Contents

Preface

The salmon farming industry has been one of the fastest growing industries in the food sector since its start in the late 1960s. Today it is a multibillion-dollar industry with a yearly production above 2 million tonnes. It can rightly be called an industrial adventure. Atlantic salmon is by far the predominant salmon species used in salmon farming. Until recently, countries that have the natural conditions for sea cage farming have dominated the production of ongrowing salmon. However, the new technology of land-based farms, closed sea cages and large offshore cages is opening up the areas in the world that can be used for salmon production. Owing to increased demand and with little increase in production, the profitability of salmon farming has been very high in recent years. The future for salmon farming seems to be bright; even if prices drop, the market is growing. Atlantic salmon is a species known worldwide. It is healthy and can be used and processed in different ways.

This book gives an overview of salmon production, from eggs to slaughtering size, starting at the broodstock farm, continuing through the hatchery and smolt farm and ending up in the ongrowing sea cage farm until the salmon are ready for harvesting. Planning and forecasting of production on the farm, including the design of production plans, is also an important part of the salmon farming process and is covered in detail with worked examples. Supplementary chapters on salmon biology, feeding, diseases and breeding are also included. These are less substantial as these subjects lie outside the author's scientific background and are included as a introduction and guide to more detailed resources.

This book is based on material successfully used for BSc and MSc courses in intensive aquaculture given at the Norwegian University of Life Sciences (NMBU). The university has included courses in aquaculture since 1973. From 1990, it has provided special masters courses in aquaculture engineering, and from 2000, courses in optimalization of Atlantic salmon production. This textbook was written for a basic course in salmon production, but the university also has its own courses focusing on anatomy and physiology, feeding, breeding, diseases and harvesting and processing. The courses are parts of masters programmes in aquaculture and aquatic food production (for details, see www.nmbu.no).

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Tore Ensby has drawn the majority of the line illustrations, and all photographs have been taken by the author.

Abbreviations

ADC	apparent digestibility coefficient
ADG	average daily growth
AGD	amoebic gill disease
AOP	apparent optical properties
ATU	accumulated temperature units
BFCR	biological feed conversion rate
BKD	bacterial kidney disease
CaSR	calcium sensing receptors
CCS	closed containment systems
CF	condition factor
CFTR	cystic fibrosis transmembrane conductance regulator
CV	coefficient of variation
DAA	dispensable amino acids
DE	digestible energy
DEN	digestible energy need
DM	dry matter
DP	digestible protein
EGI	Ewos growth index
EPA	eicosapentaenoic acid
FA	feed allowance
FAD	flavin adenine dinucleotide
FCR	feed conversion ratio
FE	feed efficiency
FF	feed factor
FFDR	forage fish dependency ratio
FIFO	fish in fish out
FSH	follicle-stimulating hormone
FT	flow through
GE	gross energy
GF	growth factor
GI	growth indexes
GIS	geographical information system
GM	genetically modified
GMO	genetically modified organism

GSI	gonad somatic index
HAB	harmful algal blooms
HI	heart index
HOG	head on gutted
HSMI	heart and skeletal muscle inflammation
HSS	haemorrhagic smolt syndrome
HUFA	highly unsaturated fatty acids
IAA	indispensable amino acids
IHN	infectious haematopoietic necrosis
IPN	infectious pancreatic necrosis
ISA	infectious salmon anaemia
LAP	land animal by-products
LED	light emitting diodes
LH	luteinizing hormone
LTLS	low trophic level species
MAB	maximum allowed biomass
MAS	marker-assisted selection
ME	metabolic energy
MR	mitochondria-rich
NALO	National Aquaculture Legislation Overview
NASCO	North Atlantic Salmon Conservation Organization
NE	net energy
NINA	Norsk Institutt for Naturforskning
NSP	non-starch part
OWI	operational welfare indicators
PAP	processed animal protein
PAR	photosynthetically active radiation
PD	pancreas disease
PGC	primordial germ cell
QTL	quantitative trait locus
RAS	recycling aquaculture system
RE	retained energy
RGL	relative gut length
ROMS	regional ocean modelling systems
ROV	remotely operated vehicles
SCM	single celled microorganisms
SCO	single cell oil
SCP	single cell protein
SGR	specific growth rate
SNP	single nucleotide polymorphisms
SPC	soy protein concentrate
SPDV	salmon pancreas disease virus
SRS	salmon rickettsial septicaemia
TAN	total ammonia nitrogen

TDC	true digestibility coefficient
TDER	total digestible energy requirement
TER	theoretical energy requirement
TGC	thermal growth coefficient
TU	thermal units
VHS	viral haemorrhagic septicaemia
WFE	whole fish equivalent

CHAPTER 1

Introduction

The Earth's growing population requires an ever increasing volume of food, including the provision of protein. The ocean makes up almost 71% of our planet's surface. By including the depth of the ocean, it is possible to grow and harvest in three dimensions, unlike on land where most food production is limited to two. The ocean therefore offers far greater potential for biological growth than dry land. To achieve future food security the ocean must factor as an important contributor [1–3].

Currently, only about 7% of protein for human consumption comes from fish [4]. It is therefore reasonable to expect that this sector has the potential for significant growth. Of the world's animal protein consumption, 17% comes from the ocean; the rest is represented by traditional livestock, such as poultry, pork and beef [5].

Food from the sea either comes from the capture of wild fish stock or from aquaculture. Wild catches have been quite stable during the last decades, at around 90 million tonnes. Most wild fish stocks are either fully exploited (61%) or overexploited (29%) [5]. The possibilities for increasing the tonnage of wild catches are very limited. The only way that the harvest from the ocean could increase appreciably is therefore through aquaculture. This has been recognized for some time; from the 1950s until today the aquaculture sector has been the fastest growing food production sector. In the early 1950s production was less than 1 million tonnes while production in 2018 was reported to be 81 million tonnes [6]. In the period from 2000 to 2018 there was a yearly increase in world aquaculture production of almost 6%.

Comparing the relationship between fishing and aquaculture to that between hunting and farming on land strengthens the claim that aquaculture will grow. Agriculture has almost totally taken over from the hunting of animals and gathering of edible plants in the wild in order to provide food for the growing human population. Through this shift, total harvested volumes have increased tremendously compared to those for hunting and gathering. It is obvious that traditional agriculture and fishing cannot support the growing population and this further indicates that the aquaculture sector must grow and develop in sophistication.

The aquaculture sector can be divided into shellfish (molluscs and crustacea), plants (seaweed and algae) and finfish. Finfish aquaculture (salmonids included) is of particular interest when it comes to satisfying the world's protein production needs. To be able to start sustainable aquaculture production of a species, the entire production cycle must be known and controlled,

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including spawning, hatching and start feeding. This means that the life cycle can be managed and manipulated artificially. Breeding programmes can then be established in which the best strains and individuals can be picked out as broodfish for the following generations. Through breeding programmes the fish will become better adapted to aquaculture production by selection of those best suited and, as a result, increased domestication will occur. Of course, also of major importance when starting aquaculture or farming of a new species is that it is a known species in the consumer market and that the price is high enough to cover the production cost related to farming.

Farming of Atlantic salmon (*Salmo salar*) has been a great success from the start, partly because it successfully fulfils the above-mentioned criteria, and the species has become a reference when it comes to aquaculture success. The salmon farming industry of today has a high level of industrialization compared to other farmed species within aquaculture, but salmonids still only account for 4.4% of the global seafood supply [4]. When commercial farming of Atlantic salmon started in the early 1970s the species was well known in the market and was a high-cost product; the market price then was higher than today's price (even taking account of inflation). The large-scale commercial fishing of Pacific salmon, another genus of salmon species quite equal in look and taste, was therefore an important door opener to the market. This was typically a seasonal fishery, so by use of aquaculture the market could be supplied with salmon all year round; this was successful in practice as the large growth in volume was consumed by the market. The biology and life cycle of Atlantic salmon are well known. Salmonids, especially Atlantic salmon, are highly appreciated by recreational anglers, which has driven an interest in enhancing wild stocks. From the 1950s a large number of hatcheries have been established worldwide for wild salmonid stock enhancement. There were even private initiatives undertaking private salmon ranching, through which knowledge about how to farm salmon was accumulated. Salmon ranching includes the set out of salmon in freshwater (or seawater) locations and letting them migrate to the sea where they find sufficient food to reach adult size, so there are no feed costs. When the salmon return to the place they were released as juveniles, they can be caught. However, the recapture percentage of this type of private ranching has been too low to achieve private economical sustainability.

To begin farming of a fish species domestication is a requirement. Domestication is necessary to ensure that the fish can perform optimally under farming conditions so that economic sustainability and profitability can be achieved. Atlantic salmon responded well to domestication and showed great potential for improvement by breeding. A large variation between families was documented and a large genetic gain has been attained on factors important to economy in farming.

Purely biologically, the salmonids, including Atlantic salmon, have a great advantage compared to other sea- and freshwater species because the eggs are large and result in larger fry. In addition, the hatched fry are equipped with a yolk sac, which supports growth in the first period of life. As a result, when the fry start to feed they are already well developed, and possess a functional digestive system that can digest dry formulated feed. Feeding can therefore be done directly with dry feed with a reasonable particle size. Other freshwater and seawater species are, however, so small and little developed after hatching that it will typically be necessary to use live feed in the first period of feeding. This is much more tricky and reduced survival rates should be expected. Compared to other salmonid species, including hybrids, Atlantic salmon offer a great advantage when it comes to growth in seawater and increased size at first maturation [7].

What makes modern salmon farming so sustainable is the good artificial control of the entire production cycle that can be obtained. Broodstock salmon are kept in sea- and freshwater. There is good knowledge of how to strip the brood fish and good fertilization rates of the eggs are achieved. The hatching process is known, and yolk sac fry can be relatively easily kept in good condition. Adapted feed for start feeding has been developed and low mortality occurs in this phase. Ongrowing in freshwater typically goes well, as does salmon smoltification before transport to sea cage farms for ongrowing until the required size for slaughter for human consumption or transfer to a broodstock farm is reached. The fish are then around 3 years old; brood fish approach maturity from the summer of their third or fourth year.

The success of Atlantic salmon aquaculture is evident when compared to other finfish species in aquaculture. During recent decades no other fish species have come close to the same growth in tonnage, and Atlantic salmon still achieve reasonably high prices.

Compared to traditional animal livestock, such as beef, pork, chicken and lamb, farming of Atlantic salmon has a number of advantages. The production represents a low overall carbon footprint, a high feed conversion ratio (FCR) is achieved, and less freshwater is used for production [8]. For the production of 1 kg edible product the release of carbon dioxide is estimated to be 7.9 kg, while for chicken, pork and beef similar values are estimated to be 6.2 kg, 12.2 kg and 39 kg, respectively [4,9]. Freshwater requirements are also favourable with 2000 l/kg for salmon (farmed salmon fillet in Scotland) compared to 4300 l/kg, 6000 l/kg and 15,400 l/kg, respectively, for poultry, pork and beef [4].

Atlantic salmon has good nutritional value; the protein content is high, it is rich in vitamins and minerals and it contains the healthy omega-3 fatty acids, which gives an advantage over traditional animal livestock. The edible meat produced per kilogram of food supplied is also much higher than for traditional animal livestock. To provide for the protein requirements of the growing human population a high FCR is required, which is another advantage of salmon farming. Atlantic salmon are also cold blooded and therefore do not need to spend energy on heating up their bodies as land animals do. They are weightless in water, meaning no energy is needed to stay in an upright position. Also, the release of metabolic waste products (ammonia) is more effective.

Today, farming of Atlantic salmon has become a large worldwide industry creating many jobs both directly related to the farming process and indirectly in the supplier industries, related to the processing of salmon and logistic services. Taking Norway as an example, over 8000 people are directly employed in the aquaculture industry in work related to salmon production [10] and more than twice as many are employed if activities connected to the business are included, meaning close to 30,000 full-time jobs either directly or indirectly. Similar numbers are reported from the other salmon producing countries, such as Scotland with over 8000, Canada with over 10,000 and Chile (including processing) with over 30,000 employed [11]. Taking the entire salmon farming industry, including processing and services related to the industry, it can be estimated that more than 100,000 jobs are sustained worldwide. Furthermore, it is also of major importance that many of the jobs are based in rural areas and in areas with limited employment, such as in small communities in coastal areas. In both the salmon production and processing industries both genders are employed, which is of additional importance to maintain settlement in rural areas. In many rural districts salmon aquaculture has also been a major driver for improving infrastructure, such as roads, bridges, electricity and the internet, and salmon farms and salmon slaughterhouses have become cornerstone companies in many rural communities.

However, only a limited number of countries have the natural conditions suited to production of Atlantic salmon in sea cages, which until today has been the method used to farm salmon for the consumer market (excluding a low tonnage produced on land or in closed cages) (Figure 1.1). The ideal natural conditions for sea cage farming include an acceptable seawater temperature and a sheltered coastline with fjords and bays. Such conditions feature in a latitude belt in both the northern and southern hemispheres. Today, Norway, Chile and the UK are top among a short list of producers (see Figure 2.3). Atlantic salmon is only a native species in the countries with a coastline on the Atlantic Ocean in the northern hemisphere; in all other salmon producing countries it is a non-native species. The introduction of land-based farms and the use of recycling aquaculture system (RAS) technology will allow other countries to efficiently farm salmon. These production method developments are already evident in the planning and establishment of a number of land-based farms, several outside the native area of the species. Also, the introduction of offshore cages that can tolerate higher waves will increase the number of countries that can start salmon production, because this removes the need for a sheltered coastline. Global heating will also be an important regulator for where it is possible to grow Atlantic salmon in the future. The rise in seawater temperature due to climate change will push ongrowing sea cage farms further north and south.

Figure 1.1 Ongrowing sea cage farm, with a well boat collecting fish for slaughtering.

The aim of this textbook is to supply information on how to produce Atlantic salmon under aquaculture conditions in an effective way. It is divided into chapters covering the operation of broodstock farms (5), hatcheries and smolt farms (6 and 7), ongrowing in sea cage farms (8) and production planning in salmon farms (9). Chapters 2 and 3 give an overview of the Atlantic salmon farming industry and the history of the salmon industry. Chapters 4 and 10–12 are simpler supplementary chapters covering salmon biology, salmon feeding, salmon breeding and the diseases encountered in salmon farming. The book concludes with Chapter 13 which discusses future perspectives.

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