae

FAO common names: En – Atlantic salmon, Fr – Saumon de l'Atlantique, Es – Salmón del Atlántico

Figure 1. Atlantic salmon, *Salmo salar* (courtesy of S.P. Lall)

Figure 2. A fillet of Atlantic salmon (*Salmo salar)* fed feeds containing astaxanthin (courtesy of S.P. Lall)

Biological features

Atlantic salmon (Figure 1) has an elongate body that is somewhat compressed laterally; the greatest depth is at the dorsal fin origin and it becomes deeper with age. Scales small, 114–130 in lateral line, 109–121 above lateral line and 11–15 obliquely from adipose fin to lateral line. A fleshy adipose fin on the back just in front of the tail fin. Mouth large; gill rakers may range from 15 to 20 and vertebrae from 56 to 81 (Scott and Crossman, 1973). Caudal fin is fairly deeply forked. Small parr have 8–11 pigmented bars along each side of the body that alternate with a single row of red spots along the lateral line. These marks are lost when fish reach smolt stage and body colour becomes silvery and back shows shades of green, blue and brown. Adult body colour varies, but fish are generally silver-skinned with distinct dark blue-green, cross-like spots over the body and head, and above the lateral line. After spawning body colour of males (kelts) turns dark. The head of the male becomes elongated and grows a "kype" from the tip of the lower jaw, making males and females easily distinguished. The flesh colour of juveniles is nearly white, which changes to pink and then to deep reddish orange (Figure 2) at market size or maturity.

In the natural environment, this anadromous fish spawns in freshwater and alevins (~ 2 cm) emerge from eggs, subsisting off the attached yolk sac until reaching the fry stage when they are ready to accept exogenous food. The young remain in freshwater for 2 to 5 years depending on the water temperature and food supply. Prior to migration, smolts undergo physiological and behavioral changes, a process called smoltification that prepares them for their life at sea. After spending 1–2 years at sea, they return to their freshwater rivers to spawn. At sea, the Atlantic salmon prefers temperatures from 4 to 12˚C but can withstand short periods of time at lower or upper lethal temperatures of -0.7 and 27.8˚C, respectively (Bigelow, 1963). Salmon farming requires both freshwater and saltwater operations. Because of the efficiencies of farm husbandry practices, the farming process accelerates the life cycle to 1 year or less in freshwater and from 10 to 15 months at sea.

PROFILE

A. Natural food and feeding habits

Atlantic salmon in streams feed mainly upon aquatic insects, including larvae and nymphs of chironomids, mayflies, caddisflies, blackflies and stoneflies. At sea, Atlantic salmon eat a variety of marine organisms, including crustaceans such as euphausiids, amphipods and decapods, and such fishes as sand lance, smelt, alewives, herring, capelin, small mackerel and small cod (Scott and Crossman, 1973) (Table 1). On entering freshwater, particularly prior to spawning, salmon do not feed.

Digestive system

The major divisions of the digestive tract are the mouth, esophagus, stomach, pyloric caeca, rectum and secretory glands, which include the liver and pancreas (Figure 3). The newly hatched fry (alevin) has a yolk sac attached to its stomach that supplies the essential nutrients stored for its subsistence until the digestive tract is functional and ready to accept exogenous food. Pyloric caeca, blind-ended finger-like projections (40–74) extend outward from the pyloric valve regions of the stomach and the anterior intestine (Rust, 2002). Their function resembles that of the intestine rather than the stomach, and digestion and some absorption occur in these regions. The small intestine contains the openings for the bile and pancreatic ducts and provides neutral to alkaline pH. Atlantic salmon have a full complement of digestive enzymes to hydrolyze protein, carbohydrate and lipid into smaller molecules for absorption. These enzymes are secreted in the pyloric caeca and small intestine and nutrient absorption occurs in both. The regulation of digestive function is under the combined actions of the nervous system and chemical signals that regulate motility of food through the alimentary canal, secretion of digestive enzymes and absorption of nutrients. Limited information exists on osmoregulation and the regulation of immune functions of the alimentary canal. However, the role of the distal intestine in osmoregulation and as a site for electrolyte secretion and absorption is widely recognized.

Figure 3. Gastrointestinal tract (GI) of Atlantic salmon displaced from the body cavity. GI tract length can be as long as total length of fish in juvenile fish (courtesy of S.P. Lall)

B. Growth characteristics

Atlantic salmon growth is affected by environmental factors (e.g. temperature, photoperiod and water quality), social parameters (e.g. stocking density and hierarchical structures), genetic factors and nutrition. Atlantic salmon parr are known to develop a bimodel size distribution due to individual differences in growth rate (Thorpe *et al*., 1992). Two groups of fish, slow- and fast-growing parr, differ in their age of smolting and migration to sea; thus growth of salmon under natural and farm conditions is highly variable. Farmed salmon cultured in freshwater hatcheries under controlled temperature and photoperiod on well-balanced diet reach the smolt stage (50–80 g) within one year (Figure 4). Smolts transferred to sea cages reach harvest size (~ 4 kg) in 10–15 months (Figure 5). Growth rates of farmed Atlantic salmon are much higher than those of wild fish. Sea-run sexually mature salmon returning to their rivers range from 2.3 to 9.1 kg in weight (Scott and Crossman, 1973). However, the weight of farmed broodstock salmon may range from 6 to 20 kg, depending upon their genetic background and whether fish are single or repeat spawners. Some small salmon, often referred as “grilse” (<1 kg), attain early sexual maturity, and they are culled from stocks to be used for reproduction.

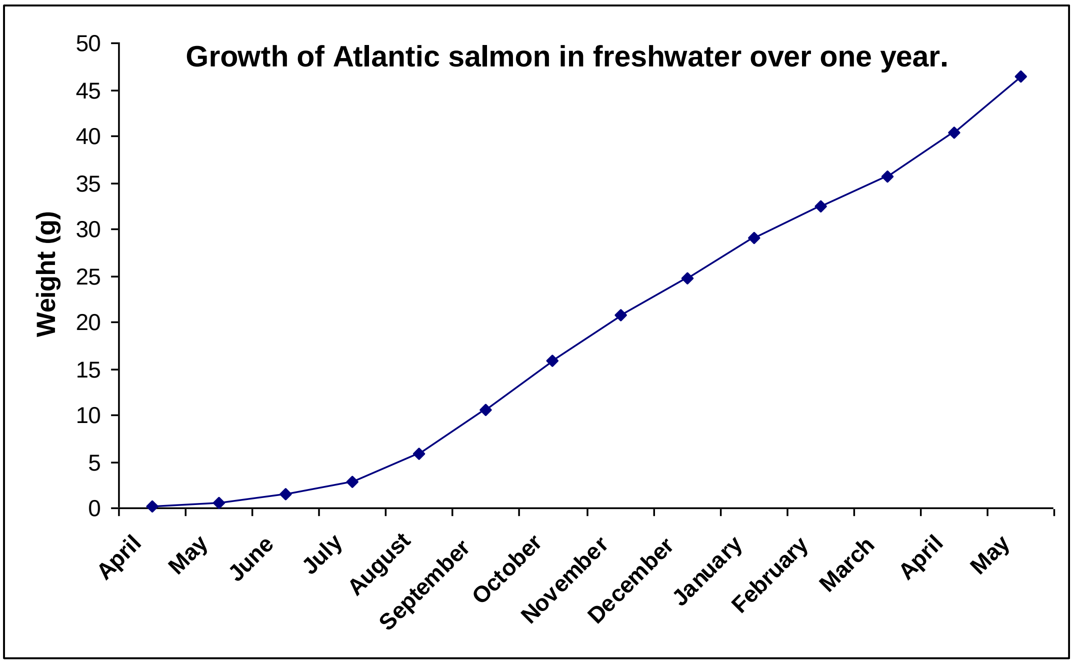

Figure 4. Growth of Atlantic salmon from fry to smolt stage in freshwater

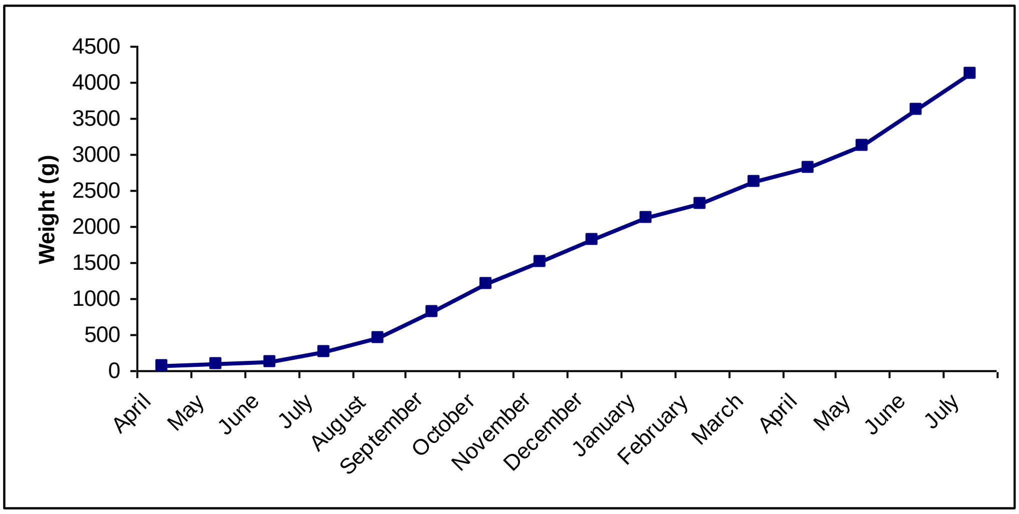

Figure 5. Growth of Atlantic salmon smolts after seawater transfer to market size

C. Nutritional requirements

Although Atlantic salmon is the most successfully farmed salmonid, the nutrient requirements of this species are not well defined, and the available information is based on studies conducted on young fish. Similar to other fish species, salmon require the same nutrients (protein, amino acids, essential fatty acids, vitamins and minerals) for normal growth, reproduction, and immune and metabolic functions (Table 2). Nutrient requirements of rainbow trout (*Oncorhynchus mykiss*) and chinook salmon (*O. tshawytscha*) have been used to predict the requirements of certain micronutrients such as amino acids, minerals and vitamins for feed formulation when this information is not available for Atlantic salmon (NRC, 1993; Storebakken, 2001).

Like other fish species, salmon do not have a protein requirement, but they require essential amino acids (arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine) contained in protein for normal growth. Early research based on purified diets showed that juvenile Atlantic salmon reared in seawater required 45 percent protein (Lall and Bishop, 1977). Rapidly growing salmon fry and juvenile fish perform better on high protein diet (~50 percent) and grower diets containing 42–48 percent protein (Table 2). For the most part, the quantitative dietary essential amino acids requirement established for rainbow trout is also used for Atlantic salmon. Lysine, methionine and arginine (or threonine) are the most limiting amino acids in salmon feeds when fishmeal level is reduced and plant protein sources are increased. As is the case with most fish, the optimum protein level in feeds depends upon dietary energy content and the ratio of essential to non-essential (or indispensable to dispensable) amino acids. The disproportionate levels of specific amino acid antagonistics such as leucine and isoleucine and others (arginine/lysine, cystine/methionine) in the diet may result in marginal or severe amino acid deficiency, particularly when fish are under certain environmental and physiological stress. Certain essential amino acids (e.g. leucine) may also be toxic when present in excess in diets. In Atlantic salmon smolts, dietary histidine appears to be one of the important factors in preventing cataracts, and the beneficial effects are related to high levels of histidine and the build up of N-acetyl histidine (NAH) in the lens, which possess buffering and antioxidant properties (Bjerkås, Breck and Waagbø, 2006).

Atlantic salmon have no specific requirements for dietary carbohydrates. The following two types of carbohydrate are derived from the feed ingredients of plant origin used in salmon feeds: starch and non-soluble polysaccharides (NSP). Starches are also added as binders to improve the stability of extruded feed pellets. Raw starch is essentially unavailable to salmonids, but cooking during feed processing improves its digestibility. Atlantic salmon has poor ability to regulate blood glucose when carbohydrate load is excessive (Hemre *et al*., 1996). NSP are not available to fish (reviewed by Stone, 2003).

The energy requirement for maximum growth is influenced by water temperature, size of fish, and diet composition and nutrient availability. The efficiency of energy utilization is improved by reducing dietary protein content and increasing dietary lipid, thereby reducing the digestible protein (DP) to digestible energy (DE) ratio. The ratios of DP to DE for maximum growth have been measured using practical diets: fingerlings, 23 g/MJ; smolts, 20 g/MJ; grower (0.2 –2.5 kg), 19 g/MJ ; and grower (2.5–4 kg), 16–17 g/MJ (Storebakken, 2001). Recent genetic improvements in growth and feed formulation strategies to provide optimum DP:DE ratio in feeds at different stages of the life cycle of Atlantic salmon have resulted in higher growth and feed utilization.

Dietary lipids supply energy and essential fatty acids (EFA). Increasing levels of dietary fat (up to 24 percent) increases the efficiency of protein utilization. The EFA requirement of Atlantic salmon can only be met by supplying the long-chain highly unsaturated fatty acids, eicosapentaenoic acid (EPA), 20:5n-3, and/or docosahexaenoic acid (DHA), 22:6n-3. Based on total body and tissue fatty acid composition data, the estimated EFA requirement of salmon is 1 percent of the diet for 20:5n-3 and 22:6n-3 fatty acids combined (Ruyter *et al*., 2000). EFA deficiency causes reduced growth, increased mortality, and reduced concentrations of EPA and DHA in the blood and liver phospholipids and an increase in 20:3n-9 level. Although marine fish oils (MFO) have been traditionally used in salmon diets, the overexploitation of marine resources has resulted in limited supply of this oil supplement. Recent research has shown that it is possible to replace the major proportion of MFO with vegetable oils (VO) and still maintain optimum growth and feed utilization over the major part of the life cycle. The partial substitution of MFO in fish diets with vegetable and animal lipid sources affects tissue and cellular lipid composition. Finishing diets based on MFO can be used to tailor the desired level of EPA and DHA in the final product. To date, any significant effects of either partial or full replacement of MFO with vegetable oils (canola, rapeseed and flaxseed oils) on flesh and sensory quality of fish have not been observed. Diets containing high levels of n-3 and n-6 fatty acids from fish and vegetable oils modify the tissue and cellular phospholipid’s fatty acid composition (Bell, Dick and Sargent, 1993).

Qualitative and quantitative requirement values of most fat-soluble (A, D, E and K) and water-soluble (thiamin, riboflavin, niacin, pyridoxine, pantothenic acid, biotin, folic acid, vitamin B_{12} and vitamin C) vitamins established for rainbow trout and chinook salmon have been used for the feed formulation of Atlantic salmon with some exceptions (NRC, 1993). For juvenile salmon, the minimum requirement of vitamin E has been estimated as 60 mg/kg dry feed (Hamre and Lie, 1995), a value higher than that for other salmonids. A dietary supplement of 500 mg/kg has been recommended as a measure to prevent oxidative damage of salmon fillet during storage, as well as to maintain optimum flesh pigmentation. It appears that requirements of water-soluble vitamins are lower than values recommended in early studies (NRC, 1993; Woodward *et al*., 1994). The requirement values determined by maximum liver storage or certain enzyme activity data are often higher than values based on weight gain and the absence of deficiency signs data. There is evidence of improvement on health immune function and disease resistance in salmon with higher supplementation of vitamin C and other vitamins; however, the response under farming conditions is not always consistent with laboratory findings. Ascorbic acid appears to protect phagocytic cells and surrounding tissues from oxidative damage. An increased immune response due to high levels of ascorbic acid supplementation has been demonstrated in several fish species (reviewed by Gatlin, 2002). Dietary and environmental contaminants such as heavy metals increase the ascorbic acid requirements of fish. Reduced reproductive performance has also been reported in rainbow trout fed ascorbic acid-deficient diets (Sandnes *et al*., 1984). Ascorbic acid reserves are rapidly depleted during the embryonic and larval development of certain fish, suggesting essentiality of this vitamin during early life stages as well as a higher requirement than in juveniles and adult fish. Liver and kidney ascorbic acid concentrations of less than 25 µg/g have been suggested as an indicator of ascorbic acid deficiency in salmonids (Sandnes *et al*., 1992).

Generally, fat-soluble vitamins function as an integral part of cell membranes; in addition, some of them may have hormone-like functions. Water-soluble vitamins act as coenzymes accelerating enzymatic reactions and often serve as carriers for specific chemical groupings. Diseases due to vitamin deficiencies are a gradual process. When the deficiency persists, the level in cells falls and the metabolic processes involving a particular vitamin are impaired. However, the changes do not occur at a uniform rate throughout all tissues of the body because some retain particular vitamins more strongly, while other tissues, by virtue of their metabolic peculiarities, are sensitive to change in vitamin availability. Therefore, vitamin supplementation of feeds takes into account genetic strains, physiological status, growth and stress.

Most essential elements required by terrestrial animals are also considered essential for Atlantic salmon, and thus requirements have been reported for phosphorus, magnesium, iron, copper, manganese, zinc, selenium and iodine (Lall, 2002, 2008). The exchange of ions from the surrounding water across the gills and skin of fish complicates the measurement of mineral requirements, and uptakes of water-borne minerals were not taken into account in requirement studies. Mineral deficiency signs in salmon and other fish include reduced bone mineralization, anorexia (potassium), lens cataracts (zinc), skeletal deformities (phosphorus, magnesium, zinc), fin erosion (copper, zinc), nephrocalcinosis (magnesium, selenium toxicity), tetany (potassium), thyroid hyperplasia (iodine), muscular dystrophy (selenium) and hypochromic microcytic anemia (iron).

Bioavailability of dietary phosphorus is influenced by several factors, including chemical form, digestibility of diet, particle size and interaction with other nutrients, feed processing and water chemistry. High concentrations of some minerals can create a mineral imbalance in the diet and cause a pollution problem in effluent waters. The digestibility of P in fishmeals ranges between 40 and 60 percent. Plant proteins contain phytates (inositol hexaphosphoric acid), which are unavailable to salmonids. Supplementation of microbial phytase has been effective in improving P bioavailability of plant feed ingredients provided the activity of this enzyme is maintained and water temperature is optimum for feed utilization. Zinc bioavailability is reduced by plant phytates and higher concentrations of calcium phosphate supplied by bones in fishmeal. Atlantic salmon feeds may contain a high proportion of fishmeal and marine by-products supplemented with trace elements at a higher concentration than required due to limited information on their requirements and bioavailability from feed ingredients. Feeds are often supplemented with zinc, iron, copper, manganese, selenium, iodine and phosphorus; however, they may also contain other trace elements supplied from common feed ingredients. Elevated levels of zinc, copper, cadmium and manganese have been found in sediments under sea cages and in solid wastes generated by fish farms that affect the ecology of benthic organisms (reviewed by Lall and Milley, 2008).

D. Feed production

Atlantic salmon are cultured in freshwater tanks and raceways in flow-through systems prior to transfer to sea. In the marine environment, they are farmed in sea cages where they depend solely on formulated feeds. The use of fertilizers to increase the natural productivity of aquatic organisms is therefore not necessary either in hatcheries or sea cages.

Live food

Supplemental feeds and feeding is not practiced for the hatchery and cage culture of Atlantic salmon.

Formulated feed

Atlantic salmon feeds formulated for various stages of development and production cycle in freshwater and seawater are broadly classified as freshwater (starter, grower, smolt transfer), seawater grower and broodstock feeds (Tables 3, 6 and 7). Freshwater feeds contain 45–54 percent protein and 16–24 percent lipid. The protein content is decreased after salmon fry reach fingerling size. Feed manufacturers use seawater transfer feeds for salmon going through parr-smolt transformation. These diets contain salt, betaine, amino acids, nucleotides and other supplements to improve the osmotic adaptation of smolts to seawater and for better survival. Smolts are fed marine grower feeds after the seawater acclimation is complete. The protein content is reduced from 45–48 percent to 36–42 percent and lipid content increased from 24 to 30–40 percent during their seawater grow-out phase to market-size salmon (~ 4 kg). Most feeds used are highly digestible and the fines are negligible, which allows minimum impact of aquaculture feeds on the environment.

Starter feeds are made by crumbling extruded pellets, but agglomeration technology is now widely used to produce modern starter feeds for salmon and marine fish. Most salmon feeds are manufactured by extrusion technology to produce slow-sinking pellets. A vacuum infusion coating process allows fat to penetrate the pellet, and this has led to a new generation of salmon feeds containing high amounts of lipid ranging from 18 to 40 percent. Certain heat unstable nutrients such as ascorbic acid, astaxanthin, feed attractants and other additives are also externally coated. The diameter of pellets can vary from 1 to 11 mm or larger. Feeds are delivered to marine cage sites packed in large bags (500 kg or larger) by boat. Salmon hatchery feeds are packed in 25 kg bags (Figure 6). Under feed regulations, each bag must have a label that provides information on proximate composition, certain nutrients (e.g. phosphorus) and feed additives, as well as the feed ingredients used for feed formulation (Figure 7).

Figure 6. Feed bags of different sizes stored in a feed mill. Plastic bag used to prevent oil seepage from bag as well as to protect light sensitive vitamins and carotenoids from sunlight

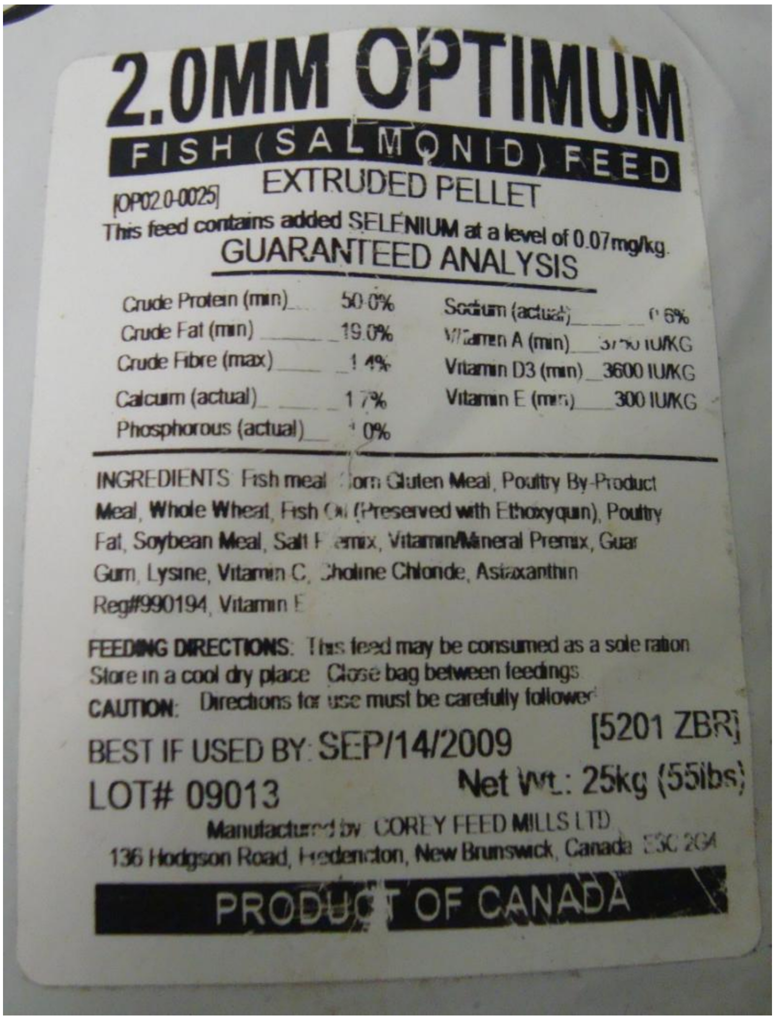

Figure 7. Atlantic salmon extruded pellet. Feed label showing information on proximate composition, list of ingredients and feeding direction

Feed ingredients

A wide range of ingredients is used in the formulation of Atlantic salmon feeds (Tables 4 and 5). They are selected on the basis of available energy content and nutrient composition as determined through chemical analyses. They are broadly classified as to the source of protein (amino acid), energy, essential fatty acids, vitamins and minerals. Several protein supplements such as high-quality fishmeal, plant protein products (soybean meal, corn gluten meal, canola meal, pea meal), animal by-product meal (poultry by-product meal, meat meal, blood meal, hydrolyzed feather meal) and crustacean meal (krill, shrimp, crab) are used in salmon feed formulation depending upon economics and availability. The nutritional value of common feed ingredients used in feed formulation is provided in Tables 4, 5 and 8. One of the major shifts in the selection of salmon feeds has been from the use of fishmeal and fish oils to terrestrial vegetable oils and plant proteins due to the high demand for marine by-products by the global aquaculture industry (Tacon and Metian, 2008).

Feed additives

Several feed additives are added to salmon feeds to enhance growth, flesh pigmentation, physical properties, digestibility, osmoregulation, palatability and preservation of the feed. Several carotenoids, including synthetic astaxanthin and canthaxanthin, and certain natural supplements such as yeast (e.g. *Phaffia rhodozyma*), algae (e.g. *Hematococcus pluvialis*) and crustacean products (e.g. krill and shrimp) are used to impart an attractive pink-red colour to the salmon flesh. Enzymes, particularly microbial phytase, increase the bioavailability of phytic acid in oilseed proteins. Certain amino acids, peptides and betaine are added to increase feed intake. Other feed additives include immunostimulants (e.g. β-glucans and nucleotides), prebiotics and probiotics (Gatlin, 2002). Selenium and vitamins C and E in conjunction with other immunostimulants have been also used for disease prevention. Antioxidants such as ethoxyquin are added to fishmeal and fish oil to increase their stability; however, farmed salmon feeds are used within a short period after their manufacture, thus reducing the use of synthetic antioxidants. Natural tocopherols have antioxidant activity, however α-tocoherol acetate supplement in the diet has limited antioxidant activity until hydrolyzed in the digestive tract. Although several binders are available to improve the stability of feed pellets, salmon feed manufacturers rely on gelatinization of starch during extrusion to improve feed stability.

Feeding schedules

After hatching from eggs, swim-up fry (alevins) depend on endogenous nutrients from the yolk sac. The most appropriate time to start feeding small-size particles in the form of granules or crumbles is when this reserve is completely absorbed. At this stage, they are switched to starter feeds and fed frequently by automatic feeders (Figure 8) or belt type clockwork feeders throughout daylight hours or during a set photoperiod regime. Swim-up fry are fed in slight excess so that slow-sinking feed is visible for capture. However, an excessive amount of feed particles suspended in the water column may affect gill respiration and predispose fry to bacterial infections. The frequency of feeding is dependent on the water temperature and body size. Generally, feeding is reduced from 8–12 times or more daily to 3–4 times a day for fingerlings and parr (Table 9). Feed consumption is readily reduced by poor water quality, low water exchange, high density of fry and physiological state of fish.

In sea cages, feeding practice includes hand feeding (Figures 9a and b) and the use of automatic feeders equipped with video monitoring systems (Figure 11). It has been observed that peak feeding time during summer months is in the early morning, followed by another peak 12 hours later (Kadri *et al*., 1991). In addition to temperature, appetite also depends upon gut fullness and the evacuation rate of food from the gut. Modern demands feeders and feeding schedules developed by feed manufacturers based on fish size, water temperature and energy content of feed provide appropriate directions to achieve maximum growth and feed utilization under diverse environmental and culture conditions (Table 10).

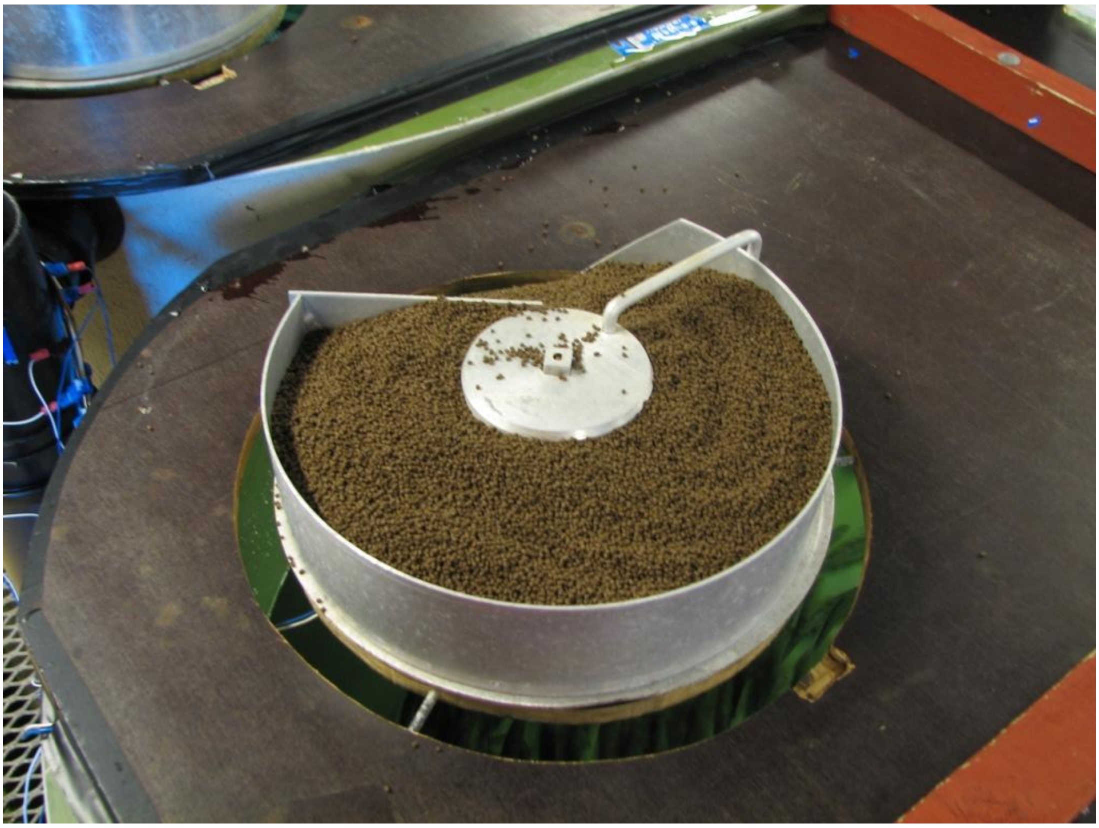

Figure 8. An automatic feeder used to feed Atlantic salmon in a freshwater hatchery (courtesy of R. E. Olsen)

Figure 9a. Atlantic salmon circular cages in a farm where fish are hand fed or fed by feeders located on a small boat that distribute feeds to each pen (courtesy of: S.P. Lall)

Figure 9b. Atlantic salmon rectangular cages in a small farm where fish are hand fed or fed by feeders located on a small boat that distributes feeds to each cage (courtesy of R. E. Olsen)

Figure 10. Atlantic salmon feeds transported by a large boat and delivered to a large off-shore farm (courtesy of R.E. Olsen)

Figure 11. Advance feeding that delivers feeds to cages according to the feeding schedules with automatic controls for individual cages (courtesy of J. Sweetman)

Water stability

New developments in fish feed technology have resulted in production of stable feeds with insignificant amount of leaching of nutrients in water. When lipid is not properly coated on extruded feed pellets, a thin layer of oil may be observed on the water surface.

Feeding methods/method of feed presentation

Maximum growth and feed conversion depends on avoiding over- and under-feeding of fish. Feeding in excess of voluntary appetite causes waste, environmental pollution and higher feed conversion ratios (FCR). Devices used to monitor the feeding of salmon include cameras, air-lift waste feed collectors, pellet counters, and various radar and sonar systems.

E. Fertilizers and fertilization

Atlantic salmon are cultured in freshwater tanks and raceways in flow-through systems prior to transfer to sea. In the marine environment, they are farmed in sea cages where they depend solely on formulated feeds. The use of fertilizers to increase the natural productivity of aquatic organisms is therefore not necessary in either hatcheries or sea cages.

F. Deficiency diseases

Several nutrient deficiencies have been characterized using semi-purified diets; however, deficiency of a single nutrient is rare in farmed fish (Tables 11–13). In farmed fish fed commercial feeds, micronutrient deficiencies of specific nutrients are rare. Generally, micronutrients are supplemented above the requirement levels with a safety of margin to offset nutrient losses during processing and storage, poor digestibility, low absorption from gastrointestinal interferences by antinutritional factors and excessive nutrients supplied by certain feed ingredients (e.g. high ash fishmeals). Environmental stress, altered gastrointestinal activity, disease state, higher physiological needs (e.g. iodine during smoltification), drug-induced anorexia, metabolic defects and food contaminants may all lead to malnutrition and nutrient deficiencies. The most well characterized cause of a feed-related intestinal disorder in salmonid fishes is induced by full-fat and extracted soybean meal (Baeverfjord and Krogdahl, 1996; Ingh, Olli and Krogdahl, 1996). It causes a sub-acute inflammatory response in the distal intestine of Atlantic salmon and rainbow trout and is often associated with reduced growth performance and nutrient utilization, as well as diarrhea in a dose-dependent manner.

All salmonids and certain marine fish are susceptible to lipoid liver degeneration when fed rancid feeds containing oxidized lipid. Generally, oxidized lipid affects liver lipid metabolism and leads to several metabolic disorders of the liver, including lipoid degeneration (ceroid accumulation), depigmentation, distention of the bile duct and an anemic, pale, swollen liver. In Atlantic salmon, cataracts develop in certain genetic strains during the smoltification and post-smoltification periods (Bjerkås *et al*., 1996). Several dietary factors are implicated in the pathogenesis, including histidine deficiency (Breck *et al*., 2005) and higher growth of smolts fed high energy diet containing high levels of lipid and a low protein content (Waagbø *et al*., 2003). Deficiencies of eight nutrients have been linked to the pathogenesis of eye disorders: exophthalmia, clouding and severe degeneration of the lens caused by vitamin A deficiency; clouding of the cornea due to thiamin deficiency; degeneration of the cornea and retina caused by riboflavin deficiency; and lenticular opacity with no involvement of other ocular tissues by sulfur amino acids (methionine and cystine), tryptophan, histidine and zinc (Hughes, 1985; Bjerkås, Breck and Waagbø, 2006). Biochemical mechanisms involved in cataract formation are not well understood because multiple nutrients and genetic and environmental factors may be involved. Excessive amounts of minerals (high ash), particularly high levels of calcium and phosphorus, reduce zinc bioavailability and cause cataract formation in salmonid fishes. Skeletal disorders in farmed fish are linked to a complex and poorly understood relationship between nutrition, environment and genetic factors; however, limited information is available on pathogenesis of bone disorders linked to specific nutrient deficiencies in fish (reviewed by Lall and Lewis-McCrea, 2007). Nutrient deficiencies or toxicities of minerals (calcium, phosphorus, zinc, selenium and manganese) and vitamins (A, D, C, E and K), as well as their interactions and lipid peroxidation may cause pathogenesis leading to skeletal deformities. Fin and skin lesions are commonly observed and are often interpreted as unspecific reactions to environmental and mechanical stress factors. However, a number of dietary factors, including deficiencies of lysine, tryptophan, essential fatty acids, zinc, copper, riboflavin, inositol, niacin and vitamin C; toxicities of vitamin A and lead; lipid peroxidation and feed rancidity can cause these lesions (Tacon, 1992; Lall, 2002).

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