CRC

CULTURE *of* SALMONID FISHES

Robert R. Stickney

CRC PRESS

Culture of Salmonid Fishes

Editor

Robert R. Stickney
Professor
School of Fisheries
University of Washington
Seattle, Washington

CRC Press
Boca Raton Ann Arbor Boston London

Library of Congress Cataloging-in-Publication Data

Culture of salmonid fishes / editor, Robert R. Stickney.
p. cm.
Includes bibliographical references (p.) and index.
ISBN 0-8493-5310-6
1. Salmon. 2. Trout. 3. Salmonidae. 4. Fish-culture.
I. Stickney, Robert R.
SH167.S17C85 1991
639.3'755--dc20 91-4104
CIP

Direct all inquiries to CRC Press, Inc., 2000 Corporate Blvd., N.W., Boca Raton, Florida 33431.

International Standard Book Number 0-8493-5310-6

Library of Congress Card Number 91-4104

Printed in the United States of America 1 2 3 4 5 6 7 8 9 0

PREFACE

Aquaculture is the rearing of aquatic organisms under controlled or semi-controlled conditions.[1] That definition carries no implication that aquacultured products are reared with a profit in mind or that they are strictly reared for human consumption, though both objectives (often in combination) commonly exist. With respect to finfish aquaculture, particularly in North America, the objective is often to produce fish for stocking into sport and/or commercial fisheries.

Various species of trout and salmon, members of the family Salmonidae, are cultured in temperate and sub-Arctic climates around the world. In North America, salmonid fishes are cultured in nearly all 50 of the United States as well as in the provinces of Canada. Six species of salmon are produced, along with various species of trout. Spawning, egg incubation, and early rearing strategies are virtually the same whether the fish are to be released into the natural environment or maintained in captivity for extended periods. We have attempted to avoid redundancy in the chapters which follow by presenting early rearing methods only once for any given species. In general, chapters dealing with production of fish for release cover the early life history stages, as for example, with regard to Pacific salmon. That information is not repeated in subsequent chapters that deal with Pacific salmon.

Species discussed below were selected on the basis of their importance to the aquaculture community in the broad sense. Several additional species have been, or are being, cultured to various extents, but the bulk of the production involves the species or species groups discussed in the various chapters that follow.

The same principles of fish culture are generally applicable to all species. Culture techniques vary with respect to details, of course, but the needs for adequate culture systems, suitable water quality, properly formulated and manufactured feeds, disease control, and so forth are universal. Aquaculturists do tend — perhaps by convention or the temperature difference that is readily detected by the human senses — to make a distinction between warmwater and coldwater species. While there is really no logical reason for this separation, practitioners typically consider themselves to be specialists in the culture of warmwater fishes or coldwater fishes, rarely both. There is also what is arguably an illogical distinction by many between those who work with marine species as opposed to those who limit their activities to freshwater. The arbitrary nature of the latter distinction is obviated when one considers anadromous species (such as salmon) or catadromous species (such as eels).

In a companion volume, *Culture of Nonsalmonid Freshwater Fishes*,[1] we bowed to convention in two ways: by considering warmwater species and the so-called midrange species (those with a temperature optimum between those of coldwater and warmwater fishes), and by considering only freshwater species. In this volume, we concentrate on the salmonids, which represent the primary coldwater fishes of culture interest in the world today.

In recognition of the growing worldwide concern that aquaculture development has the potential, which in some cases has actually been realized, to negatively impact the natural environment, a chapter on controversies surrounding salmonid culture has been included in this book. That approach is a departure from the initial volume,[1] as is the first chapter, which provides a summary of life history information of the species covered in the book.

Robert R. Stickney
Seattle, Washington

THE EDITOR

Robert R. Stickney, Ph.D., is a professor in the School of Fisheries at the University of Washington, Seattle, Washington. The School of Fisheries is the oldest academic fisheries program in the United States and has a faculty in excess of 30 and a student enrollment of about 200, the majority of whom are graduate students.

Dr. Stickney took his B.S. and M.A. in Zoology at the University of Nebraska (1967) and the University of Missouri (1968). He received his Ph.D. in Oceanography from Florida State University in 1971. He was on the staff at the Skidaway Institute of Oceanography in Savannah, Georgia from 1971 to 1975, then joined the faculty of the Department of Wildlife and Fisheries Sciences at Texas A&M University, College Station, Texas. In 1984, Dr. Stickney accepted the position of Director of the Fisheries Research Laboratory at Southern Illinois University in Carbondale, Illinois. He accepted his current position in the summer of 1985.

Dr. Stickney's research has involved studies on aquatic organisms ranging from phytoplankton to marine mammals, but he has concentrated his work in the area of fish culture. He and his graduate students have conducted extensive studies on channel catfish, tilapia, and more recently, salmon, trout, and Pacific halibut. Dr. Stickney has been primarily interested in fish nutrition and the environmental requirements of fish under culture conditions.

Over 100 scientific papers have been authored or co-authored by Dr. Stickney. He has also written or been involved in editing eight books. He is a certified fishery biologist and member of the American Fisheries Society and has served as President of the Fish Culture Section and the Education Section of the Society. He is a member of the World Aquaculture Society and has served on its Board of Directors since 1987. He was elected to the office of President-elect in 1990 and assumed the presidency of the World Aquaculture Society in 1991. Dr. Stickney is also a member of the American Association for the Advancement of Science, the American Society of Limnology and Oceanography, the American Institute of Nutrition, and is a Fellow of the American Institute of Fishery Research Biologists.

Dr. Stickney serves as Chairman of the Board of Institutional Advisors for the Fish Stock Assessment Collaborative Research Support Program of the Agency for International Development, and on the Board of Directors of the Western Region Aquaculture Consortium (past Board Chairman). He has been actively involved in international development with respect to aquaculture and fisheries.

TABLE OF CONTENTS

Chapter 1
Salmonid Life Histories 1
Robert R. Stickney

Chapter 2
Trout Culture 21
Ernest L. Brannon

Chapter 3
Culture of Pacific Salmon for Stocking 57
John D. McIntyre

Chapter 4
Growout of Pacific Salmon in Net-Pens 71
Robert R. Stickney

Chapter 5
Culture of Atlantic Salmon 85
Arni Isaksson

Chapter 6
Coho Salmon Farming in Japan 131
Conrad V. W. Mahnken

Chapter 7
Policy Issues with Respect to Salmonid Culture 151
David Fluharty

References 163

Index 181

Chapter 1

SALMONID LIFE HISTORIES

Robert R. Stickney

TABLE OF CONTENTS

I. Introduction 2

II. Taxonomy 2

III. Life History Information 3
- A. Pink Salmon (*Oncorhynchus gorbuscha*) 4
- B. Chum Salmon (*Oncorhynchus keta*) 5
- C. Coho Salmon (*Oncorhynchus kisutch*) 6
- D. Sockeye Salmon (*Oncorhynchus nerka*) 8
- E. Chinook Salmon (*Oncorhynchus tshawytscha*) 10
- F. Rainbow Trout (*Oncorhynchus mykiss*) 12
- G. Cutthroat Trout (*Salmo clarki*) 14
- H. Atlantic Salmon (*Salmo salar*) 16
- I. Brown Trout (*Salmo trutta*) 17

IV. Homing in Salmonids 18

V. Parr-Smolt Transformation in Anadromous Salmonids 19

I. INTRODUCTION

Traditionally, mention of the word trout has often conjured up the image of a person in waders, standing in a clear mountain stream and casting a dry fly into a pool. On the other hand, the word salmon may elicit a mental picture of bears pulling bright red fish out of the water during the spawning season. These are just two possibilities among many, but in North America, at least, most people are familiar with both groups of fishes, whether they are personally involved in fishing or just see trout and salmon in their local supermarkets.

Trout have been produced in hatcheries for well over a century. Various native species have been widely introduced around the country, and a European cousin was brought in many decades ago to augment existing sport fisheries. In many states, sportfish populations of trout would not be sustained without augmentation stocking. Some populations are maintained solely by stocking as there is little or no natural recruitment.

Commercial trout culture began in earnest within the past few decades, and it was not until the 1970s that the industry began to mature. Today, the production of trout for direct sale in restaurants and supermarkets is centered in the Hagerman Valley of Idaho where large underground streams outcrop along the Snake River Canyon and pour thousands of cubic meters per second of almost ideally suited water into the Snake River. A significant portion of that water is now intercepted and run through raceways on aquaculture facilities which produce the bulk of all commercially produced trout in the nation.

Up until a few years ago, the only access most people in the United States had to salmon was from a can. Today, fresh salmon fillets and steaks are available in most major cities, typically on a year round basis. Fish from the wild contribute to the fresh fish market during the portion of the year when they are available to commercial fishermen, while cultured fish are responsible for expanding the market nationwide and making the product available through the year. Some cultured salmon are produced in the United States, but a large percentage comes from Norway and, increasingly, Canada, Chile, Scotland, and a few other countries are also culturing significant amounts of salmon.

In this book, we examine the production of fishes within the family Salmonidae, which includes the various species of trout and salmon. Some of the material deals with the extremely important subject of producing fingerlings for release by government agencies into the natural environment for enhancement of sport and, in some cases, commercial fisheries. The subject of ocean ranching, wherein private enterprise produces fish, releases them into the marine environment, and harvests their own stock when it returns, is also covered in these pages. Trout and salmon are also being produced entirely in captivity, primarily in raceways, marine net-pens, and freshwater cages, and those techniques are fully described.

This chapter describes the basic life histories of the important species of trout and salmon. While many of the species share similar environmental requirements, habitats, and behavioral patterns, there are significant distinctions among them, some of which impact culture strategies. The culture of many of the species outlined in this chapter is detailed later in the book.

II. TAXONOMY

Trout and salmon are members of the family Salmonidae. The family is characterized by torpedo-shaped fishes with soft fin rays and adipose fins. Salmonids produce large eggs (several mm in diameter), the sexes are separate, and spawning generally occurs in the gravel of streams or, less commonly, along the shorelines of lakes or in the brackish water areas of estuaries.

TABLE 1
Scientific and Common Names of Selected Salmonid Fishes[2,3]

Scientific name	Common name
Oncorhynchus gorbuscha	pink salmon
Oncorhynchus keta	chum salmon
Oncorhynchus kisutch	coho salmon
Oncorhynchus mykiss (formerly *Salmo gairdneri*)	rainbow trout
Oncorhynchus nerka	sockeye salmon
Oncorhynchus tshawytscha	chinook salmon
Salmo clarki	cutthroat trout
Salmo salar	Atlantic salmon
Salmo trutta	brown trout
Salvelinus fontinalis	brook trout
Salvelinus namaycush	lake trout

The primary genera of interest to culturists are *Salmo* and *Oncorhynchus,* and to a lesser extent, *Salvelinus.* It has generally been true in the past that trout were placed in the genera *Salmo* and *Salvelinus,* while salmon were in the genus *Oncorhynchus.* The exception was the Atlantic salmon, *Salmo salar,* which, because of the genus to which it has been assigned, has been considered a trout by many scientists.

Added confusion was created in 1989 when the rainbow trout, *Salmo gairdneri,* was reclassified and placed in the genus *Oncorhynchus.*[2] Today, rainbow trout are recognized as *O. mykiss,* which may technically make them a species of salmon rather than trout. The fact that the steelhead trout is recognized as a sea-run strain of the rainbow (both being *O. mykiss)* provides credibility for the argument, though cutthroat trout (*Salmo clarki*) also have strains which migrate to saltwater for portions of their lives.

To avoid clouding the issue, throughout this book we utilize the American Fisheries Society taxonomy for both scientific and common names,[3] with the exception that we have adopted the new taxonomy for rainbow trout[2] because it has now been accepted by the American Fisheries Society.

III. LIFE HISTORY INFORMATION

Included in the family Salmonidae are various species commonly known as cisco, trout, salmon, whitefish, and grayling. Those which are of current interest to fish culturists are included in Table 1. Listed in that table are such species as chum and pink salmon which have not received anything comparable to the attention that has been focussed on coho salmon, chinook salmon, Atlantic salmon, and rainbow trout. There are hatcheries, particularly those associated with ocean ranching operations in Alaska, which are producing chum and pink salmon. Sockeye salmon were studied for a period in the past and found difficult to rear, but recent attempts to revisit that species have resulted in the development of what appears to be dependable culture practices.[4] Interest in the culture of Arctic char (*Salvelinus alpinus*) is developing, and that species could become a commercial aquaculture species at high latitudes where temperatures do not support rapid growth of other salmonid species.

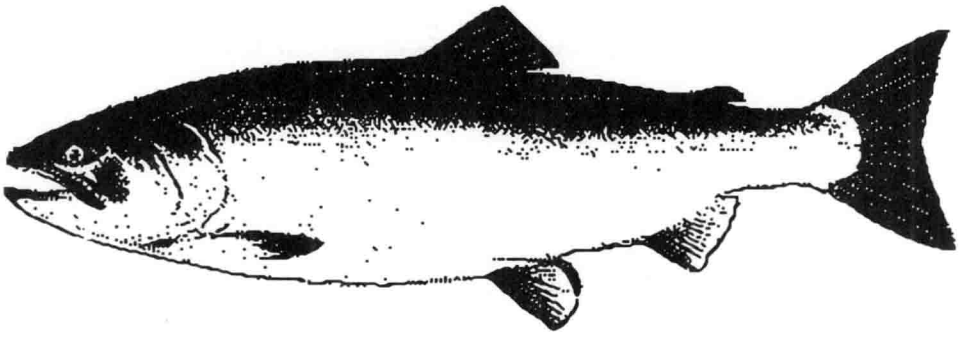

FIGURE 1. Pink salmon (*Oncorhynchus gorbuscha*) immature form. (Computer-generated drawing by Kenneth Adkins, School of Fisheries, University of Washington, Seattle.)

A. PINK SALMON (*ONCORHYNCHUS GORBUSCHA*)

Of the five species of Pacific salmon which are native to North America, the pink salmon is one of the smallest. It reaches up to 76 cm in length and weighs from 1.4 to 2.3 kg at maturity. Spawning populations are distributed in rivers and small streams most commonly from northern California to Alaska. They can also be found in the Aleutian, Commander, and Kuril Islands of the North Pacific Ocean.[5]

The physical characteristics of pink salmon (Figure 1) have been described as follows:[5]

- Fins — dorsal fin with 10 to 15 rays
  caudal fin slightly forked
  anal fin with 13 to 17 rays
  pectoral fins each with about 15 rays
  pelvic fins each with about 10 rays
- Gill rakers — 26 to 34 on the first arch
- Scales — 150 to 205 on the lateral line

In general, pink salmon are metallic blue on their dorsal surface and silvery on the sides. There are numerous black, oval spots on the upper sides of the body, the back, and the caudal fin. Characteristic of species within the genus, mature fish take on different colors from the immature form. Mature males are red to yellow on the sides of the body with blotches of brown; they are dark along the back. Females are olive green on the sides of the body with dusky stripes.[5]

As is true of the other species of Pacific salmon, pink salmon are anadromous. They spawn in freshwater, spend a portion of their life in that environment, go through a process called smoltification which physiologically prepares them for entry into the marine environment, then migrate to the sea for a period of time. They return to their natal stream to spawn upon reaching maturity. A summary of the life history patterns of the five species of Pacific salmon found in North America is presented in Table 2.

Pink salmon spawning has been described by Bailey.[6] Spawning occurs during late summer or early fall, depending upon the location of the spawning stream. As is generally true for all species of Pacific salmon, spawning occurs later in the year at the lower latitudes and earlier at high latitudes. Spawning typically occurs in short streams, though the species has been known to spawn at least 330 km from the mouth of certain streams in British Columbia and California, and twice that far upstream in Asia. The fish may also spawn in

TABLE 2
Life Cycle Patterns of Five Species of North American Pacific Salmon in Alaska Waters[8]

Species	Freshwater habitat type	Time in freshwater after fry emergence	Time at sea (yr)
Pink	short streams and lakes	usually less than 1 day	1
Chum	short and long streams	less than 1 month	2—4
Coho	short streams and lakes	12—24 months	1—3
Sockeye	short streams and lakes	12—36 months	1—4
Chinook	large rivers	3—12 months	1—4

the lower reaches of short streams or even in intertidal areas where the eggs may be alternately exposed to fresh and brackish water during incubation.

Female pink salmon, again typical of the other Pacific salmon, construct nests, called redds, in the spawning gravel. The redds may be from 10 to 25 cm deep and usually occur in riffles.[6] Females generally release from about 1,500 to 1,900 eggs[5] which are fertilized as they fall into the redd and become deposited in the interstices that exist in the gravel.

Incubation requires up to several months, depending upon temperature, with hatching occurring in the spring of the year following spawning. Normal development will not occur at constant temperatures below about 5°C, though exposure to that temperature for a month before exposure to 2°C apparently results in normal larval development.[7] During the spawning season eggs may be destroyed as females construct redds in areas which were previously utilized by other fish. Other losses can occur because of low dissolved oxygen levels in the gravel, eggs becoming dislodged by floods, mortality caused by freezing temperatures, and predation. The percentage of eggs that survive until emergence of the fry is often less than 25%.[6]

Upon hatching, larval pink salmon remain in the gravel for a period, usually a few weeks, during which they obtain nutrition from their large yolk sacs. Pink salmon fry emerge from the gravel at night and migrate directly to the sea (Table 2). The young fish form schools near the surface once they reach the estuary and will then migrate along the shore. They are carried out to sea by currents within a few days to several weeks.[6]

Pink salmon are predaceous sight feeders. They initially feed on planktonic organisms but adjust their food habits to squid and other fishes as they reach sizes where they can capture and consume those types of prey.[6] The fish prefer temperatures between 7 and 15°C in the Gulf of Alaska.[5] They return to spawn in their second year of life.[8] As is true of all Pacific salmon species, the adults die soon after spawning.

B. CHUM SALMON (*ONCORHYNCHUS KETA*)

Chum, also known as dog salmon, occur from southern California to Alaska. They can be found in the Aleutian, Commander, and Kuril Islands, as well as in the Siberian Arctic region, and are distributed southward in Asia to Japan.[5] The chum salmon is the most widely distributed of the Pacific salmon species and is second in abundance.[8] Distinguishing characteristics are as follows:[5]

- Fins — dorsal fin with 10 to 13 rays
  caudal fin slightly forked
  anal fin with 13 to 17 rays
  pectoral fins each with about 16 rays
  pelvic fins each with about 10 rays

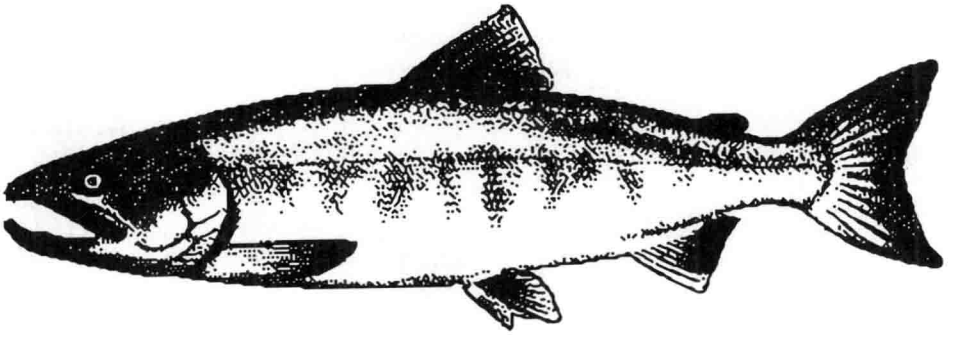

FIGURE 2. Chum salmon (*Oncorhynchus keta*) immature form. (Computer-generated drawing by Kenneth Adkins, School of Fisheries, University of Washington, Seattle.)

- Gill rakers — 18 to 26 on the first arch
- Scales — 126 to 131 on the lateral line

Chum salmon are metallic blue in color on their dorsal surfaces with occasional black speckling but no distinct black spots. The tips of the pectoral, anal, and caudal fins are dark at their tips (Figure 2). When they mature in freshwater, they develop reddish or dark streaks or bars. The species has been known to reach lengths slightly in excess of 100 cm and may weigh up to 15 kg.[5]

Spawning occurs during late summer and fall in streams of various lengths[5,8] (Table 2). Most fish spawn from June to January, with northern populations spawning by the end of August or early in September.[9] Southern populations spawn later.[10,11] Spawning sites are known from the United States, Canada, Japan, Korea, and the U.S.S.R.[9] Adults generally select gravelly riffles in habitats ranging from tidal flats associated with small streams to springs in the headwaters of larger stream systems. The Yukon River run is the longest, with spawners being found over 2,500 km upstream from the river mouth.[8]

Fry emerge from the gravel in the spring and migrate directly to sea, with the trip requiring up to a month in streams where the young fish have to negotiate long distances (Table 2). Those which have short distances to traverse between the spawning grounds and the sea do not feed until they reach the ocean. During their first summer at sea they consume small invertebrates. The food habits of chum salmon change to larger invertebrates and fish as they grow and are able to catch and consume the larger prey species. The fish spend 2 to 4 years at sea and return to spawn at 4 to 5 years of age.[8]

C. COHO SALMON (*ONCORHYNCHUS KISUTCH*)

The coho salmon (also known as the silver salmon) is a popular sport fish in the Pacific Northwest and is one of the salmon species that has been introduced to the Great Lakes where a large sport fishery has developed. The first coho salmon eggs, over one million in number, were introduced into Lake Michigan by the Michigan Department of Natural Resources in 1966. Introduction of the fish to the other Great Lakes was conducted in both the United States and Canada in 1968 and 1969. By 1983, the total number of fish planted in the Great Lakes had reached 83.9 million.[12]

Natural coho salmon populations occur most commonly from Monterey, California north to Point Hope, Alaska. The species has been reported as far south as Chamalu Bay, Mexico.[13] Coho are found throughout the Aleutian Islands, and from the Anadyr River in the U.S.S.R., southward to Korea and Hokkaido, Japan.[14] The fish are most abundant between Oregon

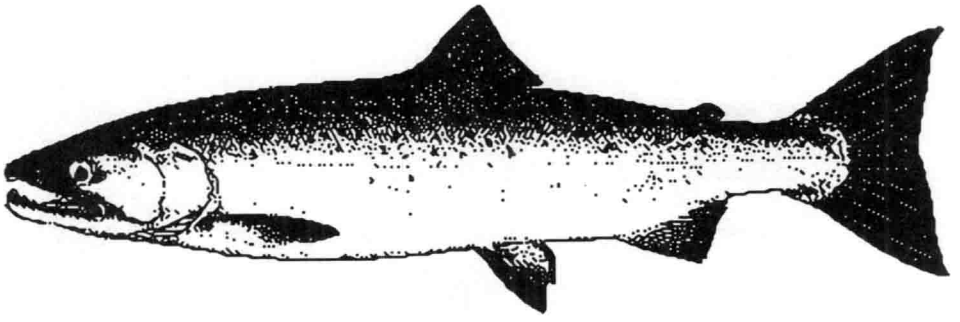

FIGURE 3. Coho salmon (*Oncorhynchus kisutch*) immature form. (Computer-generated drawing by Kenneth Adkins, School of Fisheries, University of Washington, Seattle.)

and southeast Alaska[5] and were rare in the Sacramento River system of California until the California Department of Fish and Game stocked them in 1956 to 1958.[15] They have the following characteristics:[5]

- Fins — dorsal fin with 9 to 13 rays
  caudal fin slightly indented
  anal fin with 13 to 16 rays
  pectoral fins each with about 15 rays
  pelvic fins each with about 11 rays
- Gill rakers — 19 to 25 on the first arch
- Scales — 118 to 147 on the lateral line

Immature fish are metallic blue on the dorsal surface and silvery on the sides, ventral surface, and caudal peduncle. There are irregular black spots on the back and upper lobe of the caudal fin (Figure 3). Maturing males in freshwater are bright red on the sides, with bright green coloration on the back and head. The mature females are less strongly colored.[5]

Entry of coho salmon into freshwater begins in July throughout most of the range of the species, with upstream runs occurring from August to February. Typically, the adults spend 30 to 60 days in freshwater, with North American fish demonstrating peak spawning activity between September and January, though some fish will spawn as late as March. Spawning usually occurs in small streams, but the species has also been known to spawn in large rivers, particularly within 240 km of their mouths (Table 2). Spawning habitat typically includes current velocities as fast as 0.3 to 0.5 m/sec as compared with 0.1 m/sec for sockeye salmon.[14]

Coho salmon have been captured at sea as far as 1,930 km from their point of origin, though they tend to remain within a few hundred kilometers of the coast. They are usually found within 10 m of the sea surface except when the surface water is warm. Some fish are nearshore residents throughout the period of their lives spent in the marine environment. There are groups of coho salmon, for example, which spend the entire seawater period in the waters of Puget Sound, Washington, while others migrate out into the Pacific Ocean after variable periods in the Sound.[14]

In Kamchatka, U.S.S.R., spawning occurs at temperatures between 0.8 and 7.7°C,[16] while on the west coast of the U.S., spawning has been reported over a temperature range of 4.4 to 9.4°C.[17] When held at constant incubation temperatures, coho embryos will withstand temperatures between 1.3 and 12.4°C.[18] Small changes in temperature can lead to

relatively rapid changes in development rate. For example, incubation requires 38 days at 11°C, 48 days at 9°C, and 86 to 101 days at 4.5°C.[14,19]

Fecundity varies as a function of the size of the spawning female, the geographic area where the fish are found, and the individual year.[14] The general range is from 1,440 to 5,700 eggs for females ranging from 44 to 72 cm long in Washington.[20] Fecundity in coho salmon can be calculated from the following formula:[19]

$$\text{Number of eggs} = 0.01153 \times \text{fork length}^{2.9403}$$

The eggs are demersal, red in color, and from 4.5 to 6.0 mm in diameter.[20] A female may deposit eggs in three to four different redds which she constructs by lying on her side and beating the gravel with her tail.[14]

The newly hatched fish, called alevins, begin emerging from the gravel 2 to 3 weeks following hatching and may continue to emerge for an additional several weeks.[21] They are photonegative at first, but become photopositive with time. Emergence occurs from March to July. Fry live in shallow gravel areas, at first forming schools, which later disperse. The fry are most attracted to water temperatures between 10 and 15°C and dissolved oxygen concentrations near saturation; they are typically found in riffles that have few sediments.[17,22,23]

As the fish grow to fingerling size in freshwater, they are known as parr. Parr are characterized by the development of 8 to 12 distinct vertical dark bars along their sides. The bars are narrower than the interspaces between them.[24]

Some coho salmon migrate to sea during their first year in freshwater, but migration during the second year is more common (Table 2). Two years in freshwater is typical for fish produced in the Yukon River drainage, for example.[20] If the fish are grown in warmer than normal water, which is sometimes possible under hatchery conditions, growth to the size of smolting can be accelerated. A strain of fish at the University of Washington has been adapted to smolt at 6 months instead of the normal 18 months by rearing the fingerlings in water of approximately 9 to 13°C.[25] Those fish returned from sea after 18 months as compared with the normal 2 years at sea.

The movement of fish from freshwater to the marine environment, known as outmigration, occurs primarily at night.[26] Smoltification may occur earlier than normal when freshwater temperatures are unusually high.[27] This can lead to outmigration of young coho salmon into marine conditions that are unfavorable, e.g., limited food resources.

D. SOCKEYE SALMON (*ONCORHYNCHUS NERKA*)

The sockeye, or red salmon, is found in commercial quantities along the North American coast from the Columbia River northward to Bristol Bay, Alaska. The species occurs throughout the Aleutian, Kuril, and Commander islands in the North Pacific, and there is a large population found around the Kamchatka peninsula and in the northern Sea of Okhotsk. Sockeye salmon have been observed in Oregon waters of North America and in northern Hokkaido, Japan, but those sightings are relatively unusual. Characteristics of the species, which is depicted in Figure 4, are as follows:[5]

- Fins — dorsal fin with 11 to 16 rays
  caudal fin moderately forked
  anal fin with 13 to 18 rays
  pectoral fins each with about 16 rays
  pelvic fins each with about 11 rays

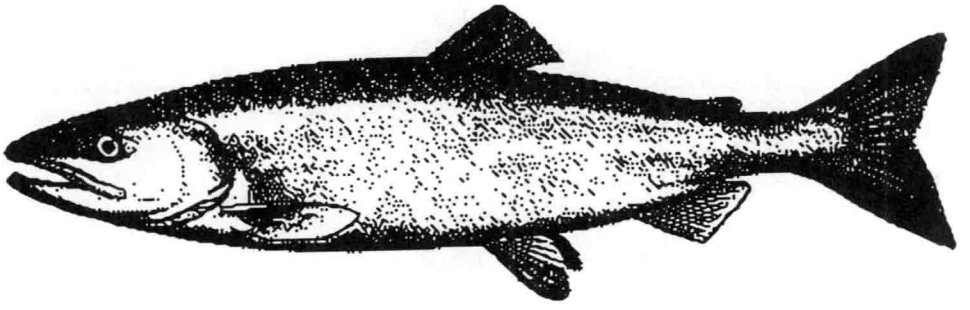

FIGURE 4. Sockeye salmon (*Oncorhynchus nerka*) immature form. (Computer-generated drawing by Kenneth Adkins, School of Fisheries, University of Washington, Seattle).

- Gill rakers — 28 to 40 on the first arch
- Scales — 125 to 145 on the lateral line

Sockeye reach lengths up to 84 cm[5] and may weigh up to 6 to 7 kg.[28] Fish from different river systems have sizes characteristic of their native stocks.[5] Spawners range in age from 2 to 7 years, with most being of ages intermediate to those extremes.[29]

The species is unusual in that it spawns in both streams and lakes (Table 2). Spawning takes place in the late summer or autumn in river inlets and outlets associated with lakes and in the lakes themselves. The females construct redds that are 25 to 40 cm deep and may occur at water depths as great as nearly 30 m. In Alaska, where the largest North American concentrations of sockeye are found, spawning occurs when the water temperature ranges from about 5 to 10°C.[29]

Fecundity ranges from about 2,200 to over 4,300 eggs per female, with the average being 3,720. Incubation can require as little as 50 days and as long as 5 months, depending upon temperature.[5] The lower temperature threshold for normal development of sockeye embryos is reportedly about 5 to 6°C, while the upper temperature limit for egg development is 13 to 14°C. If sockeye eggs are maintained at 6°C for 96 hours following fertilization, they can withstand temperatures as low as 2°C for the remainder of the developmental period.[30]

Sockeye fry emerge from the gravel in the winter and form schools. Those that emerge in streams migrate to lakes, while those spawned in lakes remain in those bodies of water. While in freshwater they are subject to predation by char, sculpins, trout, and birds.[29] In Lake Washington, predation from squawfish has also been reported.[31]

The rivers associated with Bristol Bay, Alaska often have large lakes associated with them, some of which have been heavily studied by salmonid biologists. Lake Iliamna and the Wood River lake system, which features a series of large lakes connected to one another by short stretches of river, are two systems that have been studied since the mid-1940s by scientists associated with the Fisheries Research Institute of the University of Washington.[32] Annual estimates of Bristol Bay sockeye runs are produced by biologists associated with the University of Washington and the Alaska Department of Fish and Game who study the Alaska lake systems.

Young sockeye spend from 1 to 3 years in freshwater and an additional 1 to 4 years at sea as shown in Table 2, though some authors give a range of 1 to 4 years in freshwater and 1 to 3 years at sea.[29] Outmigration of smolts usually occurs at night. When the fish reach the sea they feed first on planktonic crustaceans and eventually convert to shrimp, squid, and small fish as the salmon attain sufficiently large sizes to accept those prey items.

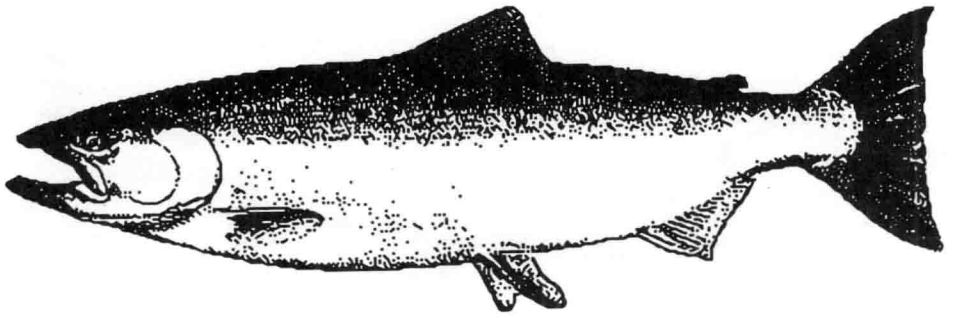

FIGURE 5. Chinook salmon (*Oncorhynchus tshawytscha*) immature form. (Computer-generated drawing by Kenneth Adkins, School of Fisheries, University of Washington, Seattle.)

E. CHINOOK SALMON (*ONCORHYNCHUS TSHAWYTSCHA*)

The chinook, or king salmon (Figure 5), is the largest of the Pacific Ocean species, and is highly prized as a sportfish. The famous Kenai River salmon run, for example, is fished on by thousands of anglers in search of trophy chinooks that may exceed 30 kg in weight. The record for the species is over 57 kg, though the common range of chinooks seen in both the sport and commercial catches is generally from 6 to 23 kg.[33] The fish has the following characteristics from which it can be identified:[5]

- Fins — dorsal fin with 10 to 14 rays
  caudal fin moderately forked
  anal fin with 13 to 19 rays
  pectoral fins each with about 14 rays
  pelvic fins each with about 10 rays
- Gill rakers — 18 to 30 on the first arch
- Scales — 130 to 165 on the lateral line

Chinook are greenish blue to black on the dorsal surface. They have irregular black spots on the dorsal fin, both lobes of the caudal fin, back, and upper sides. There is also black along the bases of the teeth;[5] thus, the fish is also called the blackmouth.

The original range of the chinook salmon was from the Ventura River, California to Point Hope, Alaska in the northwestern Pacific Ocean. In the northeastern Pacific, the species has been found from the Anadyr River in the U.S.S.R. to Hokkaido, Japan.[34,35] Spawning populations now occur from the Sacramento-San Joaquin River system in California north to Point Hope, Alaska.[36] Chinook spawn in some 640 streams along the Pacific coast, with major populations occurring in the Sacramento, Columbia, Copper, Nushagak, Kuskokwim, and Yukon Rivers of the U.S. and some 14 rivers in Canada.[37]

Chinook salmon, like coho, have been planted in the Great Lakes and contribute significantly to the sport fishery that has developed in those bodies of water. Chinook plantings began in lakes Michigan and Superior in 1967. By 1983, 108 million fish had been stocked. The fingerlings are maintained for 6 months in hatcheries before release. The stock utilized in the Great Lakes matures in 3 to 4 years.[12]

There are four recognized races of chinook salmon: spring, summer, fall, and winter. There is a great diversity which exists in races of chinook with respect to time of entry of the adults into river systems, the timing of their spawning activities, the distance that they travel from sea to the spawning grounds, the length of time that they spend in both freshwater and the marine environment, and their average age and size at maturity (Table 2).[33] The

Columbia River is an example of this population diversity in action. Three races are recognized in the Columbia River on the basis of time of entry into the river, time of spawning and age, and time of smolt outmigration. Spring chinook enter from February through May, summer chinook from June through August, and fall chinook from mid-August through October.[34,38]

As one moves from the south to the north, the following tendencies are found:

- The number of races decreases from four in the Sacramento River to three in the Columbia, Fraser, and Nanaimo Rivers, to two in southeastern Alaska, and one in northern Alaska[33]
- Spawning occurs earlier in the year, with peaks coming in late August through October in the south and July through August in the north[33]
- The length of freshwater residence increases from a few weeks to a year in the southern portion of the range to an average of 1 to 2 years in the north[39]
- Average age at spawning increases from 3 to 6 years in California to 5 to 8 years in central and northern Alaska[33]

Chinook are well known for the prodigious lengths they may travel upstream on spawning runs. There are reports of returning adults finding their way up to 3,000 km in the Yukon River.[33] Returning adults that move into freshwater during the fall tend to spawn in mainstem or tributary streams shortly after they reach the spawning grounds. Those which make their runs into freshwater in the winter and spring may remain in deep pools near the spawning grounds for as long as 5 months before their eggs ripen and spawning activity is initiated.[15]

Female spawners typically select their nesting sites in gravel at the lower lip of a pool just above the riffle.[40,41] The redds average about 6 m^2 in size.[40] During the act of spawning, as many as 10 to 12 males may attempt to mate with a single female by the time all of her eggs have been deposited.[41,42] After spawning, the adults begin to deteriorate rapidly. They exhibit large open wounds and heavy fungal infections. Death normally occurs within 2 to 4 weeks.[41]

Fecundity varies from one chinook stock to the next. For example, in the Sacramento River, the average number of eggs per female is in excess of 7,000, while in the Klamath River, the average is just over 3,600.[36] Some individual females may produce up to 20,000 ova.[42] Eggs range in size from 6.3 to 7.9 mm in diameter,[43] and weigh 0.35 to 0.40 g.[44] The eggs, which are particularly vulnerable to shock,[36] will hatch over a range of 4 to 16°C, though colder temperatures can be tolerated during the later stages of development.[17,30,45] Spring chinook usually spawn when temperatures are declining. Their spawning occurs over a range of 4.5 to 18°C,[46] while fall chinook usually spawn over a temperature range of 5.0 to 13.4°C.[33] Hatching requires 204 days at a constant temperature of 1.7°C and only 28 days at 18.1°C.[47] The time required for hatching is equivalent to roughly 900 to 1,000 thermal units[48] (there is one thermal unit for each degree C above freezing for a 24-hour period).

Following hatching, the fry spend several weeks in the gravel before emerging. The alevins become positively phototaxic when they begin to migrate up out of the gravel.[36] Emergence generally occurs at night[36] in the period from February through June and will vary as a function of latitude, temperature, and the time at which the eggs were deposited.[33] An exception to the spring emergence of fry is the Sacramento River where winter chinook spawn during the spring and the fry hatch and emerge during mid-summer.[33]

Overwinter losses of juvenile chinook salmon (as well as juvenile coho salmon and steelhead trout) have been attributed to stranding and freezing, low dissolved oxygen, and