# Salmon and Sustainability: The Biophysical Cost of Producing Salmon Through the Commercial Salmon Fishery and the Intensive Salmon Culture Industry

by

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# Abstract

Technologies play a critical role in mediating the impact of the human enterprise on the ecosphere. Consequently, the adoption of more biophysically efficient technologies is essential if the sustainability of the human enterprise is to improve as populations and per capita consumption demands increase. Within this context, the biophysical efficiency of two salmon production technology systems were analysed and compared using ecological footprint and energy analysis. The two systems evaluated are the vessel-based commercial salmon fishery and the salmon farming industry, as both exist in British Columbia, Canada. In addition, the relative efficiency of the three harvesting technologies employed within the commercial fishery were also evaluated. The ecological footprint analyses entailed quantifying the marine and terrestrial ecosystem support areas needed to grow salmon, sustain labour inputs, and assimilate $CO_2$ equivalent to the greenhouse gases that result from industrial energy and material inputs. The energy analyses focussed exclusively on the direct and indirect industrial energy inputs to both systems. The results of both the ecological footprint and energy analyses indicate that salmon farming is the least biophysically efficient, and hence least sustainable system for producing salmon currently operating in British Columbia. On a species-specific basis, farmed chinook salmon (*Oncorhynchus tshawytscha)* appropriated the largest total area of ecosystem support at 16 ha/tonne. This was followed by farmed Atlantic salmon (*Salmo salar*) at 12.7 ha/tonne, and commercially caught chinook and coho salmon (*Oncorhynchus kisutch*) at 11 ha/tonne and 10.2 ha/tonne, respectively. Commercially caught sockeye (*Oncorhynchus nerka*), chum (*Oncorhynchus keta*), and pink salmon (*Oncorhynchus gorbuscha*) had the smallest total ecological footprints at 5.7, 5.2 and 5 ha/tonne, respectively. Results of the energy analyses followed a similar pattern. Farmed chinook salmon required a total fossil fuel equivalent industrial energy input of about 117 GJ/tonne while at the other extreme, total energy inputs to commercially harvested pink salmon amounted to only 22 GJ/tonne. Within both systems, however, opportunities exist to improve the biophysical efficiency of salmon production. Finally, amongst the three commercial fishing technologies evaluated, purse seining was approximately twice as efficient at harvesting an average tonne of salmon as were either gillnetting or trolling.

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# Dedication

For Adam Walker Tyedmers. May he share a future with wild salmon.

# Chapter 1: Introduction

> "The human species, considered in broad perspective, as a unit including its economic and industrial accessories, has swiftly and radically changed its character during the epoch in which our life has been laid. In this sense we are far removed from equilibrium – a fact which is of the highest practical significance, since it implies that a period of adjustment to equilibrium conditions lies before us, and he would be an extreme optimist who should expect that such adjustment can be reached without labour and travail. We can only hope that our race may be spared a decline as precipitous as is the upward slope along which we have been carried, heedless, for the most part, both of our privileges and of the threatened privation ahead. While such sudden decline might, from a detached standpoint, appear as in accord with the eternal equities, since previous gains would in cold terms balance the losses, yet it would be felt as a superlative catastrophy [sic]. Our descendants, if such as this should be their fate, will see poor compensation for *their* ills in the fact that *we* did live in abundance and luxury."
>
> Alfred Lotka 1924 (as appears in the 1956 reprint edition, p. 279)

I was motivated to undertake this dissertation because I am concerned, as was Alfred Lotka over 75 years ago, about the fate of human society. As a result, in this chapter I present some of the theoretical issues that both inspired and informed my research. I begin by briefly introducing the multifaceted ideal of sustainability and explore in greater detail the competing "weak" and "strong" approaches to it. Within this context, the important yet contrasting roles that technologies are believed to play in the pursuit of sustainability are discussed, as are the ways in which the competing visions of sustainability reflect profoundly divergent worldviews. This is followed by a discussion of the need for biophysical techniques for evaluating human activities which includes a brief review of some of the more prominent methods currently in use.

In the penultimate section of this chapter, I state my personal pre-analytic vision regarding the relationship between the economy and the ecosphere, and the role that technology plays in mediating this relationship. Finally, I introduce the case study that I have undertaken: an evaluation of how the use of different technologies affects the biophysical costs, and hence the relative sustainability, of producing salmon in British Columbia.

## Sustainability

During the closing decades of the 20$^{th}$ century, concern has grown regarding humanity's impact on the natural environment, or ecosphere, and its capacity, in turn, to continue to meet the resource

extraction and waste assimilation needs of a growing human population with rising per capita consumption demands. As a result, individuals, governments and private organisations are embracing the ideals of sustainable development and sustainability. However, because of the complexity of the relationships between humans and our environment and amongst ourselves, the apparently singular ideal of sustainability has likewise emerged as a complex multidimensional objective. Consequently, no single definition or evaluation method has been developed that encompasses all aspects of sustainability.

There is a long intellectual history of concern regarding the fate of human societies[1] and our impact on non-human life. However, it was arguably not until the publication of *Our Common Future* by the World Commission on Environment and Development (WCED) in 1987 that the concepts of sustainable development and sustainability were popularised. The WCED can also be credited with providing the first definition of sustainable development when it wrote: "Humanity has the ability to make development sustainable - to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs." (WCED 1987, p. 8).

Since the WCED first provided this rudimentary definition countless books and articles have been written that explore both quantitative and qualitative aspects of sustainability. While this has resulted in a more complete understanding of what sustainability entails, the picture that has emerged is not a simple one. In its broadest sense, sustainability encompasses three main domains; the social/cultural (Boothroyd 1991, Berkes and Folke 1994, Daily and Ehrlich 1996, Hediger 2000), the economic (Common and Perrings 1992, Pearce *et al.* 1994, Victor *et al.* 1995, Pearce 1998) and the ecological/biophysical (Rees 1990, 1995, 1996, Arizpe *et al.* 1991, Costanza and Daly 1992, Daily and Ehrlich 1992, Goodland *et al.* 1992, Rees and Wackernagel 1994). But while the importance of each of these broad domains, along with their many linkages and interactions, is now widely recognised, their integration into a single coherent solution to the sustainability challenge has remained elusive (Perrings 1994, Charles 1994, Robinson and Tinker 1995, Arrow *et al.* 1996, Daily and Ehrlich 1996, Costanza *et al.* 2000). In large part this reflects the difficulty of finding an optimal solution when as yet there is no one common framework or language available for evaluating and trading off the social, economic and biophysical dimensions of a given problem on an equal footing. This situation is exacerbated where an apparent improvement in one dimension results in a deterioration in other dimensions. Consequently, to date, most practical attempts to improve the

sustainability of human activities focus primarily on one or another of its aspects, resulting in the pursuit of partial solutions.

Without diminishing the importance of social/cultural aspects of sustainability, the issues that most interested me, and which consequently influenced my research, fall within the ecological/biophysical and, to a lesser extent, the economic realms of sustainability. As a result, the remainder of this chapter focuses in these areas.

## *Alternative Ecological Economic Approaches to Sustainability*

To date, a great deal of attention has been directed at understanding the interactions between and integrating the economic and ecological/biophysical aspects of sustainability (Daly and Cobb 1989, Daly 1991, Common and Perrings 1992, Pearce *et al.* 1994, Victor *et al.* 1995, Pearce 1998, Lange 1999). The trans-discipline that has emerged almost expressly in response to this challenge is known as ecological economics (Costanza 1991, Jansson *et al.* 1994). Within ecological economics, much of the current sustainability dialogue revolves around two related yet fundamentally conflicting approaches to achieving sustainability.

### Weak and Strong Sustainability

For simplicity, these concepts have become known as the weak and strong approaches to sustainability (Daly 1991, Pearce *et al.* 1994, Victor *et al.* 1995, Pearce *et al.* 1998). What they have in common is that in both cases their bottom line objective is the long-term maintenance or improvement of per capita human welfare. As such, both are fundamentally anthropocentric. The key differences arise, however, with respect to 1) the role that natural capital[2] is seen as playing in the maintenance of human welfare into the future, and 2) the importance of technologies, and human ingenuity generally, in overcoming scarcities in ecosystem goods and services. Underlying these differences are profoundly opposed worldviews with respect to the nature of the relationship between the human enterprise and the ecosphere.

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[1] In the West, formal concern regarding the fate of society dates to at least the Reverend Thomas Malthus' "Essay on the Principle of Population", published in 1798. For a review of many lesser known early writers on the limitations faced by society see Martinez-Alier (1987).

[2] Natural capital, together with manufactured and human capital, are the three forms of productive capital recognised by ecological economists. They are roughly analogous to the three factors of production - land, capital and labour respectively - as traditionally defined within neo-classical economics. Natural capital, however, encompasses a far greater range of ecosystem sourced goods and services than is traditionally associated with "land". It includes all the biotic and abiotic goods and services that either directly or indirectly contribute to the maintenance of the human enterprise. As with more traditionally defined resources, natural capital is often sub-divided into both non-renewable and renewable forms (Daly 1991, Costanza and Daly 1992, Goodland *et al.* 1992, Rees 1993, 1995, 1996).

Founded on neo-classical economic capital theory, weak sustainability would be achieved whenever per capita consumption of resources flowing from the *aggregate* stock of natural, manufactured and human capital remains constant or increases over time (Victor 1991, Daly 1991, 1994, Pearce *et al.* 1994, Victor et al. 1995, Pearce 1998)[3]. Consequently, it is possible to conceive of a "sustainable" human enterprise in which all natural capital assets are systematically liquidated[4] as long as part of the resulting stream of rents is re-invested in other forms of capital so as to maintain the productive capacity of the remaining aggregate capital stock. The key assumption underlying this approach is that manufactured and human capital are ultimately perfectly substitutable for all forms of natural capital. Closely tied to this belief is the faith that advocates of weak sustainability have in the creative genius of humanity to provide the technologies and innovations necessary to facilitate this substitution. As a result, within the context of weak sustainability, there are no limits to the growth potential of the human enterprise that result from fundamental resource scarcity[5]. A famous example of the technological optimism and faith in the boundlessness of the human enterprise held by many weak sustainability advocates was provided by the late Julian Simon when he wrote:

> "We now have in our hands - in our libraries, really - the technology to feed, clothe, and supply energy to an ever-growing population for the next 7 billion years. Most amazing is that most of this specific body of knowledge developed within the past hundred years or so, though it rests on knowledge that had accumulated for millennia, of course.
>
> Indeed, the last necessary additions to this body of knowledge - nuclear fission and space travel - occurred decades ago. Even if no new knowledge were ever invented after those advances, we would be able to go on increasing forever, improving our standard of living and our control over our environment. The discovery of genetic manipulation certainly enhances our powers greatly, but even without it we could have continued our progress forever." (Myers and Simon 1994, p. 65)

While strong sustainability shares a common bottom-line objective with weak sustainability, it differs markedly with respect to the means by which non-declining per capita welfare may be achieved. The key point of departure is that proponents of strong sustainability believe that manufactured and human capital are not perfectly substitutable for all elements of natural capital. Indeed, it is argued that manufactured and natural capital are overwhelmingly complementary and at best only marginally

[3] It has been argued that the maintenance of non-declining per capita utility rather than consumption may be a more appropriate basis upon which to evaluate sustainability (Pearce *et al.* 1994, Pearce 1998). Daly (1991), however, argues that such an approach amounts to a very weak sustainability criterion as it hinges on the psychic benefits that flow the aggregate capital stock and not on the physical productivity of the stock itself.

[4] In essence, this approach treats all forms of natural capital as non-renewable resources.

[5] Indeed, it has been argued that the only possible limits faced by humanity result from too small a human population. More people, the argument goes, would not only provide a greater pool from which creative genius would emerge but would also provide the impetus for innovation that results from short-term scarcity constraints.

substitutable (Daly 1991 & 1994, Costanza and Daly 1992, Goodland *et al.* 1992, Rees 1995). Paraphrasing Herman Daly (1994), more fishing boats can't substitute for fewer fish just as more carpenters or hammers can't substitute for less wood with which to build houses. Furthermore, the inherent complementarity of natural and manufactured capital remains true regardless of the amount of technology or human ingenuity that is brought to bear[6]. Consequently, if per capita welfare is to be maintained through time, then it is argued, the productivity of *each form of capital*, and in particular natural capital, must be maintained independently (Daly 1991 & 1994, Costanza and Daly 1992, Goodland *et al.* 1992, Rees 1995).

Although there is considerable scepticism regarding the capacity of technology to facilitate the substitution of manufactured for natural capital, this does not mean that technologies are irrelevant from a strong sustainability perspective. In fact, there is a great deal of interest in the role that they play in mediating the impact of the human enterprise on the ecosphere. By way of illustration, the **I=PAT** equation, used to describe the impact of the human enterprise on the ecosphere (Ehrlich and Holdren 1971, Holdren and Ehrlich 1974, Ehrlich and Ehrlich 1990, Daily and Ehrlich 1992), explicitly acknowledges the role of technologies through the inclusion of the term "T", an index of environmental damage that results from the specific technologies used to supply a given unit of consumption[7]. As a result, there is considerable interest in promoting the development of "eco-efficient" technologies that would allow society to maintain or increase per capita utility while reducing material and energy diverted through the economy (Costanza and Daly 1992, Business Council for Sustainable Development 1993, Ekins 1993, Schmidt-Bleek 1993a & 1993b, Pearce 1994, Rees 1995). In this regard, research suggests that for the global economy to become biophysically sustainable over the next 30 to 50 years and still meet growing demands for goods and services, there needs to be at least a 50% reduction, from present levels, in the material and energy that is cycled from the ecosphere through the economy. And if this "dematerialization" of the global economy is to be accompanied by a more equitable distribution of resources, industrialised countries will have to reduce their material throughput ten-fold (Schmidt-Bleek 1993a & 1993b, Rees 1995, Hinterberger and Schmidt-Bleek 1999).

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[6] As a result, proponents of strong sustainability are frequently referred to as "technological sceptics".

[7] The remaining terms of the equation represent: **I** = the total impact of the human enterprise on the ecosphere; **P** = the human population; and **A** = the average per capita affluence (which is often approximated by average per capita consumption).

## Conflicting Worldviews

Underlying these contrasting visions of how sustainability can be achieved, are profoundly divergent worldviews with respect to the relationship between the economy and the ecosphere. From a weak sustainability perspective, and one that dominates current mainstream economic and political thinking, the economy and the natural environment are seen as separate, largely independent systems (Daly 1991 & 1994, Rees 1995). Indeed, within the context of traditional economics, the environment seldom enters into consideration as attention is focussed almost exclusively on the flow of exchange value between households and firms. At most, the physical interactions that are acknowledged are only material and energy exchanges, either in the form of resource imports to, or wastes exports from the economy (Daly 1991 & 1994, Rees 1995).

In contrast, proponents of strong sustainability see the economy as a materially and energetically open, yet wholly dependent, subsystem of the ecosphere (Goodland 1991, Goodland *et al.* 1992, Daly 1991 & Daly 1994, Rees 1995). As such, the economy is therefore ultimately constrained by the carrying capacity of the ecosphere. This worldview is founded, in large part, on an understanding of how physical and energetic laws apply to economy/ecosphere interactions.

While the application of the first law of thermodynamics - the law of conservation of energy - together with the law of conservation of mass dictate that imports of matter and energy to the economy must ultimately balance exports, and the scale of the human enterprise is constrained by the matter available, their implications are not universally recognised. For example, an analysis of Julian Simon's above quoted ebullient prognosis for humanity, indicates that even at a modest 1% annual rate of grow, after only seven *million*[8] years the human population would exceed the estimated number of atoms in the universe by over thirty thousand orders of magnitude; a clear violation of the law of conservation of mass (Bartlett 1997).

The second law of thermodynamics also has relevance to our understanding of how the economy and ecosphere interact. As classically defined, the second law can be expressed as: The entropy of an isolated or closed system will tend towards a maximum (Binswanger 1993). Defined in this way, however, it is of little direct utility for analysing problems associated with the economy or the ecosphere. This is because the original formulation of the second law applies only to systems near thermodynamic equilibrium[9], and it "can only quantify reversible processes that take place infinitely slowly with infinitesimal changes of thermodynamic variables." (Binswanger 1993, p. 212). In other

[8] Not the seven billion as originally projected by Simon (Myers and Simon 1994).

words, it formally applies only under ideal conditions that cannot be reproduced in the real world where open conditions prevail and complete reversibility is impossible.

The second law has, however, been reinterpreted to explain how self-organising, open systems far from thermodynamic equilibrium - which include everything from simple physical and chemical systems to organisms, ecosystems and the economy - arise, evolve and achieve relatively stable states. The resulting theory of dissipative structures states that the evolution and maintenance of an open system far from equilibrium is only possible as a result of irreversible processes that dissipate matter and available energy[10] from the environment surrounding the system with the result that there is an overall increase in the entropy of that surrounding environment (Nicolis and Prigogine 1977, Prigogine and Stengers 1984, Kay 1991, Schneider and Kay 1992, Kay and Schneider 1992, Hornborg 1992, Binswanger 1993). Or stated more generally, all processes of energy or matter conversion *must* entail a net increase in entropy and a reduction of order in the universe.

Applying the theory of dissipative structures to the relationship between the economy and the ecosphere, due to the inherent inefficiencies of all transformative processes, the maintenance and accumulation of order within the economy can only be achieved at the expense of greater amounts of order from the surrounding ecosphere (Geogescu-Roegen 1971 & 1977, Binswanger 1993, Kay 1991, Giampetro, *et al.* 1992, Kay and Schneider 1992, Schneider and Kay 1992, Rees 1995). Moreover, as the scale of the human enterprise increases, either biologically and technologically, the proportion of the order required for maintenance also increases. In other words, the human enterprise becomes increasingly thermodynamically inefficient as its grows (Giampetro, *et al.* 1992, Hornborg 1992). Finally, if the integrity of the ecosphere is to be maintained, at a minimum, the rate at which the human enterprise appropriates order must be less than the rate at which the ecosphere can itself accumulate or reproduce its own order. Once we appropriate order faster than it can be reproduced by the ecosphere then there must be, without question, a net decrease in order embodied in the ecosphere (Giampetro and Pimentel 1991, Giampetro, *et al.* 1992, Rees 1995).

## How Much Natural Capital is Enough?

A challenge that then emerges within strong sustainability is how much of the diverse natural capital endowment of the earth is critical and must be preserved if long-term productivity is to be maintained. For some, the answer is simple. The entire natural capital endowment inherited by one

[9] A state in which all thermodynamic variables such as temperature, volume etc. remain constant.

generation must be passed on to the next. This interpretation has been termed *very strong* sustainability by some who have also observed that it functionally has the effect of making the natural environment "sacred capital" (Hediger 2000). A more moderate approach, however, allows that many aspects of the original natural capital endowment of the earth have already been converted to manufactured and human capital (hence their complimentarity) and some forms of extant natural capital may yet be convertible to manufactured and human capital. The difficulty is knowing where to draw the line that separates critical and non-critical natural capital. This issue is confounded by: 1) our limited understanding of the interdependence of both biotic and abiotic components of the ecosphere; 2) the existence of irreducible uncertainty with respect to understanding these relationships; and 3) the irreversible nature of liquidating many components of natural capital (for example the extinction of a species). In addition, there may be a substantial difference between the optimal level of a natural capital asset required to maximise human welfare and that level needed purely for human survival. As a result, it has been observed that the process of identifying critical levels of natural capital is inherently a subjective process (Hediger 2000).

Although it may be difficult to determine with any certainty how much and which types of natural capital are critical, a broad consensus is emerging that current consumption/waste production from the human enterprise has, or may soon, transgress the criticality thresholds of many natural capital assets with the result that long-tem productivity may be impaired (Daly 1991 & 1994, Goodland 1991, Rees 1995). Examples include: the overexploitation of individual stocks of fish and shellfish (Sissenwine and Rosenburg 1993, Greenpeace International 1993, Emerson 1994, Garcia and Newton 1994, Hagler 1995, Parfit 1995, Safina 1995, Walters 1995, Slaney *et al.* 1996) together with the serial over-fishing of multiple stocks (Pauly *et al.* 1998), biodiversity loss in general (Hughes and Noss 1992, Pimm *et al.* 1995), the appropriation of net primary productivity both on land (Vitousek, 1986, Haberl 1997) and from marine ecosystems (Pauly and Christensen, 1995), soil erosion and the depletion of its productive capacity (Pimentel 1993, Brown 1994), increasing scarcity of renewable freshwater (Postel *et al.* 1996), the deterioration of the ozone layer, and the accumulation of carbon dioxide in the atmosphere (Intergovernmental Panel on Climate Change 1990 & 1996, Office of Global Change 1997, Vitousek *et al.* 1997, Meyerson 1998).

[10] Available energy or essergy, is a quality of energy which can be thought of as a measure of the orderliness, non-randomness or information inherent in energy.

## *Biophysical Assessment Techniques*

If we accept that the economy is indeed a wholly contained subsystem of a finite ecosphere, and that much of the current evidence of resource exhaustion/waste accumulation is non-trivial, than two observations follow: 1) the absolute scale of the human enterprise and its impacts is important, and 2) the consumption of many forms of ecosystem goods and services may be approaching or have already exceeded critical thresholds. As a result, if society is to become more biophysically sustainable, it is important that we evaluate human activities using techniques that explicitly account for the scale of our impact on ecosystem goods and services.

### The Limitations of Economic Analyses

Conventional economics provides a range of techniques that are useful for evaluating many aspects of human activities. Unfortunately, they are of relatively little use when attempting to assess ecological sustainability. This is largely because of the need to translate all values into monetary prices. As a result, for ecosystem goods and services not traded in markets, their nominal value is zero and consequently they escape being accounted for within conventional pecuniary techniques. And for those goods and services for which markets exist (essentially natural resources), the prices so established typically reflect only a fraction of their total value. This chronic under-pricing of ecosystem assets results for a number of reasons. Market prices reflect the marginal cost of providing a given good or service, and not its absolute scarcity. Non-renewable resources such as fossil fuels and minerals provide the most obvious examples of this. In addition, natural capital assets often provide many structural and functional benefits to the economy, as well as to ecosystems, that are simply not reflected in their derivative commodity values. For example, the price of lumber does not reflect all the other goods and services associated with a forest. Nor do prices reflect the increased risk of destabilising ecosystem structures and flows that result from increased scarcity (Norton 1986 & 1988, Randall 1986, Rees and Wackernagel 1999).

Although techniques have been developed to assign prices to non-marketed values, they are either of limited applicability or their efficacy is suspect. For example, implicit pricing methods such as hedonic pricing and the travel cost method can only be used to estimate non-market values that are reflected in marketed goods or services (Randall 1988, Jacobs 1993, Simpson 1998). And while contingent valuation is frequently used to generate prices for ecological goods and services in

situations in which there are not even surrogate markets available[11], because of a range of unresolved theoretical and methodological issues, the results generated are of uncertain utility (Vatn and Bromley 1993, Jacobs 1993, Portney 1994, Diamond and Hausman 1994).

Fortunately, other evaluation techniques are available that explicitly track biophysical flows of matter and energy.

## Energy Analysis and Related Techniques

Energy flows have been used to evaluate human activities for over 100 years (Martinez-Alier 1987). It was not until the oil price shocks of the 1970's, however, that energy analysis rose to prominence[12]. Since then, a number of variations and related techniques have also been developed.

In its more traditional form, energy analysis entails quantifying the primary direct and indirect industrial energy inputs that are dissipated to produce a given object or provide a service (Peet 1992, Brown and Herendeen 1996)[13]. In doing so, energy analysis provides a measure of the energy cost of production - or what is frequently referred to as an item's embodied[14] energy (Kåberger 1991)[15]. The primary rationale underlying its use is "to quantify the connection between human activities and the demand for this important resource." (Brown and Herendeen 1996, p. 220)[16]. However, because

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[11] For a review of the contingent valuation method see Mitchell and Carson (1991). For examples of its use in pricing environmental goods and services see: Schulze *et al.* 1983, Whitehead 1990, Carson and Mitchell 1993, and Stevens 1995.

[12] To date, energy analysis has been used to evaluate thousands of activities. Some of the most relevant to the research undertaken here include analyses of commercial fisheries (Wiviott and Mathews 1975, Edwardson 1976, Rochereau 1976, Leach 1976, Rawitscher 1978, Ágústsson et al. 1978, Lorentzen 1978, Nomura 1980, Brown and Lugo 1981, Hopper 1981, Veal *et al.* 1981, Watanabe and Uchida 1984, Ishikawa *et al.* 1987, Sato *et al.* 1989, Mitchell and Cleveland, 1993) and aquacultural systems (Mathews, *et al.* 1976, Pitcher 1977, Rawitscher 1978, Bardach 1980, Li 1987, Folke 1988, Larsson *et al.* 1994, Berg *et al.* 1996).

[13] When quantifying energy inputs, one of two methods are typically used. In process or vertical analysis, the chain of activities required to yield a specific good or service is deconstructed, and the major types and quantities of primary energy required at each stage are identified and summed (Hall *et al.* 1979, Peet 1992, Brown and Herendeen 1996). Generally, direct inputs are accurately captured using process analysis. However, indirect inputs are often underestimated because of the limitations of time and data available (Hall *et al.* 1979). In contrast, input-output energy analysis, patterned on input-output economic models, employs detailed economic survey data together with data on the energy inputs to various sectors of the economy to generate estimates of the total direct and indirect energy required to produce various goods and services (Bullard and Herendeen 1975, Hall, *et al.* 1979, Peet 1992, Brown and Herendeen 1996).

[14] While the term embodied energy is frequently used in energy analyses, it can be misleading. This is because only part of the energy dissipated in the process of producing a given item is retained in the item itself. As a result, embodied energy is often described as the energy use history of a good or service.

[15] While energy analysis measures the energy cost of production, it does not provide a measure of an items value (Kåberger 1991, Brown and Herendeen 1996). It does, however, provide " a way of comparing the efficacies [sic] of the different technologies available for transforming available resources into a desired product or service. Thus you may see energy cost of production not as a measure of the product, but as a measure of the instrumental value of the process." (Kåberger 1991, p. 72).

[16] For a review of the importance of energy to the human enterprise and our collective vulnerability to its increased scarcity see Duncan (1993) or Price (1995).

industrial energy use - and in particular fossil energy use - correlates with a number of major environmental issues including global climate change (Intergovernmental Panel on Climate Change 1990 & 1996, Sundquist 1993, Meyerson 1998) and biodiversity loss (Ehrlich 1994b), it also has value as an indicator of biophysical sustainability (Kåberger 1991, Brown and Herendeen 1996).

Because humans are also dependent upon flows of solar energy through ecosystems, efforts have been made to extend conventional energy analysis to include these flows. For example, in an effort to demonstrate a relationship between the market price and the energy cost of producing an item, Costanza (1980) expanded the boundaries of his analysis to include solar energy flows. Taking this process a step further, Odum (1988) developed an entirely new analytical technique called EMERGY analysis in which all forms of energy, along with material inputs and human and environmental services[17] that combine to provide a good or service, are converted into their solar energy equivalents (Odum 1988, Odum and Arding 1991, Brown and Herendeen 1996)[18].

### Material Throughput Based Techniques

Pursuant to the widely perceived need to dramatically reduce the physical quantities of matter that are cycled through the economy, Schmidt-Bleek developed the concept of material intensity per unit service, or MIPS for short, and an associated accounting framework called material intensity analysis (Schmidt-Bleek 1994, Hinterberger and Schmidt-Bleek 1999). Within MIPS, the entire mass of material inputs[19] associated with manufacturing, packaging, transporting, operating, re-use, re-cycling and disposing of a given good or service is quantified and summed to provide a measure of its material intensity and relative eco-efficiency (Hinterberger and Schmidt-Bleek 1999).

Related to MIPS, a second material consumption-based technique is known as environmental space. Unlike MIPS, however, environmental space focuses on the equitable distribution of material consumption by comparing the per capita mass of specific resources consumed by a given society with the world average use of those resources. The types of resources typically used in an environmental space analysis are non-renewables, water, arable land, and forestry resources (Buitenkamp *et al.* 1993, Moffatt 1996, Hanley et al. 1999).

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[17] Some of the environmental services that are typically accounted for within EMERGY analyses include; rain, wind, currents, waves, geologic uplift, earthquakes etc (Odum and Arding 1991).

[18] While EMERGY analysis is not used as frequently as energy analysis, it has been used to evaluate at least one fishery (Hammer 1991) and one aquaculture system (Odum and Arding 1991)

[19] This includes the mass of energy inputs.

Reflecting the growing concern regarding the impact of greenhouse gases on global climate, a third material-based technique could be called greenhouse gas emission intensity analysis. Based in part on energy analysis[20], over the last decade a growing body of research has been undertaken to evaluate the lifecycle greenhouse gas emissions associated with a wide range of products, services and energy sources (Moriguchi *et al.* 1993, Pinguelli and Schaeffer 1995, Gielen 1995, Delucchi 1997, Gagnon and van de Vate 1997, van de Vate 1997, Subak 1997, 1999). A major difference between many of these analyses and simply converting the results of a conventional energy analysis into resulting greenhouse gas equivalents is that non-fuel related emissions are explicitly included. This can have a significant impact on the outcome of an analysis; for example, non-fuel related greenhouse gas emissions (expressed in terms of $CO_2$ equivalents) account for 63% and 99% of total emissions from pastoralist, and feedlot beef production systems, respectively (Subak 1999).

### Carrying Capacity Based Techniques

The ecological concept of carrying capacity[21] has been used for decades to help contextualise the problem of human over-consumption of natural capital assets (Ehrlich and Holdren 1971, Holdren and Ehrlich 1974, Hardin 1974, 1986, Rees 1990, 1993, 1996, Daily and Ehrlich 1992, Ehrlich 1994a, Rees and Wackernagel 1994, Daily and Ehrlich 1996, Arrow *et al.* 1996, Seidl and Tisdell 1999). It also forms the basis of a biophysical evaluation technique, ecological footprint analysis (Rees and Wackernagel 1994, Rees 1996, Wackernagel and Rees 1996).

Ecological footprint analysis measures the material and energy flows required to sustain a defined human population or activity, and converts these flows into a commensurate variable - ecosystem area - for evaluation and comparison. Consequently, it not only provides a measure of the ecosystem service appropriated by human activities, regardless of where on earth the source ecosystems occur, when used in comparative studies it provides a measure of relative ecological efficiency (Rees and Wackernagel 1994, Rees 1996, Wackernagel and Rees 1996).

The rationale underlying ecological footprint analysis is that human activities are inexorably, though often not obviously, tied to limited ecologically productive land and water to sustain both our biological and industrial metabolisms[22]. And it is this process of revealing the links between human

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[20] Reflecting the close linkage between energy use and greenhouse gas emissions.

[21] As defined within ecology, carrying capacity is the maximum population that can be sustained indefinitely by a given quantity of habitat without impairing the habitat.

[22] The extent of this dependence has been conservatively estimated at 40% in the case of terrestrial ecosystems (Vitousek 1986, Haberl 1997). Similarly, between 25-35% of the primary productivity available from shallow coastal marine waters is currently appropriated solely to sustain fish and shellfish harvests (Pauly and Christensen. 1995).

consumption and sustaining ecosystem services that may be one of the greatest strengths of ecological footprint analysis.

In practice, ecological footprint analysis proceeds initially much like a process energy analysis. The major direct and indirect material, labour, and energy inputs and outputs to a population or activity of interest are quantified. These are then converted, where possible, into corresponding ecosystem support areas; i.e. the areas of ecologically productive land and water required to produce the resource inputs and assimilate waste outputs on a continuous basis (Rees and Wackernagel 1994, Wackernagel and Rees 1996). While ideally all inputs and waste products would be convertible into a corresponding ecosystem area, functionally some are difficult if not impossible to incorporate. For example, mineral resources are conceptually difficult to footprint as are many types of wastes[23]. As a result, ecological footprint analyses generally underestimate the true appropriation of ecosystem services.

Other limitations of ecological footprint analysis include that it does not discriminate between the relative scarcity of different ecotypes nor between more or less sustainable types of land use. In addition, the multiple complementary services provided by some ecosystems are generally not accounted for in many ecological footprint analyses (van den Bergh and Verbruggen 1999)[24]. Finally, because of the uncertainties associated with some of the transformation calculations, and because some components of a typical analysis rely on notional rather than actual ecosystem support areas[25], the absolute ecological footprint values generated should generally be considered hypothetical. This problem is reduced by using input parameter values that result in conservative estimates wherever uncertainties exist. The significance of this issue is greatly reduced, however, when conducting comparative analyses where the relative results are of greater importance than the absolute ecological footprint values generated.

To date, ecological footprint analysis has been used most frequently to assess the collective and *per capita* impacts of societies under specific technological, and cultural conditions on a variety of scales including at the city (Rees 1996, Folke *et al.* 1997), regional (Rees and Wackernagel 1994, Folke, *et*

[23] While carbon dioxide (together with other greenhouse gases), nitrates, and phosphates are frequently incorporated into ecological footprint analyses on the basis of the primary productivity required for their assimilation (see for example, Larsson *et al.* 1994, Berg *et al.* 1996, and Folke *et al.* 1997), other waste chemicals such as pesticides, herbicides, antibiotics, ozone-depleting chemicals etc. are conceptually very difficult to include.

[24] An exception to this is the analysis by Berg *et al* (1996) in which complementary ecosystem services (oxygen production, and waste assimilation) are accounted for within the same ecosystem area.

*al.* 1997), and national level (Rees and Wackernagel 1994, Wackernagel and Rees 1996, Wackernagel *et al.* 1997, 1999, Wada 1999). It has, however, also been used to evaluate alternative technology systems including field versus greenhouse tomatoes (Wada 1993), alternative forms of transportation (Wackernagel and Rees 1996), intensive versus pond culture of Tilapia (Berg *et al.* 1996) and intensive shrimp culture (Larsson *et al.* 1994).

## Pre-Analytic Vision

My pre-analytic vision when undertaking this research was that the long-term interests of society will best be served through the pursuit of strong sustainability. As such, my vision of sustainability, and in particular biophysical sustainability, mirrors the definitions of Daly (1991), Giampetro *et al.* (1992), and others: sustainability is the achievement of a state of dynamic equilibrium between the ecosphere and its sub-component, the human enterprise. For this condition to be satisfied, our appropriation of natural capital goods and services through the extraction of resources and the discharge of wastes must not exceed that which the ecosphere can provide/assimilate on an ongoing basis. In other words, stocks of self-producing natural capital must remain constant and our collective impact must not exceed the carrying capacity of the ecosphere. Within this context, I believe that the adoption of more eco-efficient technologies is essential if biophysical sustainability of the human enterprise is to be achieved.

## Introduction to the Case Study

My chosen case study - salmon production in British Columbia, Canada - provided an opportunity to conduct a detailed assessment of the biophysical efficiency, and hence relative sustainability, of two highly distinct technology systems, and several smaller sub-system technology options that yield a comparable commercial product: salmon for human consumption. The two salmon "production" technology systems that I evaluated are the vessel-based commercial salmon fishery and the intensive salmon culture industry, commonly referred to as salmon farming, as both systems exist as of the late 1990's.

The commercial salmon fishery in British Columbia (B.C.) harvests both wild spawned and artificially enhanced stocks of five Pacific salmon species: sockeye (*Oncorhynchus nerka*), pink

[25] For example, when accounting for fossil fuel use, most ecological footprint analyses employ hypothetical carbon sink forest land as the basis upon which an ecosystem support area is calculated (see Rees and Wackernagel 1994, Wackernagel and Rees 1996).

(*Oncorhynchus gorbuscha*), chum (*Oncorhynchus keta*), chinook (*Oncorhynchus tshawytscha*), and coho (*Oncorhynchus kisutch*). The contemporary commercial salmon fleet in British Columbia is comprised of over 2,500 vessels that deploy one of three fishing technologies or gears - purse seine, gillnet or troll fishing gear - in pursuit of salmon. Annual landings have typically varied between 40,000 and 100,000 round tonnes throughout the history of the fishery.

The intensive salmon culture industry in British Columbia employs land-based hatchery and marine-based net-cage technology to produce chinook, coho and Atlantic salmon (*Salmo salar*). After its inception in the 1970's, the industry in British Columbia grew rapidly throughout the late 1980's and 1990's to the point that in 1998, industry-wide production of farmed salmon surpassed the harvest of wild salmon for the first time in British Columbia.

## Research Objectives

Given the existence of these two technologically distinct salmon production methods, this research was undertaken to address the following questions:

1. Are there differences between the biophysical costs associated with the commercial salmon fishery and the intensive salmon culture industry as both are currently conducted?

2. Are there differences between the biophysical costs associated with catching salmon using purse seine, gillnet or troll fishing technologies under recent historical conditions?

3. What opportunities exist to reduce the biophysical costs associated with producing salmon via the intensive farming process and the salmon fishery?

The answers to these questions are important for several reasons. Should biophysical efficiency differences exist, either between production systems or harvesting technologies used in the salmon fishery, it will provide a strong indication of their relative biophysical sustainability. Moreover, it will confirm that alternate technology systems can indeed play a role in moving society away from or towards sustainability. Regardless of the relative outcome, however, this research will provide decision-makers both in government and industry with a quantitative basis for evaluating the sustainability implications of possible changes to these salmon production systems.

### *Methods Used*

Two biophysical accounting techniques - ecological footprint analysis and energy analysis - were used to evaluate and compare the average biophysical costs associated with producing a tonne of salmon from each system. The "downstream" boundary used in both analyses was the point at which unprocessed salmon figuratively hit the dock just prior to processing.

In the case of the farmed salmon system, the biophysical costs associated with Atlantic and chinook salmon culture were analysed separately where this was possible[26]. The salmon farming sub-systems and inputs encompassed by the analysis include the major direct material, labour and energy inputs to smolt production, marine grow-out operations, and adult salmon transport. In addition, detailed analyses were conducted of the inputs associated with providing salmon feed as well as building and maintaining grow-out site infrastructure.

With respect to the commercial salmon fishery, biophysical costs were calculated on both a fishing gear-specific and a species-specific basis. The inputs to the commercial fishery encompassed by the analysis include the direct fuel and labour associated with fishing, as well as the direct and indirect inputs required to build and maintain the fishing vessels themselves and provide fishing gear. In the case of chinook and coho salmon, the material, labour and energy inputs associated with artificial smolt production were also evaluated.

## Outline of Remaining Chapters

The balance of the dissertation comprises six chapters. Chapter 2 introduces the commercial salmon fishery and the intensive salmon culture industry in British Columbia. This includes a discussion of the basic life history characteristics of salmon, brief histories of the two industries in British Columbia and descriptions of the major technologies employed in both systems.

In Chapter 3, I review the major assumptions, research materials and methods that were common to both the analysis of intensive salmon culture and the commercial fishery. In Chapter 4 the research materials and methods used to analyse the biophysical costs of intensively cultured salmon are described in detail. Similarly, in Chapter 5, I present the research materials and methods used to analyse the biophysical costs of the commercial salmon fishery. The results of both the ecological footprint and energy analyses of the two salmon production systems appear in Chapter 6 along with a

[26] The biophysical costs of coho salmon farming were not analysed.

sensitivity analysis that explores the effect that altering four major assumptions or input parameters has on the results.

In the seventh and final chapter, I consider the results in terms of the original research questions posed, and locate my results within the context of previous ecological footprint and energy analyses of seafood and other food production systems. Finally, I discuss additional insights that emerged as the research was conducted along with the broader sustainability implications of the work.

# Chapter 2: Salmon Production in British Columbia

> "As a fishery, salmon are ideal. They comb the ocean for its abundant food, convert this to delectable flesh, and return regularly in hordes to funnel through a limited number of river mouths exposing themselves to the simplest of capture – a gill net, trap, or seine net."
>
> John R. Brett 1983, p. 29

> "Aquiculture [sic] is as susceptible to scientific treatment as agriculture; and the fisherman who has been in the past too much the hunter, if not the devastating raider, must become in the future the settled farmer of the sea, if the harvest is to be less precarious."
>
> W.A Herdman as quoted in Lotka 1925 (as appears in the 1956 reprint edition, p. 172)

In this chapter, I review the major features of the commercial salmon fishery and the intensive salmon culture industry in British Columbia (B.C.). This includes a description of the life history characteristics of the salmon native to B.C., reviews of the history and current status of commercial salmon fishing in the province, and overviews of the techniques used to artificially enhance wild salmon populations. With respect to the intensive salmon culture industry, I briefly describe the history of the industry in B.C., and the processes and technologies used currently.

## The Commercial Salmon Fishery

The commercial salmon fishery, in what is now British Columbia, has existed for over 130 years. Throughout this period, it has been one of the largest and most lucrative commercial fisheries in the province employing thousands of fishermen and shore workers annually. The contemporary fishery is conducted using three distinct fishing gears or technologies: gillnets, purse seines and troll fishing gear. Although the size of the B.C. salmon fleet has been reduced in recent years, over 2,500 licensed vessels remain in the fleet.

All five species of Pacific salmon native to the province are fished commercially. They are the sockeye salmon (*Oncorhynchus nerka*), pink salmon (*Oncorhynchus gorbuscha*), chum salmon (*Oncorhynchus keta*), chinook salmon (*Oncorhynchus tshawytscha*), and coho salmon (*Oncorhynchus kisutch*)[27]. In addition, steelhead trout (*Oncorhynchus mykiss*) [28] are also taken by

[27] The other two species of Pacific salmon, the masu salmon (*Oncorhynchus masou*) and the amago salmon (*Oncorhynchus rhodurus*) are only native to Asia.

commercial salmon fishers in British Columbia. However, as the total landings of steelhead in any one year are relatively small, and they are not the explicit target of commercial fishing activities, they are not considered further in this research.

Of the five species of interest, chinook are the largest on average, usually weighing between 5 and 20 kg when mature. Next in size are chum, typically weighing between 2.5 and 10 kg, and coho, which run between 2.5 and 7 kg. The two smallest species are sockeye and pink salmon, which typically weigh between 2 and 4 kg, and 1.5 and 3 kg, respectively, when mature.

Sockeye, pink and chum salmon are by far the most plentiful of the five species. Each year typically between 25 and 70 million mature adults of these three species combined return to British Columbian waters. In contrast, total coho returns to B.C. typically run well under 10 million adults annually, while returns of chinook generally number under 3 million fish per year.

As the general and species-specific life history characteristics of salmon have shaped or influenced the manner in which they are harvested, and artificially enhanced, it is important to review some of those characteristics.

## Basic Life History of Pacific Salmon[29]

All commercially harvested Pacific salmon in British Columbia are anadromous[30]. All spawn in gravel beds in streams, rivers, and in some cases along the margins of lakes, typically between late summer and early winter. After emerging from the gravel during the subsequent late winter or spring, juvenile salmon migrate to the sea after an initial period spent in freshwater.

The juvenile freshwater residency period may be as short as a few hours or as long as a few years. In general, chum and pink salmon spend the least amount of time rearing in freshwater and usually migrate to estuarine areas within hours to weeks of emerging (Salo 1991, Heard 1991). At the opposite extreme, most sockeye and coho spend at least a full year rearing in freshwater. The

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[28] Recently both the steelhead trout and the cutthroat trout were re-classified as members of the genus *Oncorhynchus* (as *Oncorhynchus mykiss* and *Oncorhynchus clarki,* respectively). Previously they had been classified as members of the genus *Salmo* along with the Atlantic salmon (*Salmo salar*) and the brown trout (*Salmo trutta*) amongst others.

[29] Pacific salmon display a tremendous range of life history characteristics reflecting both interspecific differences and diversity between populations and individuals of a given species. As such this section can only provide a highly generalized overview of their life history patterns. For a much more exhaustive review the reader is referred to *Pacific Salmon Life Histories,* edited by Groot and Margolis (1991).

[30] Some populations of Pacific salmon, however, complete their entire lifecycle in freshwater. The most prominent example of this life history pattern in British Columbia is provided by the kokanee salmon, a landlocked version of the sockeye salmon.

sockeye's freshwater residence is spent primarily in lakes (Burgner 1991) while coho rear mainly in streams, rivers and adjacent slack-water off-channel areas (Sandercock 1991). Chinook salmon display perhaps the greatest range of freshwater rearing habits. Some populations of chinook, referred to as "ocean type", migrate to saltwater within their first year of life while "stream type" chinook typically spend at least one year, and sometimes much longer, in freshwater before heading to sea (Healey 1991).

Upon entering saltwater, Pacific salmon begin an extensive migration that sees them range over a wide area, feeding and growing rapidly[31]. The length of time spent at sea varies among species, stocks, and individuals within a given population, but typically ranges from one and a half to four years[32].

The migration routes and the regions of the north Pacific ocean used by salmon originating in British Columbia also vary between species and stocks. In general, however, most young salmon migrate in a northwesterly direction along the coast of British Columbia and Alaska during their first summer at sea. After this, most B.C. sockeye, pink, chum and, to a lesser extent, coho salmon, spend the majority of their remaining time in saltwater foraging offshore in the Gulf of Alaska, where they intermingle with other salmon from the Pacific Northwest, Alaska and Asia[33]. Figure 1 illustrates the general migration pattern that is believed to hold for most North American sockeye, chum and pink salmon during their first summer, fall and winter at sea. Thereafter, their seasonal movements follow the general pattern of migrating with the flow of the Alaskan Gyre current into more southerly offshore waters during the winter and spring, and into more northerly near-shore waters during the summer and fall.

[31] For a review of the early oceanic migration patterns and growth rates of Pacific salmon while at sea, see Hartt and Dell (1986).

[32] As a species, pink salmon have the shortest marine residency largely as a result of their relatively short, two-year, lifecycle.

[33] Some B.C. salmon, however, are known to range west of the Aleutian Islands and north into the Bering Sea.

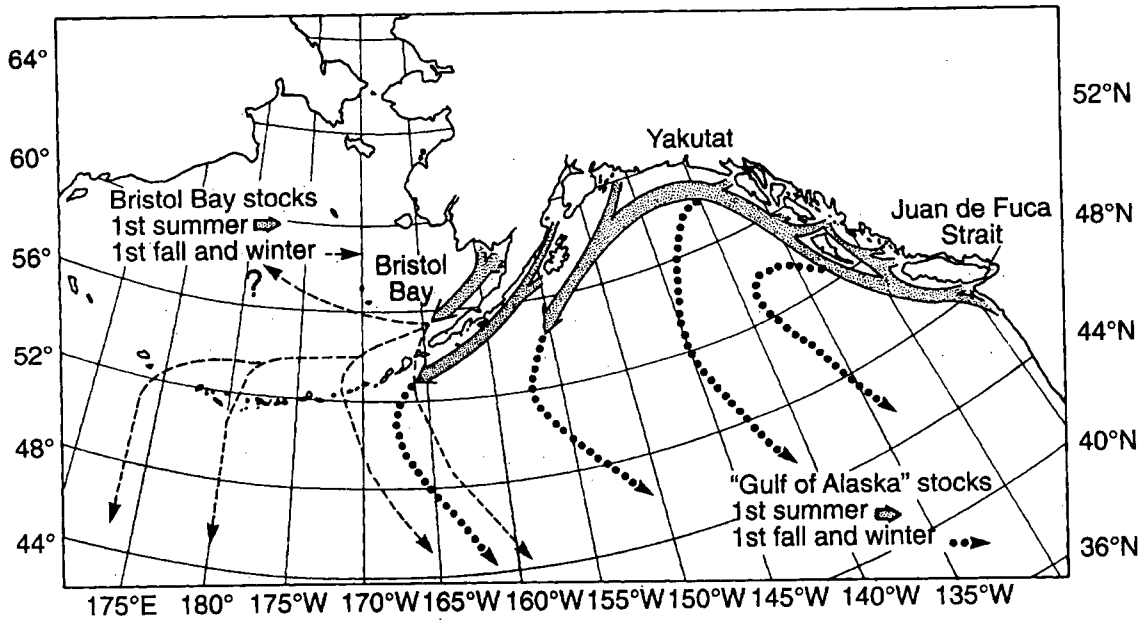


*Figure 1. Ocean Migration Patterns of Major Stocks of North American Sockeye, Chum and Pink Salmon During Their First Summer at Sea, Along with Their Probable Migrations During the Subsequent Fall and Winter (reproduced from Salo 1991, p. 264)*

Chinook salmon display much greater diversity in their marine life history behaviour. In general, "ocean-type" chinook appear to strongly favour inshore coastal waters, and relatively few stray more than 1,000 km from their natal river (Healey 1991). In contrast, "stream-type" chinook from British Columbia will often venture further from their natal river and "are probably distributed mainly in the eastern North Pacific with the greatest concentrations over the continental shelf waters along the North American coast." (Healey 1991, p. 367).

While at sea, Pacific salmon are opportunistic, generalist feeders that exploit a wide range of planktonic[34] and micro-nektonic[35] food items. Sockeye, chum and pink salmon appear to depend more heavily upon planktonic prey while coho and chinook appear to be more heavily dependent upon micro-nektonic prey[36]. Of the five species, chinook tend to be the most piscivorous and, depending on the relative availability of prey species, focus mainly on small pelagic fish including herring, sandlance, anchovy and pilchards (Healey 1991).

[34] The most common planktonic prey items include euphasiids, copepods, amphipods and decapods.

[35] Micro-nektonic prey includes a wide range of fish species, including herring, anchovy, sandlance, pilchards, juvenile rock fish, and in some cases juvenile salmon, squid and occasionally jellyfish.

[36] As part of my analysis of the marine ecosystem support required to sustain the commercial salmon fishery (Chapter 5), I reviewed a large number of published quantitative stomach content analyses for each of the five species of salmon. Summaries of these analyses appear in Appendix I.

As salmon begin to sexually mature at sea, they home in on their natal watershed. During their homeward migration, salmon continue to feed and grow rapidly[37]. Upon entering freshwater, salmon stop feeding and for the rest of their lives live off their reserves of fat and ultimately their muscle protein. The time spent in freshwater before spawning can range from as short as a few days to many months reflecting primarily the distance that a given stock must travel to reach its spawning grounds. Within a few days or weeks of spawning, all Pacific salmon die[38].

Their abundance, together with their anadromous life history and widespread distribution throughout accessible watersheds, both along the coast and into the interior of British Columbia, has meant that salmon are an important component of many coastal, riverine, lacustrine and riparian ecosystems (Cederholm *et al.* 2000). These same qualities along with the high yield of palatable flesh that can be taken from a salmon carcass has also meant that they have been an important source of food for humans for probably as long as people have inhabited this coast.

## *Salmon Harvesting in British Columbia*

In British Columbia salmon are harvested by three broad sectors, aboriginal, recreational and commercial fishers. In terms of tonnage, the commercial sector accounts for roughly 90% of the total British Columbia salmon catch while the aboriginal fishery for food and ceremonial purposes and the recreational sector each take about 5% of the total.

### A Brief History of the Commercial Fishery and the Technologies Used

For most intents and purposes, the commercial salmon fishery in British Columbia was launched in 1871 with the advent of the salmon canning industry on the Fraser River (Copes 1995, 2000, Meggs 1995)[39]. The early fishery that developed to supply the canneries relied heavily upon both aboriginal fishermen and fishing technologies, and in particular fish traps[40] and dipnets[41] to harvest the

[37] For example, Brett (1986) estimated that, on average, Babine Lake sockeye double their weight during their last 5 to 6 months of ocean life.

[38] The only exception to this general rule are steelhead and cutthroat trout which can survive the rigours of spawning to return to spawn again after recovering for a time at sea.

[39] It is worth noting, however, that prior to the start of the salmon canning industry in British Columbia, salmon had been an important trade good both within the context of the pre-contact aboriginal economy and post-contact as an important trade item between aboriginals and the early European settlers, miners and traders (Copes 1995, 2000, Meggs 1995). For example, the Hudson's Bay Company was shipping barrels of salted salmon, that had been caught and traded by aboriginal fishers, from their trading post at Fort Langley to markets in Asia and South America via Hawaii as early as 1830 (Foerster 1968, Roos 1991).

[40] Fish traps, trap nets and reef nets are closely related passive fishing devices (i.e. they rely on the movement of fish and water currents to capture fish) that generally consist of a maze or a series of progressively smaller openings in an otherwise impassable series of barriers that ultimately lead to a holding pen from which escape is difficult. As a salmon fishing technology, traps of one form or another emerged independently in at least three parts of the world, Japan,

abundant runs of sockeye that returned to the Fraser River. Very quickly, however, gillnets[42], a European fishing technology that had first been introduced to British Columbia in the mid-1860's, began to replace the indigenous technologies within the context of the commercial fishery (Meggs 1995)[43]. As a result, for the first 30 years of its existence, the commercial fishery in British Columbia was predominantly a gillnet fishery that was conducted from small wooden skiffs primarily in the tidal and estuarine portions of the province's major rivers[44]. The main targets of this early fishery were the relatively abundant runs of sockeye and pink salmon. During this phase of the fishery the catch grew steadily to the point that by the turn of the last century, landings routinely exceeding 20,000 tonnes per year in British Columbia (Figure 2).

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northern Europe and along the Pacific coast of North America (see Stewart 1977 for examples of indigenous North American salmon traps and other fishing gears and Hallock *et al.* 1957, Dunn and Lincoln 1978 and Nomura 1980 for examples of relatively contemporary salmon traps). In certain locations in the Pacific Northwest, British Columbia and Alaska, traps were used to great effect both by pre-contact aboriginal communities (see Copes (1995, 2000) for a discussion of the efficacy and demise of aboriginal fish traps in British Columbia) and by the post-contact commercial salmon fishery. In many instances, their demise as a commercial salmon fishing technology was due not to their ineffectiveness at catching salmon but as a result of political pressure brought by other salmon fishing sectors that saw traps as being too efficient (for an excellent review of the political demise of both the Columbia River and Puget Sound commercial trap fishery for salmon, see Higgs 1982).

[41] Dipnets are simple long-handled bag-like nets, typically handled by a single person, that are used, as their name implies, to simply dip or scoop migrating salmon from the water. While dipnets can be a very effective salmon harvesting devise under the right conditions, their use is restricted to locations in which the progress of salmon migrating in freshwater is slowed, and as a result fish become concentrated, behind either a naturally occurring or artificial barrier. Furthermore, by their relatively small-scale nature, dipnet fisheries are generally not productive enough to form the basis of a commercial fishery.

[42] Gillnetting is a method of fishing in which a virtually invisible net, designed with a mesh-size that is slightly larger than the head of the species being targeted, is suspended in the water like a curtain in front of, and perpendicular to the path of migrating salmon. Gillnets are bouyed along their top edge by a series of floats and weighted along their bottom by a lead line. Once deployed, a gillnet is typically allowed to drift with the tides for anywhere from one to four hours before being retrieved. As fish swim into the net, they become entangled in the net's mesh by their gill plates and/or jaws. Historically, gillnets were made from flax twine but since the advent of synthetic fibers, most gillnets are made from nylon or monofilament. On average, modern salmon fishing gillnets in British Columbia are about 360 metres long and 60 mesh-widths deep.

[43] This early technological evolution to a predominantly gillnet-based commercial fishery was largely the result of two related factors. Along the lower Fraser River, in the vicinity of where most of the early canneries were established, the catch from the existing trap and dipnet-based fishery simply couldn't keep up with the demand for salmon created by a rapidly growing canning industry. For example, by 1880, there were ten canneries located along the banks of the lower Fraser River and one cannery on the Skeena River in northern British Columbia (Meggs 1995). By 1881, additional canneries were also opened on the Nass River and in Rivers Inlet (Foerster 1968). And by 1890, there were 17 canneries on the lower Fraser (Meggs 1995).

[44] Most early gillnet fisheries occurred in these areas because with only sail and oar power available, the fishery had to be conducted within fairly close proximity to the canneries in order to deliver the catch in a timely manner. However, many contemporary salmon gillnet fisheries are still conducted in the lower reaches or off the mouth of rivers as the turbid conditions associated with these areas help disguise the presence of gillnets in the water.

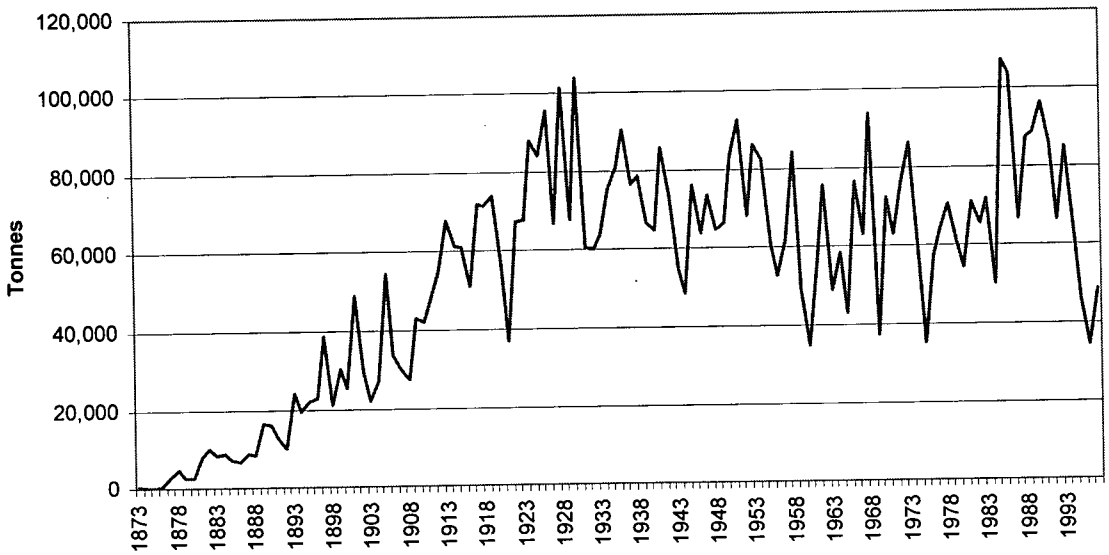


*Figure 2. Commercial Salmon Landings in British Columbia, 1873 to 1997 (from Wallace 1999)*

From a technological perspective, the commercial fishery began to change again shortly after the turn of the century with the introduction of the gasoline engine (Higgs 1982). Until this point, another introduced fishing gear, the purse seine[45], had only seen limited use in the British Columbia fishery. This was largely because with only human power available to handle the net, and in particular to purse the seine, only relatively small nets could be effectively deployed. However, once equipped with engines, not only could larger nets be handled more easily[46] but the seine vessels themselves could range much further in pursuit of salmon. As a result, over the first two decades of this century, purse seining came into its own as a salmon fishing technology both in British Columbia and throughout the coast[47].

As purse seining is most effective where fish occur in relatively large, dense schools, it has been used most extensively to harvest the more plentiful sockeye, pink and chum salmon in areas in which these stocks are naturally concentrated. As a result, most purse seining for salmon is conducted in coastal

[45] Purse seining is an active fishing method in which a school of fish is first sighted and then trapped using the purse seine net. The purse seine net itself is a relatively long, deep, small mesh-sized net that is bouyed along its top by floats and weighted along its bottom by leadline. In addition, a heavy-duty "purse line" is strung through a series of metal rings along the entire bottom length of the net. When a school of fish is sighted or is believed to occur in a certain area, the net is typically deployed from the stern of the seiner using a small skiff to essentially hold one end of the net in place in the water. Alternatively, in near-shore areas, the lead end of the net may be tied to a fixed point on shore. The seiner then quickly maneuvers so as to encircle or trap the school of fish in the net. Once the ends of the net are joined, the purse-line is drawn tight, thus prohibiting the downward escape of fish. The trapped fish are then either brailed aboard the seiner using a dipnet or the entire catch can be hauled over the stern of the boat (see Ledbetter (1986) for a more detailed description of purse seining for salmon in British Columbia).

[46] For example, a typical contemporary purse seine net used in the British Columbia salmon fishery is about 390 metres long and 21 metres deep (Mr, Chris Cue, seine operations manager, Canadian Fishing Company, pers. comm. 1998).

[47] See Higgs (1982) for a description of the growth of the commercial salmon purse seine fishery in Washington State.

waters where mixed stocks of migrating salmon funnel through narrows, into inlets, between islands and around promontories.

The introduction of the gasoline engine also meant that a third fishing technology, trolling[48], emerged to become an important component of the commercial salmon fishery. While pre-contact aboriginal fishers trolled behind canoes (Stewart 1977) and early European trolling was conducted behind sail powered and rowed boats prior to the turn of the century (Higgs 1982), with gasoline engines trollers could operate regardless of the wind and for much longer periods of time than previously. Gasoline engines also allowed trollers to deploy more lines and to venture relatively far offshore to fish some of the important feeding grounds used by salmon and in particular, chinook and coho salmon[49].

With the addition of both a sizeable purse seine and troll fleet to the already well-established gillnet fleet, by the end of the First World War, the commercial salmon fishery in British Columbia had essentially reached maturity with landings often exceeded 60,000 tonnes annually (Figure 2).

## The Contemporary Commercial Salmon Fishery

Landings by the commercial fishery in British Columbia vary considerably from year-to-year reflecting changes in the relative and total abundance of salmon stocks. In broad terms, the annual catch over the last 20 years has remained more or less consistent with the longer term history of landings, and generally falls between 40,000 and 100,000 tonnes (Figure 2)[50].

As has been the case throughout its history, sockeye, pink and chum salmon together account for the majority of commercial salmon landings in British Columbia (Figure 3).

[48] Trolling is a fishing method in which one or more fishing lines, each equipped with one or more lures or baited hooks, are slowly dragged through the water in areas in which the targeted species is known to feed. When a fish mistakes the lure or bait for a natural prey item and becomes hooked, the line is hauled in and the fish is landed individually. In the contemporary British Columbia salmon fishery, trollers typically deploy 6 to 8 stainless steel lines at a time with up to 80 lures or baited hooks per line.

[49] Trollers have traditionally targeted chinook and coho salmon for a variety of reasons including: a larger proportion of chinook and coho (in contrast with sockeye, pink and chum salmon) tend to spend a greater proportion of their marine life-history feeding year-round in inshore waters, chinook and coho tend to favour prey items (such as squid, and small pelagic fish) that are easily replicated by lures and baits used by trollers, and chinook and coho have traditionally fetched relatively high prices especially for fish landed in good condition as is the case with troll caught fish.

[50] It should be noted, however, that since the late 1980's, the trend in landings have progressively declined each year, with only two minor reversals, causing many observers of the fishery to express concern regarding the state of the stocks and fisheries management in British Columbia.

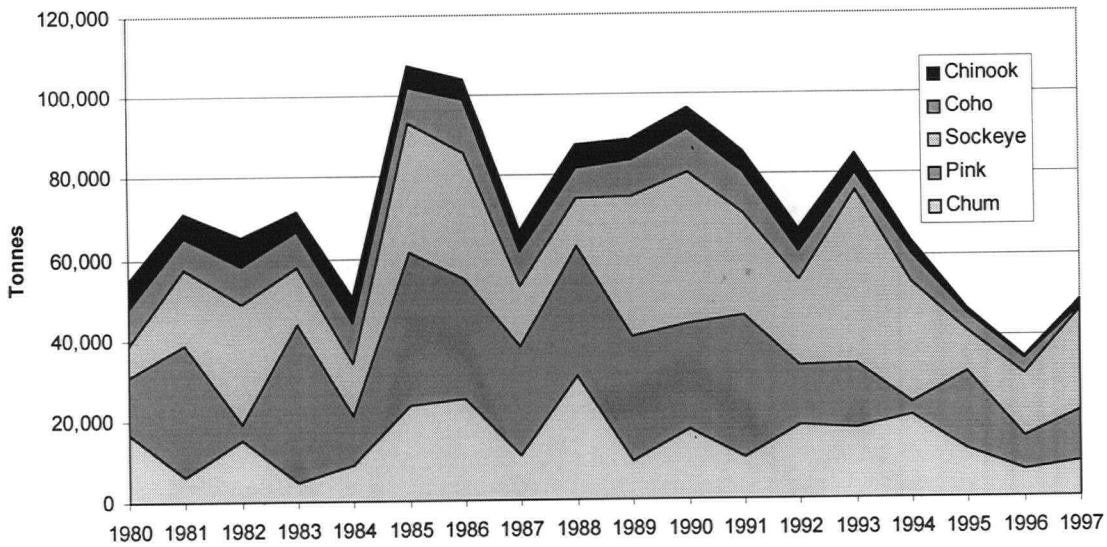


*Figure 3. British Columbia Commercial Salmon Landings by Species, 1980 to 1997 (data from Department of Fisheries and Oceans Annual Commercial Catch Statistics, 1980-1997)*

From a technological perspective, all three fishing gears; gillnet, purse seine and troll, continue to contribute to the commercial catch (Figure 4). In most years the seine fleet, while representing the smallest number of vessels, typically accounts for the largest proportion of the landings with the much larger troll[51] and gillnet fleets accounting for smaller and often approximately equal proportions of the catch (Figure 5).

[51] Over the 1990's, however, trollers have been landing a progressively smaller proportion of the total catch largely as a result of conservation concerns that have emerged with respect to some populations of chinook and coho destined for southern British Columbia and the US Pacific Northwest.

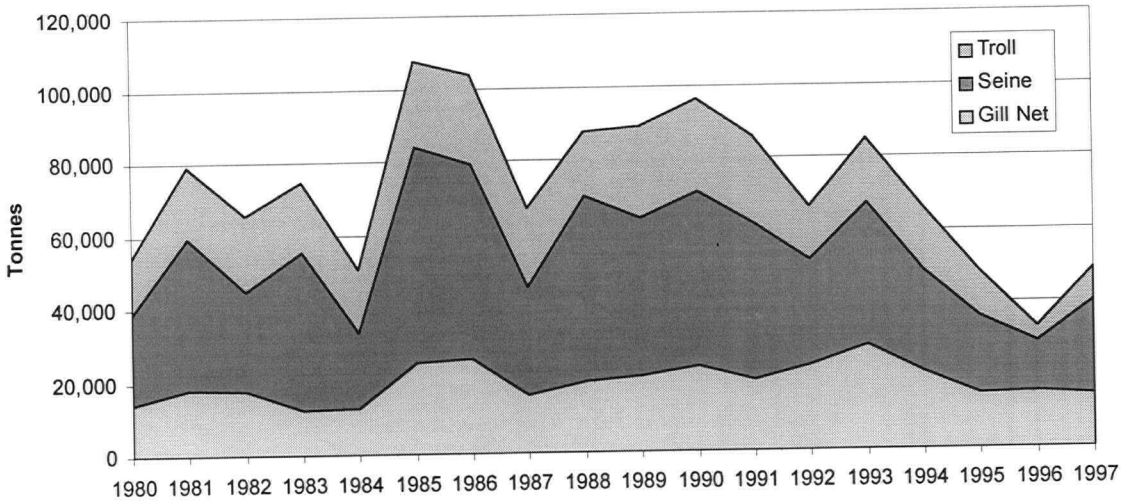


*Figure 4. British Columbia Commercial Salmon Landings by Gear Type, 1980 to 1997 (data from Department of Fisheries and Oceans Annual Commercial Catch Statistics, 1980-1997)*

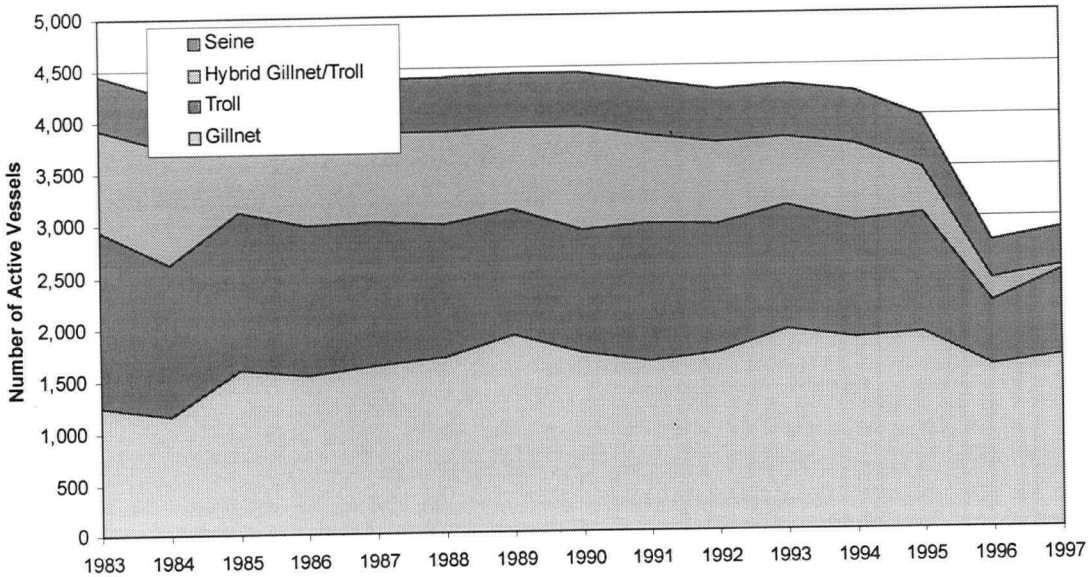


*Figure 5. Number of Active Commercial Salmon Fishing Vessels by Gear Type in British Columbia, 1983 to 1997 (data provided by Mr. Brian Moore, Program Planning and Economics Branch, Fisheries and Oceans Canada, October, 1999. Note data for 1995, 1996 and 1997 preliminary)*

While the commercial salmon fishery in British Columbia remains one of the largest and economically important fisheries in western Canada, from a global perspective, it is a relatively small contributor to total commercial salmon landings, accounting for an average of only 9% of the total

global wild caught salmon over the period 1984-97 (data from FAO FIDI statistical database Fishstat+)[52].

## *Artificial Enhancement of Salmon*

For almost as long as there has been a commercial salmon fishery in British Columbia, efforts have been made to augment the wild production of juvenile salmon that head to sea with the hope that increased numbers of adult salmon will result[53]. The techniques used to artificially enhance salmon vary considerably and include:

- efforts to maintain and in some cases restore natural spawning grounds,
- the construction of fishways and ladders around natural and artificial in-river barriers to improve adult salmon access to spawning areas[54],
- the construction of artificial spawning channels, particularly for sockeye and pink salmon[55],
- the fertilisation of sockeye rearing lakes to boost their productivity and hence their output of sockeye smolts, and
- the intensive culture of primarily juvenile chinook, coho and chum salmon in hatcheries for later release into the wild.

The modern era of salmon enhancement activities in British Columbia was launched in 1977 with the establishment of the Salmonid Enhancement Program (SEP) by the federal government. When established, the primary objective of the SEP was to double the return of salmon to the province within 30 years (ARA 1993, Pearse 1994)[56]. While this goal has yet to be achieved, and it is very unlikely that it ever will be given the change in focus of the SEP over time[57] and the generally poorer

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[52] The rest of the global commercial salmon landings over the period from 1984 to 1997 are accounted for by the United States, and in particular Alaska, with 43% of the world total commercial catch, Japan with 29% and the Soviet Union/Russian Federation with 18% (from the FAO FIDI statistical database Fishstat+).

[53] For example, the first salmon hatchery in British Columbia was built in 1882 on Bon Accord creek opposite New Westminster on the lower Fraser River and produced its first fry in 1884 (Meggs 1991, Pearse 1994).

[54] See Roos (1991) for a discussion of the need for, and the construction history of fishways for salmon on the Fraser River and its tributaries.

[55] Ibid. for a discussion of the construction of artificial spawning channels on the Fraser River and its tributaries.

[56] Secondary objectives of the program included the augmentation of national and provincial income, employment generation, improved economic opportunities for aboriginal people and economically disadvantaged communities, and improved recreational fishing opportunities (Pearse 1994).

[57] By 1983, the goal of doubling salmon returns to the province strictly through artificial enhancement techniques was beginning to be downplayed in favour of doubling salmon production using an array of stock rebuilding tools. In its place

than expected returns to enhancement facilities, its output of juvenile salmon and its contribution to British Columbia's salmon catch has been substantial[58]. For example, through the late 1980's and early 1990's SEP supported activities collectively produced between 500 to 750 million juvenile salmon annually (Figure 6).

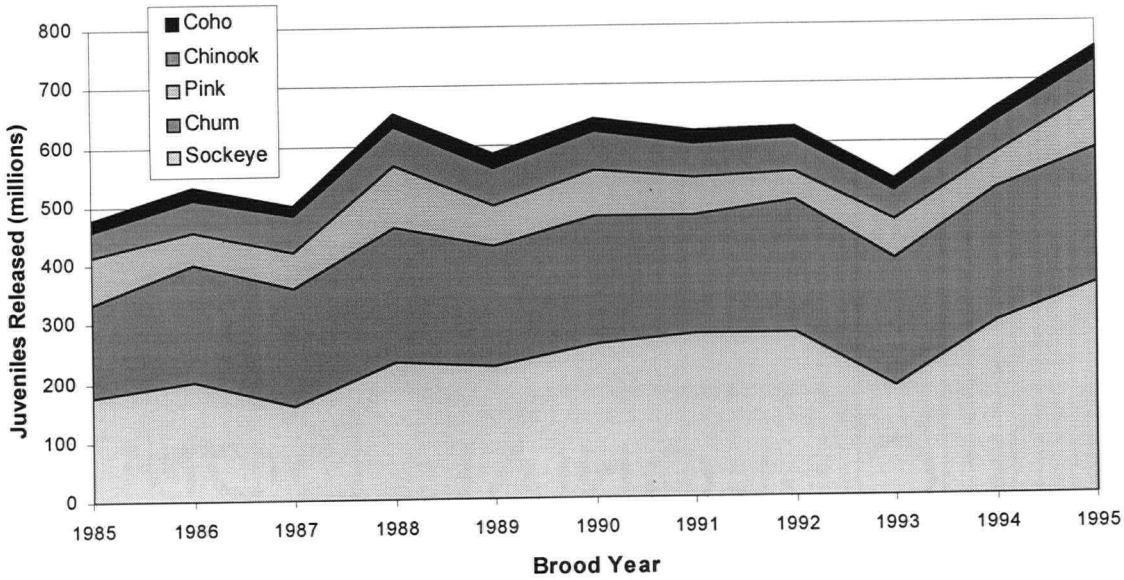


*Figure 6. Juvenile Salmon Released from Salmon Enhancement Program Supported Activities, 1985 to 1995 (data provided by Mr. Greg Steer, SEP, 1996)*

Over the same period, these releases resulted in a total annual catch of between four and nine million salmon of artifically-enhanced origin (Figure 7). Expressed in terms of tonnage landed, Pearse (1994) estimated that the SEP contributed an average of approximately 13,000 tonnes annually between 1985 and 1990 to the total Canadian catch[59] amounting to about 13% of our total commercial, recreational and aboriginal landings over the same period.

the focus of SEP had shifted, by the mid-1980's, towards the restoration of depressed stocks and in particular, coho and chinook stocks (Pearse 1994).

[58] An important caveat is necessary regarding the apparent contribution that enhancement activities have made to our total harvest of salmon. Mounting research suggests that many forms of traditional artificial enhancement have the potential to undermine the viability of remnant wild stocks of salmon through genetic interaction, resource competition, disease transfer, and resulting inappropriately high harvest levels (Meffe 1992, Hilborn 1992, McMichael *et al.* 2000, Morishima and Henry 2000, Thurow *et al.* 2000, Hillborn and Eggers 2000).

[59] This includes the aboriginal, recreational and commercial catch of SEP-origin fish.

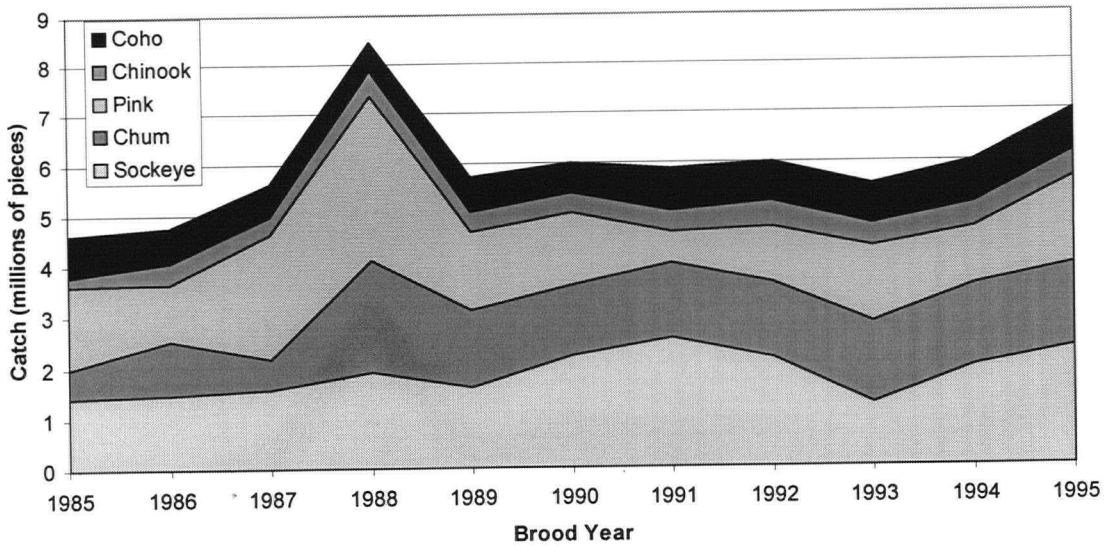


*Figure 7. Total Catch of SEP-Origin Salmon, 1985 to 1995 (data provided by Mr. Greg Steer, SEP, 1996)*

Although the SEP supports a great many small community-run enhancement projects throughout the province, most of the program's efforts and resources go towards operating the over three dozen hatcheries and spawning channel complexes that form the core of their operations (Pearse 1994).

# The Intensive Salmon Culture Industry in British Columbia

In this section I briefly review the history of intensive salmon culture both globally and within British Columbia. I then describe the major elements and activities that together make up the contemporary salmon farming industry.

## *Brief History of Salmon Farming*

While juvenile salmon and trout have been cultured to either enhance existing fisheries or create new ones[60] for well over a hundred years[61], it was not until the late 1960's, and early 1970's that the first serious attempts were made to culture salmon intensively through to adulthood for commercial sale. Early commercial salmon farming efforts were initiated in a number of jurisdictions including

[60] Once hatchery techniques were perfected for salmon and trout in the mid to late 1800's, countless attempts were made around the world to introduce salmon and trout into new ecosystems, largely to enhance recreational angling opportunities. Often these intentional introductions of non-native salmonids, including the repeated attempts to introduce Atlantic salmon into British Columbia between 1905 and 1935, failed (British Columbia Environmental Assessment Office 1997, Vol. 3). However, in many other instances they succeeded. Examples include: the introduction of brown trout (*Salmo trutta*) throughout North America, the establishment of at least three species of Pacific salmon along with rainbow into the Great Lakes, the introduction of chinook salmon, rainbow and brown trout into both New Zealand and Tasmania, and the introduction of coho salmon, rainbow and brown trout into Chile and Argentina.

[61] For a brief review of the history of public and private salmon and trout culture activities see Sylvia et al. (2000).

Norway, Scotland, Japan, Chile, both Washington State and Maine in the United States, and in British Columbia (Sylvia et al. 2000). Of these, Norwegian producers enjoyed the earliest success and in 1972 produced a total of 46 tonnes from five farms (Sylvia et al. 2000).

By 1980, global farmed salmon production amounted to under 10,000 tonnes and only Norway had established an industry of any size and stability producing 4,300 tonnes that year (Sylvia et al. 2000). However, through the 1980's and 1990's, as culture techniques, farmed stock and feeds improved, global production grew rapidly, often exceeding 25% year-over-year annual growth rates (Figure 8). Currently, while intensive salmon farming is conducted in at least twenty countries[62], production is dominated by four. Norway, Chile, the United Kingdom (Scotland), and Canada who together account for over 85% of the farmed salmon and trout that is grown in marine-based net-cages (Figure 8).

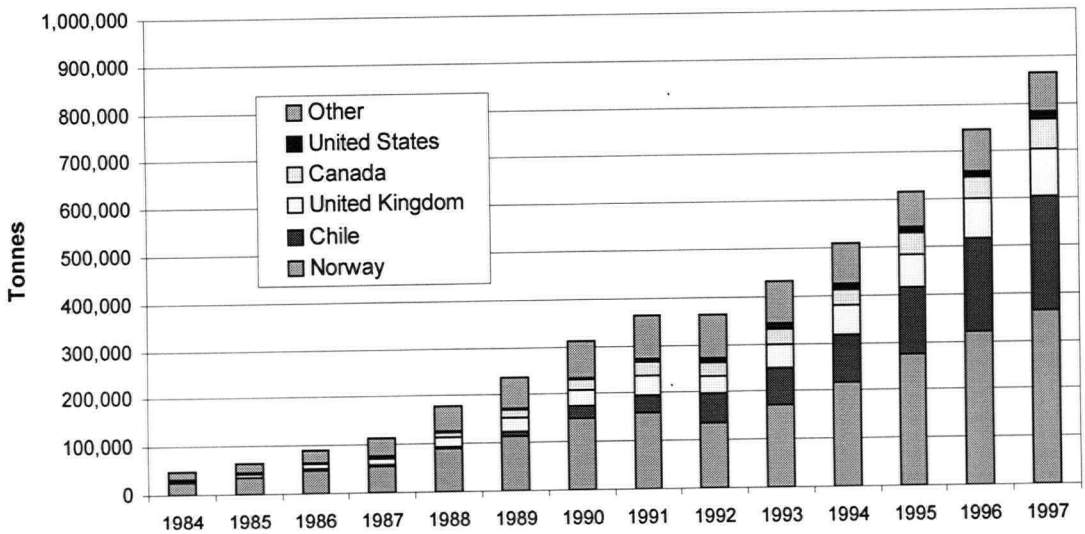


*Figure 8. World Marine-Based Farmed Salmon and Trout Production, 1984 to 1997 (data from FAO FIDI statistical database Fishstat+)*

In British Columbia, the salmon farming industry was effectively launched in 1973 when a privately owned hatchery near Duncan on southern Vancouver Island began raising juvenile salmon for later grow-out in saltwater-based net-cages using surplus eggs from government hatcheries (Keller and Leslie 1996)[63]. Early efforts were made to farm various species of Pacific salmon including chum, sockeye and coho. Coho, however, quickly became the foundation of the early industry in British

[62] From the FAO FIDI statistical database Fishstat+.
[63] For a detailed history of the British Columbia salmon farming industry see Keller and Leslie (1996).

Columbia. Throughout the 1970's the industry grew slowly as a variety of technical and financial challenges resulted in the failure of a large number of the pioneering salmon farming initiatives (Keller and Leslie 1996). As a result, by 1980, total industry-wide production in British Columbia amounted to only a few hundred tonnes of coho salmon.

As with salmon farming globally, the 1980's saw tremendous growth and change within the British Columbia industry. Early in the decade some farmers diversified into chinook salmon production. This proved successful and by 1987, chinook production exceeded coho production for the first time. Since then, chinook has been the dominant species of Pacific salmon farmed in British Columbia (Figure 9)[64].

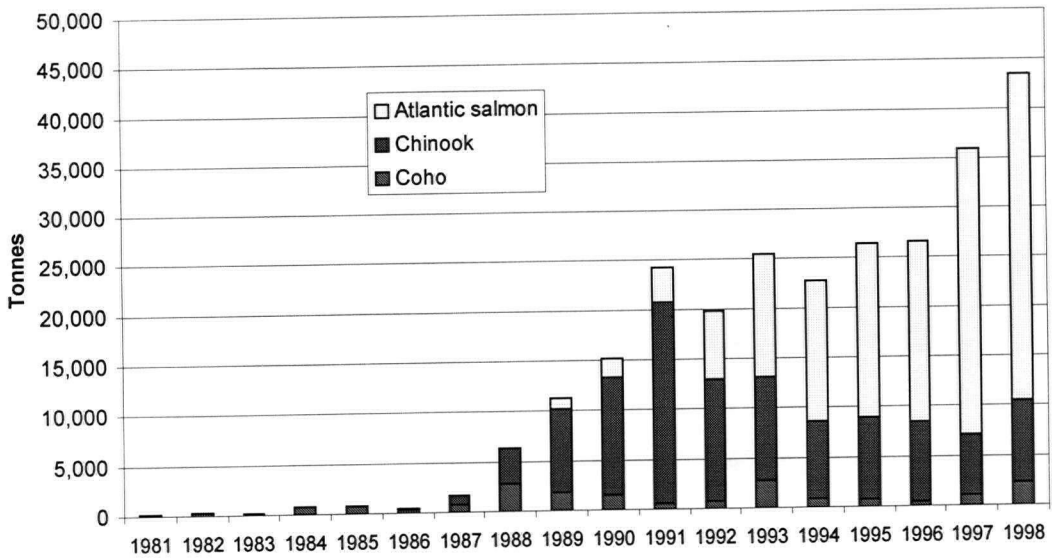


*Figure 9. British Columbia Farmed Salmon Production (round weight) by Species, 1981 to 1998*

(Notes: 1981 to 1990 data from British Columbia Ministry of Agriculture, Fisheries and Food 1992; 1991 to 1995 data from Kenney 1996; 1996 to 1998 data from British Columbia Salmon Farmers Association pers. comm. 1999. Species specific dressed weight to round weight conversion factors as follows: coho 0.859, chinook 0.868, Atlantic 0.916 from British Columbia Salmon Farmers Association pers. comm. 1999)

A second, potentially more consequential, and certainly more controversial, development occurred in the British Columbia industry during the late 1980's. Until this point, although Atlantic salmon were the principal species being farmed internationally[65], in British Columbia only indigenous Pacific

[64] It is also worth noting that British Columbia has been the largest single producer of farmed chinook in the world typically accounting for between 50% and 80% of annual global farmed chinook production over the last decade (from the FAO FIDI statistical database Fishstat+).

[65] For example, on a tonnage basis, Atlantic salmon accounted for over 80% of the annual global farmed salmon production throughout the period from 1984 to 1997 (from the FAO FIDI statistical database Fishstat+).

salmon were used. This changed when salmon farmers began importing Atlantic salmon eggs into British Columbia in 1985 and began harvesting adults in 1988 (British Columbia Environmental Assessment Office 1997, Vol. 3)[66]. The most frequently cited reasons for shifting to Atlantic salmon are that the domesticated strains of Atlantic salmon grow faster when in saltwater[67] and can be stocked at higher densities than either coho or chinook salmon (Keller and Leslie 1996, British Columbia Environmental Assessment Office 1997, Vol. 3). As a result, Atlantic salmon tend to be less expensive to raise than chinook or coho, *ceteris paribus,* while they fetch a comparable, if not slightly higher price in many markets[68]. With the addition of both chinook and Atlantic salmon to the production mix, coupled with the rapid expansion of both the hatchery and grow-out capacity of the industry and improved husbandry practices, over the course of the 1980's, total industry-wide production in British Columbia increased 30-fold, exceeding 10,000 round tonnes in 1989, with most of this growth occurring in the last two years of the decade (Figure 9).

The expansion of the industry through the late 1980's was not without problems. A combination of environmental challenges[69] coupled with a major price collapse in domestic and international markets for premium farmed and wild-caught salmon in 1989[70] wreaked havoc throughout the industry[71]. As a result, through the early 1990's the growth of the industry slowed, and in two years, 1992 and 1994, output from the industry declined from the previous year (Figure 9). At the same time, the expansion of salmon farming through the late 1980's also gave rise to public concern regarding a range of environmental issues. Pressure to address these concerns culminated in the provincial government establishing an industry-wide moratorium on the issuance of new farm tenures in April, 1995, and

[66] As of 1996, a total of almost 12 million Atlantic salmon eggs have been imported into British Columbia for the purposes of salmon farming. All have come from a small number of Canadian government approved hatcheries in Scotland, the United States, New Brunswick and Ireland (British Columbia Environmental Assessment Office 1997 Vol. 3).

[67] It is interesting to note, however, that Atlantic salmon smolts are typically more difficult to rear while in freshwater and are therefore more costly, than either chinook or coho smolts (Dr. David Groves, pers. comm. 1997).

[68] See Kenney (1996) for mid-1990's average monthly prices and markets for farmed British Columbian Atlantic and chinook salmon.

[69] These included numerous harmful algal blooms in more southern British Columbian waters that devastated many farms particularly in the Sunshine coast area and an unusually severe winter storm in January 1989 that damaged many farms (Keller and Leslie 1996).

[70] The 1989 salmon price collapse was due to a glut of salmon on international markets that resulted from over-production in most salmon farming countries (for example, Norway had forecast a production level of ~80,000 tonnes for 1989 but ended up harvesting almost 150,000 tonnes) and from a large wild salmon harvest in Alaska and British Columbia (Keller and Leslie 1996).

[71] For example, by the summer of 1990, over a third of the salmon farming companies that had been in operation in 1988 in British Columbia failed, and many of the remaining companies were financially vulnerable. As a result, the British Columbia industry underwent a process of re-organization that left only 17 producer companies by 1995 (Keller and Leslie 1996).

launching a major industry-wide environmental assessment process, the Salmon Aquaculture Review (SAR), in July, 1996 (British Columbia Environmental Assessment Office 1997)[72].

After an extensive technical review, the final report of the SAR, including 49 major recommendations covering a range of technical and regulatory aspect of the industry, was released in August 1997. It was not until October, 1999, however, that the provincial government formally responded to the SAR report and announced that it would allow limited expansion of the salmon farming industry in B.C. While in the short term, the moratorium on the issuance of new licenses technically remains in place, ten new experimental salmon farms will be allowed[73] and salmon farmers with existing tenures in unproductive sites will be allowed to change location and push their farms into full production[74] (British Columbia Ministry of Fisheries and Ministry of Environment, Lands and Parks 1999).

However, despite the moratorium that effectively limited the geographical expansion of the industry through the latter 1990's, production of farmed salmon in British Columbia increased steadily (Figure 9) to the point that in 1998 the harvest of over 43,000 round tonnes of farmed salmon exceeded the commercial harvest of wild salmon in British Columbia for the first time. In addition, the use of Atlantic salmon continued to expand over the course of the decade, to the point that Atlantic salmon now account for approximately 75% of the farmed salmon produced in British Columbia (Figure 9).

## *Contemporary Salmon Farming in British Columbia*

The process and techniques used to farm salmon in British Columbia are essentially the same as those used around the world. The production process can be broken down into six major steps:

- the harvest of eggs from broodstock followed by the artificial spawning, incubation, and hatching of eggs in land-based hatchery facilities,
- the rearing of smolts in freshwater either in hatcheries or in lake-based net-cage sites,

[72] The five main issues considered during the Salmon Aquaculture Review were: 1) the impact of escaped farmed salmon on wild salmonids, 2) fish health and the potential for disease transmission from farmed to wild fish, 3) waste discharges from marine grow-out sites, 4) the impact of farming operations on aquatic mammals and other predators, and 5)the siting of salmon farms generally (British Columbia Environmental Assessment Office 1997)

[73] These ten new farms are to be developed with partial government support specifically to foster the development of new environmentally-friendly grow-out technologies (British Columbia Ministry of Fisheries and Ministry of Environment, Lands and Parks 1999).

[74] As of mid-1999, only about 70% of the approximately 120 licensed salmon farm sites in British Columbia were occupied.

- the "grow-out" of salmon in marine-based net-cages,
- fish harvest and transport,
- processing, and
- marketing and distribution.

Of the six stages, only the first four are encompassed by the analysis that follows and as such only these processes are briefly described further.

### Hatchery Production of Smolts

Currently, virtually all salmon farmed in British Columbia are raised from eggs that are harvested from privately maintained broodstock[75] and all smolts required by the industry are produced in British Columbia as it is illegal to import live juvenile or adult fish[76]. When broodstock fish reach sexual maturity they are stripped of eggs and milt that are then combined. The newly fertilized eggs are placed in covered trays[77], or similar incubation structures[78], that are continually flushed with well oxygenated freshwater, for the duration of their incubation. Once hatched, alevins generally remain in incubators until they reach the "swim up" stage of development and are ready to begin feeding. At this point Pacific salmon fry are typically moved to relatively shallow indoor troughs or tanks to be introduced to feed while Atlantic salmon fry are usually introduced to feed in the tanks in which they were incubated. Once they attain a certain size, approximately three quarters of a gram in the case of Pacific salmon, fry are transferred to larger outdoor tanks. However, in the case of most Atlantic salmon and a small but increasing proportion of chinook salmon fry produced in British Columbia, early rearing is conducted in indoor, heated water tanks for a period of approximately six weeks before being transferred outdoors. This practice has been adopted to "accelerate" the early growth of

[75] During the industry's early development most of the eggs used came from wild broodstock that were surplus to government enhancement operations. In recent years, however, this practice has virtually disappeared as farmers have established selective breeding programs and the use of non-native Atlantic salmon has increased (Keller and Leslie 1996).

[76] However, it is worth noting that during the period 1985-1996 a total of 11,949,000 Atlantic salmon eggs were imported into the province by companies which were taking advantage of new strains of farmed stock which had been developed in other jurisdictions - (British Columbia Environmental Assessment Office 1997, Vol. 3)

[77] The standard incubators used for Pacific salmon eggs are known as Heath trays.

[78] Most Atlantic salmon eggs are incubated in what are referred to as Combi tanks whose name reflects the fact that they are also used for early rearing of fry.

fry in situations in which the ambient water temperature is lower than optimal for maximum growth[79].

The total time spent in freshwater typically varies from six months to two years depending on species, environmental factors such as rearing water temperature, feed quality, and the targeted final size of the smolt (British Columbia Environmental Assessment Office 1997, Vol. 3). Data provided by the Cooperative Assessment of Salmonid Health (C.A.S.H.) program indicate that during the mid-1990's in British Columbia, the average farmed chinook smolt weighed approximately 35 grams when entering saltwater, while the average Atlantic salmon smolt weighed approximately 75 grams (Appendix A).

In 1995, a total of approximately 8.5 million Atlantic, chinook and coho smolts were produced by the 11 privately owned and operated hatcheries in British Columbia (British Columbia Environmental Assessment Office 1997, Vol. 3). Hatcheries owned, in whole or in part, by companies which also operate grow-out sites produce the majority of the smolts used by the industry. As of 1997, of the 13 "producer" member companies of the British Columbia Salmon Farmers Association (BCSFA), eight also operated hatcheries. At the same time, three independent hatcheries also served the industry (British Columbia Environmental Assessment Office 1997, Vol. 4).

### *Lake-Based Smolt Rearing*

Most, if not all, juvenile Pacific salmon move directly from the hatchery environment to saltwater grow-out sites when they are ready to undergo the physiological transformations associated with smoltification. In contrast, somewhere between 25% and 50% of the Atlantic salmon smolts used by the British Columbia industry are currently "finished" in freshwater lake-based rearing sites prior to being transferred to saltwater (Dr. Grace Karreman, pers. comm. January 28, 1999). This extra step is employed because larger smolts typically have higher survival and faster growth rates once they enter saltwater and the industry has found that it is more cost-effective to rear smolts to a larger size in lake-based facilities than it is to grow them to a comparable size in hatcheries[80]. Currently, two lake-based rearing sites are licensed in British Columbia. One is located in Lois Lake near the community of Powell River and the other in Georgie Lake near the community of Campbell River on Vancouver Island (British Columbia Environmental Assessment Office 1997, Vol. 3).

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[79] When accelerating fry, the optimal water temperature for both Atlantic and chinook salmon lies in the 15° to 16°C (Dr. David Groves, Sea Spring Salmon Farms Limited, pers. comm. 1999).

[80] The primary advantages of lake-rearing over hatchery rearing include generally warmer water temperatures, lower capital costs, and lower operating costs because water does not have to be pumped.

## Marine Grow-out

When ready to enter saltwater, farmed salmon smolts are moved to saltwater grow-out sites. Currently in British Columbia, all commercial grow-out operations employ cage culture technology[81]. In cage culture, fish are enclosed by an appropriately sized open mesh net that is suspended within a rigid framework, typically constructed of galvanised steel, aluminium, wood or plastic,[82] that is bouyed at the surface and held in place by an extensive system of anchors (Figure 10) (British Columbia Environmental Assessment Office 1997, vol. 3).

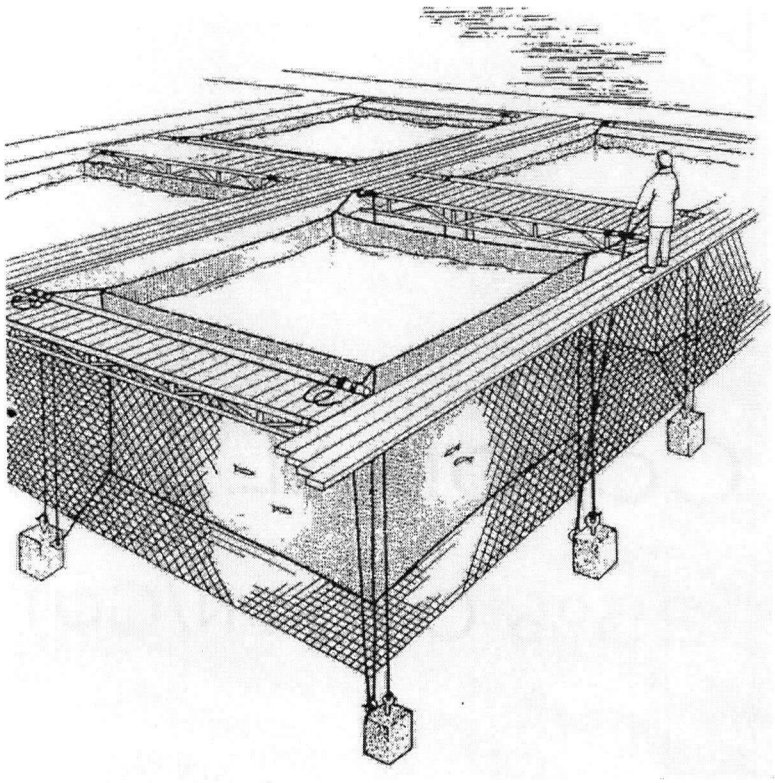

*Figure 10. Simplified Schematic of Cage-Culture Technology Typically Used for Rearing Salmon in Saltwater (from British Columbia Environmental Assessment Office 1997, vol. 3, p. B-8)*

Most cage structures currently in use in British Columbia are square in plan view, and measure either 10, 20 or 30 metres on a side and range from 10 to 20 metres in depth[83]. A typical contemporary farm site is comprised of anywhere from 10 to 30 cages that are usually arranged in two rows along either side of a central walkway. Attached or immediately adjacent to each site is one or more buildings

[81] From the perspective of the salmon farmer, the major advantages of cage culture technology are that it is relatively inexpensive to build and maintain and it allows a free exchange of water and discharge of wastes.

[82] A few cage structures still in use in British Columbia are constructed of wood and/or aluminum.

[83] Following a growing trend in Europe, some salmon farms in British Columbia have also started to use large diameter circular cage systems that are fabricated of plastic.

that serve as a bunkhouse for the farm site staff, a workshop and a feed storage shed. In some cases these structures are located on land immediately adjacent to the net-cage system and in others, they are built on floating platforms that are directly linked to the net-cages (British Columbia Environmental Assessment Office 1997, vol. 3).

A typical farm site in British Columbia is located within 100 metres of shore in areas that experience good tidal flushing yet are reasonably well sheltered from storms. The majority of operating sites are currently concentrated in four areas around Vancouver Island. The two largest concentrations occur in the Northern Strait of Georgia/Desolation Sound area and in the Johnstone Strait area. Most farms in these two regions produce Atlantic salmon. The next two largest concentrations of farms are located along the west coast of Vancouver Island in the relatively sheltered waters of Clayoquot and Quatsino Sounds. Farms in these two areas produce the majority of the chinook salmon farmed in British Columbia (British Columbia Environmental Assessment Office 1997, vol. 3).

Typically, salmon spend between 14 and 25 months growing in saltwater before they are harvested. Depending on market conditions, farmed salmon are usually harvested when they are anywhere between 2 and 5.5 kg.

### Harvesting and Transport

During a normal production cycle, farmed salmon are transported at least twice prior to being processed. At a minimum, smolts are transported from the hatchery where they were reared to a marine grow-out site. Later, when ready for harvest, they are transported from the grow-out site to one of several land-based processing plants[84]. Because the inputs associated with smolt transport are relatively trivial when compared with the other inputs to farmed salmon production, in this research, I have only quantified the inputs associated with transporting adult fish at harvest.

While some marine grow-out sites currently being used in British Columbia are accessible by road, the majority can only be accessed by water or air. As a result, at harvest, most farmed salmon are transported by boat to shore-based plants for processing. Vessels used for transporting farmed salmon are often retired salmon purse-seiners that have been converted to transport either live fish or freshly stunned, bled and iced carcasses[85]. At the farm site, live salmon are either brailed or pumped

[84] However, for the growing fraction of farmed salmon that are reared in lake-pen sites prior to entering saltwater, at least one additional transportation step is required.

[85] The practice, once fairly common in the British Columbia salmon farming industry, of processing salmon in the immediate vicinity of the marine grow-out site has virtually disappeared. Now, the vast majority of farmed salmon in

from the net-cage into the hold of the ship. Depending on the proximity of the farm site relative to the processing plant being used, transportation times may vary from as little as an hour to as much as a day. Once at the processing plant's dock, live salmon are usually brailed from the ship's hold into a receiving tank and are shortly thereafter processed.

As of 1996, four of the 16 companies operating grow-out sites in British Columbia transported their own animals to processing plants (British Columbia Environmental Assessment Office 1997, vol. 4). The remainder of the industry contracts out the transport of their animals upon harvest to one of the specialised salmon transport companies operating in the province.

British Columbia are transported to centrally located processing plants either as live animals or as freshly stunned and bled round carcasses (Mr. Don Millard, Transmar Shipping Ltd, pers. comm. 1997).

# Chapter 3: Overview of Issues, Assumptions and Methods Common to Both Analyses

In this chapter I review the issues, assumptions and methods that were common to both analyses.

## Issues and Assumptions

### The Like-Product Assumption

A major assumption underlying this research is that the "products" of the two technology systems under consideration are the same. If this assumption holds, it provides the basis upon which a direct comparison of the biophysical inputs can be made.

In simple terms, a tonne of salmon is a tonne of salmon *ceteris paribus*. Using other bases of comparison, however, this assumption begins to break down. Biological and ecological differences between the six salmon species produced in British Columbia give rise to sometimes subtle physical, bio-chemical, and palatability differences which can in turn have an effect on their relative value to humans. For example, because of the differences in diet and activity level, there are measurable differences in the average protein, ash and fat levels of farmed and wild salmon. Typically, farmed salmon have lower levels of protein and ash and higher fat levels than do wild salmon of the same species (Higgs *et al.* 1995). It is also worth noting that the composition of the whole bodies and flesh of both wild and farmed salmon can vary between individuals of the same species, and over the life on an individual fish, reflecting quantitative and qualitative changes in diet, maturity, etc.

Finally, there can be significant differences in the subjective value that humans place on different salmon species as a foodstuff that is then reflected in their market price. These price differences result from a range of factors including the flavour, relative abundance, seasonality of availability of different species, and culturally based preferences. For example, the current market value of farmed Atlantic salmon is much higher than that of an average kilogram of seine-caught pink or chum salmon. However, the price difference is minimal between farmed salmon and premium wild caught sockeye, chinook or coho salmon as evidenced by the high degree of substitutability between these products in most markets (Herrmann *et al.* 1993, Clayton and Gordon 1999).

While there are a number of ways in which the like-product assumption can be challenged, for present purposes, these differences were set aside and the analysis was conducted using mass as the basis for comparison.

## *The Partitioning Problem*

The partitioning or joint production problem arises whenever there is a need to allocate inputs to a given activity within the economy amongst two or more outputs. Patterson (1996) provides the following simple illustration of the problem within the context of an energy analysis: "For instance, a given amount of energy (MJ) is required to produce essentially two products from a sheep farm: wool (kg) and meat (kg). The problem arises when the energy input (MJ) has to be allocated to the outputs (kg)" (Patterson 1996, p. 385).

In their review of methodological issues and conventions to be observed when conducting energy analyses, the International Federation of Institutes for Advanced Studies (IFIAS) identified four broad conventions that can be adopted when addressing the partitioning problem:

1. Assign inputs entirely to the output of interest.
2. Assign inputs in proportion to the monetary value of the outputs.
3. Assign inputs in proportion to some physical parameter that characterises the outputs of the system (for example mass, volume, etc.).
4. Assign inputs in proportion to the marginal input savings which could be made if the output of interest was not provided (as summarised by Patterson 1996, p. 386).

Since these four conventions were first articulated, Patterson (1996) reports that none have received wide-spread acceptance. This lack of apparent consensus, however, probably reflects the reality that different analytical applications call for different conventions.

During this research, two forms of the partitioning problem were encountered. Both arise in the analysis of the inputs to salmon feed manufacturing. The first, and more easily addressed form of the problem arises because both fish meals and fish oils, the two outputs of the fish reduction process, are used in contemporary salmon diets[86]. In essence, the problem I faced was how to account for both fish meal and oil, without double-counting any of the inputs associated with fish production,

[86] Using Patterson's sheep farming example above, this is analogous to an activity which consumes both mutton and wool.

harvesting, and processing. In addressing this problem, I have essentially combined the first and third conventions outlined above. I account only for the inputs associated with providing the component, either fish meal or oil, which represents the greater wet weight of fish biomass.

The second, and trickier, form of the partitioning problem arises because so-called "wastes" and by-products of other economic activities are frequently used as inputs to salmon feed. For example, fish processing wastes[87] and inedible livestock by-products are used in contemporary salmon diets. The question that the use of these wastes/by-products raises is: What portion, if any, of the inputs originally required to produce and/or harvest the live weight of fish and livestock should be "charged" to the production of salmon feed and ultimately to the production of intensively cultured salmon?

This form of the partitioning problem has been addressed, at least implicitly, in four previous energy analyses of fish culture systems of which I am aware (Pitcher 1977, Rawitscher 1978, Li 1987, Berg *et al.* 1996). In three cases (Pitcher 1977, Rawitscher 1978, Berg *et al.* 1996), the study authors tacitly adopted the first convention outlined by the IFIAS, that inputs should be assigned exclusively to the primary output of interest. As a result, subsequent activities, such as fish feed production, which utilise any resulting "wastes", do so at zero energetic cost other than that needed to possibly re-process the wastes into a useable form[88]. However, Li (1987) in his analysis of a traditional integrated Chinese fish farm, partially adopted the third IFIAS convention when he accounted for the energy contributions made by chicken, cattle and human manures to the fish polyculture system he modelled. He did not, however, attempt to estimate the industrial energy inputs associated with producing the various manures that were incorporated as an input to fish feed.

The slightly different approaches taken in these analyses, and the contexts within which they were conducted highlights an important issue which, I believe, is often overlooked when accounting for "wastes" and/or by-products within a biophysical model. Essentially, I realised that the decision as to which accounting convention to employ is highly subjective and as such is influenced, amongst other things, by our cultural perceptions of "wastes" and by-products generally. Furthermore, even within

[87] Fish processing wastes are essentially the fraction of the whole fish which remains after processing has occurred to remove the portion which is desired for direct human consumption.

[88] For example, in Rawitscher's model of the energy inputs to catfish feed, she notes that "If fish waste were used instead of the herring (as the raw material to the fish meal used), it could be considered a free input and the energy in the feed would then be 3,524 kcal/kg." (Rawitscher 1978, Table G.14, p. 128) instead of 4,305 kcal/kg which results from using herring meal. Similarly, while Pitcher recognizes that the scrap meat and bone from livestock processing that is incorporated into the trout feed he is modelling "has accumulated a large energy debt during the production of meat for human

a given cultural context, the distinction between a "waste", a by-product and a *bona fide* co-product of a given activity is relatively arbitrary and highly changeable over time. For example, many people outside of the livestock processing industry perceive that many of the inedible by-products such as offal, paunch, blood, and feathers that result from animal processing are valueless wastes. However, within the livestock processing sector, these inedibles can be important sources of additional revenue which are essential to maintaining profitability in a highly competitive market. As a result, analyses which *a priori* treat wastes and by-products as "free" inputs, limit the relevance and broader applicability of their results to identical cultural and economic contexts.

I also realised that the choice of which accounting convention to adopt also depends in part upon the research question(s) being asked. Furthermore, if one is not careful in adopting an appropriate convention, the results of an analysis can be misleading. I believe that Berg *et al*'s (1996) comparative energy and ecological footprint analysis of two forms of Tilapia culture in Zimbabwe provides an example of how adopting an inappropriate accounting convention can distort results. As part of their analysis, Berg *et al.* set out to quantify and compare the area of ecosystem required to sustain feed inputs to produce an equivalent amount of Tilapia from both a hypothetical intensive cage culture, and a hypothetical semi-intensive pond culture system. In building their models, they assumed: 1) that growing a given mass of Tilapia will require approximately the same feed energy inputs regardless of whether the fish are cultured in ponds or cages[89], and 2) that the source ecosystems supplying the inputs are essentially the same in both instances[90]. However, the pond culture system was deemed to derived 90% of its feed energy requirements from fish processing and agricultural residues. Consequently, under the convention that they implicitly adopted, these inputs were biophysically available free of charge. Meanwhile, in the cage culture system only primary fishery and agricultural products were consumed as feed. Thus, the two culture systems end up with very different ecological footprints to sustain an equal amount of fish growth[91].

In light of the above, for the base case analysis of this research, I have adopted a form of the third partitioning convention outlined by the IFIAS. I assign the inputs to a given activity amongst its

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consumption." he excludes the energy costs associated with livestock production from his analysis as these activities "would continue irrespective of the needs of the feedstuff manufacturers,..." (Pitcher 1977, notes to Table II, p. 61).

[89] Berg *et al.* 1996, Figure 3, p. 146 and accompanying text.

[90] In both cases, Berg *et al.* assume that the fish based feed inputs are derived entirely from kapenta harvested from Lake Kariba, the setting of the two hypothetical Tilapia culture systems, while the plant based inputs to feed would be sourced from the local Zimbabwean agricultural sector.

[91] More precisely, they concluded that while the feed inputs associated with growing a kilogram of Tilapia in the pond culture system only required the ecosystem support of about 0.7 $m^2$ of pond ecosystem, a kilogram of cage cultured

various co-products in proportion to the relative mass of those co-products. However, as part of the sensitivity analysis presented in Chapter 6, I explore the effect of adopting other partitioning problem accounting conventions.

## The Boundary Problem

Whether explicitly recognised or not, almost every biophysical evaluation of any non-trivial system encounters the boundary problem. Simply stated, the boundary problem arises because it is seldom possible for an analysis to encompass all of the inputs to and outputs from the system(s) of interest. The major reasons for this are:

1. the diversity of inputs and/or outputs that characterise many systems of interest,

2. most systems of interest are embedded within highly complex natural and socio-economic systems that are often difficult to conceptually "untangle". Consequently, it can be hard to describe the myriad inputs and outputs, and

3. even when it is possible to fully describe and conceptually trace the origin of inputs and the fate of outputs from a given system, quantitative data upon which an analysis can be built may be lacking or of poor quality.

Given these challenges, decisions are made whenever an analysis is undertaken regarding what is to be included and excluded. Consequently, an element of subjectivity is introduced into each analysis that inevitably biases the results, to a greater or lesser extent, reflecting the choices made by the analyst. One advantage, however, of conducting a side-by-side comparative analysis of two or more systems, as is the case in this research, is that although the boundary problem related bias may still exist, its effects on the results can be minimised by establishing the same boundaries around each system.

## How Input Parameter Values Were Chosen

As the primary purpose of this research was to evaluate and compare the relative sustainability of the alternative technologies used to produce salmon in BC *as they currently exist*, throughout the base case analyses I focussed on characterising the average biophysical costs associated with yielding a tonne of salmon. Functionally, this meant that where reasonably high quality data were available

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Tilapia required the ecosystem support provided by 21,000 $m^2$ of lake ecosystem plus 420 $m^2$ of agricultural ecosystem

regarding a given input, I used average values in the models. However, in situations in which input parameter values had to be inferred or estimated, I chose values that had the ultimate effect of reducing the total resulting biophysical costs associated with producing a tonne of salmon. In other words, where I was uncertain as to what value would best represent the current average input, I used values that I believed would result in a conservative outcome.

In evaluating the various technologies based on average inputs, however, it is important to note that the results do not reflect the mix of inputs that would occur at the margin. As a result, the next unit of production added to either system may be more or less biophysically efficient than the average performance evaluated in this analysis. Similarly, this analysis does not reflect the use of best-available, least biophysical cost technologies or inputs. Thus this research provides a picture of which salmon producing system or fishing technology is currently more or less sustainable.

## Analytical Overview

As reviewed in Chapter 1, a variety of biophysical accounting techniques are available to evaluate human activities. The primary technique that I have used in this research is ecological footprint analysis. However, I have also conducted an energy analysis of the two salmon producing systems using data collected as part of the ecological footprint analysis. This secondary energy analysis was undertaken primarily because it allowed me to compare the biophysical efficiency of salmon production with a much wider range of food producing systems.

### *Ecological Footprint Analysis*

Ecological footprint analysis measures the material and energy flows required to sustain a defined human population or activity, and converts these flows into a commensurate variable - ecosystem area - for evaluation and comparison (Rees and Wackernagel 1994, Rees 1996, Wackernagel and Rees 1996). This ecological footprint analysis began with a detailed process analysis of the major elements of both salmon production systems. A range of material, labour and energy inputs and outputs were quantified and normalised per tonne of salmon produced. These inputs and outputs were then converted, where possible, into corresponding marine or terrestrial ecosystem support areas. These were then summed to provide an estimate of the total ecological footprint per tonne of salmon produced by each of the systems being examined.

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(Berg *et al.* 1996, Figure 4, p. 148 and supporting text).

## Overview of the Inputs Included in This Analysis

The inputs incorporated into this analysis included:

1. the organic material either consumed by salmon foraging in the wild or incorporated into manufactured salmon feed,
2. the direct and some indirect labour inputs,
3. the direct and some indirect fossil fuels consumed,
4. the direct and some indirect electricity consumed, and
5. the major direct inorganic and synthetic organic material inputs to the two systems including: steel, aluminium, concrete, plastics, and fibreglass.

Inputs and outputs that were not accounted for include:

1. the respired and excreted biological wastes of salmon, and fish of various species incorporated in manufactured salmon feed,
2. the marine organisms, other than the salmon themselves, that are intentionally or unintentionally killed as part of salmon fishing and salmon farming activities. This includes:
   - fishing discards and mortalities that result from interactions with fishing gear both in the salmon fishery and in the fisheries that provide inputs to farmed salmon, and
   - the mortality of marine and avian predators, in particular seals and sea lions, that are killed both intentionally by salmon fishers and farmers and unintentionally through interactions with fishing gears and salmon farm infrastructure,
3. the disposal/assimilation of salmon carcasses which formed part of the population that ultimately yields a tonne of harvested salmon,
4. dissolved oxygen required for respiration,
5. the antibiotics, pesticides and algicides used in salmon farming,
6. the government employed labour required to manage the two industries,

7. the area of watershed required to sustain flows of freshwater for spawning and rearing of wild smolts and for hatchery operations[92].

## Overview of How Ecosystem Support Areas Were Estimated

The data sources, and manipulations required to standardise the data on the inputs to, and outputs from, the salmon farming industry and the commercial salmon fishery are described in detail in Chapters 4 and 5 respectively. However, once the various inputs and outputs were normalised per tonne of salmon produced, the methods used to estimate the corresponding ecological footprint were the same (Table 1).

[92] I did not consider the area of ecosystem required to sustain flows of freshwater for both wild spawning and rearing of smolts and for hatchery operations for two main reasons. First it is both conceptually and functionally difficult to do. This is because the maintenance of both surface and groundwater flows is only partially dependent on the presence, type and extent of productive terrestrial ecosystem in a given watershed. Other factors that play a significant role in maintaining freshwater flows, and hence complicate any attempt to estimate a generalised ecosystem support area include topography, geology, and precipitation type and rate. Second, even if an area of minimum ecosystem support were quantified for a given watershed, it's inclusion within a sectoral footprinting analysis would be problematic. This is because the type and amount of ecosystem area associated with maintaining freshwater flows would almost invariably fulfil other ecological functions and as such, raises the potential of double-counting.

*Table 1. Outline of the Quantified Inputs and Methods Employed to Convert Them Into A Corresponding Area of Supporting Ecosystem*

| Input | Basis upon which the associated ecological footprint was estimated |
|---|---|
| 1) Biological inputs:<br>- direct and indirect crop-based inputs | using average Canadian agricultural productivities |
| - direct and indirect marine organisms | using average trophic transfer efficiencies of 10% and estimates of mean trophic levels of organisms and source ecosystem primary productivity |
| - indirect livestock by-products | conversion to quantity of crop-based agricultural product required, then included as an agricultural input |
| 2) Direct and indirect person-days of labour | using the area of agricultural and other ecosystem support required to sustain food intake based on the average Canadian diet |
| 3) Direct and indirect fossil fuel energy for harvesting and/or production of inputs, re-processing of inputs and transportation of inputs and final products | using the area of forest ecosystem required to assimilate the $CO_2$ equivalent to the total greenhouse gas emissions which result |
| 4) Direct and indirect electricity inputs for harvesting and/or production of inputs, and re-processing inputs | using the area of forest ecosystem required to assimilate the $CO_2$ equivalent to the total greenhouse gas emissions which result |
| 5) Direct inorganic and synthetic organic material inputs (e.g. steel, aluminium, concrete, plastics, etc.) | using the area of forest ecosystem required to assimilate the $CO_2$ equivalent to the total greenhouse gas emissions which result from providing the various material inputs |

### *Footprinting Biological Inputs*

Three types of biological inputs were encountered during the research. A common input to both salmon production systems were marine organisms that are either the prey of wild foraging salmon or that are used to produce fish meal and oil for inclusion in formulated salmon feeds. The other two biological inputs, agricultural crop-based products and livestock by-product meals, appear as inputs to salmon feeds only.

In order to simplify the analyses, in the case of all three types of biological inputs I only accounted for the ecosystem support to directly grow the biomass consumed and explicitly excluded from consideration any additional biomass that must be maintained for reproduction. For example, the ecological footprint associated with providing the seeds needed for crop inputs has been excluded as has the footprint associated with maintaining the broodstock of both wild caught salmon, and other marine species harvested for fish meals and oils.

The technique used to estimate the ecosystem support area required to produce marine organisms is based on the method used by Pauly and Christensen (1995) to estimate the primary productivity required to sustain global fisheries. The approach involved two steps. First, the grams of carbon that must be fixed by autotrophs annually so as to yield a specific quantity of marine organism consumed was estimated by assuming an average transfer efficiency between trophic levels of 10% (Pauly and Christensen 1995) and a conservative 9:1 conversion ratio from wet weight of organism to carbon content (Strathmann 1967) (see Equation 1).

$$P = (M/9) \times 10^{(T-1)} \qquad \text{Equation 1}$$

Where: P is primary productivity required, expressed in terms of grams of carbon fixed,
M is the wet weight mass, in grams, of the organisms for which an ecosystem support area is being calculated, and
T is the mean trophic level at which the organism(s) feeds using a scale in which autotrophs are assigned a trophic level of 1.0 by default.

The area of ecosystem support required was then calculated by dividing the mass of carbon fixed, using Equation 1, by an appropriate estimate of the average rate at which carbon is fixed (ie. the net primary productivity) by the supporting marine ecosystem. As published estimates of net primary productivity for a given marine ecosystem can vary considerably, reflecting different methodologies, assumptions, data sets, etc., I opted to use Longhurst *et al.* (1995) as the source of all of the estimates of net primary productivity for the different regions of the world's oceans. This paper was selected as the sole source of marine primary productivity estimates because it provides estimates for 57 discrete biogeochemical marine provinces encompassing all of the world's oceans using a consistent and analytically robust technique based on satellite sea-surface chlorophyll data[93]. Moreover, as Longhurst *et al.*'s values tend to be higher than previous estimates of marine primary productivity (Koblentz-Mishke *et al.* 1970, Platt and Subba Rao 1975, Berger *et al.* 1987), their use in this analysis will result in relatively conservative ecological footprint estimates.

The area of ecosystem required to provide the crop inputs to farmed salmon feed was calculated using average Canadian agricultural productivities for the five-year period 1992 to 1996 inclusive.

In estimating the area of ecosystem required to provide livestock by-products that are incorporated into salmon feeds as protein meals, I first assumed that all of the by-products required were derived

[93] For a complete description of their analytical technique see Longhurst *et al.* (1995).

from a single species, chicken[94]. I then assumed that the wet weight chicken biomass required for by-product meals was raised exclusively on a diet of grain corn[95]. Once I had estimated the quantity of grain corn needed to grow the wet weight of chicken equivalent to the by-product inputs, I used the five-year average Canadian yield of grain corn to estimate the ecosystem support area.

### *Footprinting Labour Inputs*

From the published literature, there is no single universally accepted method for incorporating labour inputs within biophysical accounting frameworks. Even within the limited context of energy and ecological footprint analyses of fish and shellfish production systems, a variety of approaches have been used including:

- excluding labour inputs entirely from the analysis (Mitchell and Cleveland 1993),
- incorporate only the nutritional energy content of the food required to sustain the requisite labour inputs (Rawitscher 1978),
- incorporate the industrial energy needed to provide the food required to sustain labour inputs (Pitcher 1977), and
- incorporate the total industrial energy associated with wages paid for labour inputs using the industrial energy to Gross National Product ratio for the country within which labour is supplied. (Folke 1988, Hammer 1991, Larsson *et al.* 1994, and Berg *et al.* 1996).

In this analysis, however, I have opted to use a different technique to those outlined above. I calculated the ecosystem support area associated with labour inputs (expressed in person-days) using estimates prepared by Wackernagel *et al.* (1997, 1999) of the ecological footprint required to sustain the average Canadian's annual food consumption in 1993 (Table 2).

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[94] Chicken was selected as the sole source of livestock by-products because: 1) they are the main source of feathers used to make feather meal, one of the three livestock by-product meals incorporated into salmon feed, and 2) chicken are, relative to swine and cattle, efficient converters of feed.

[95] I assumed that grain corn was the sole fodder used to grow the chicken biomass required because: 1) corn is one of the highest yielding agricultural crops, on a tonnage per hectare basis, grown in Canada – thereby resulting in a small ecosystem support area, and 2) the analysis was simplified by not attempting to model the myriad inputs associated with a highly formulated composite chicken feed.

*Table 2. Ecological Footprint of the Average Canadian's Annual Food Consumption in 1993*

| Ecosystem Type | Area Required to Sustain the Average Canadian's Annual Food Consumption (ha) |
|---|---|
| Arable land | 0.49 |
| Pasture land | 1.52 |
| All Forest land (includes land to assimilate $CO_2$ from energy used to provide food) | 0.39 |
| Total Terrestrial | 2.4 |
| Aquatic | 0.96 |

Source: Electronic data file that accompanies Wackernagel *et al*'s 1997 report.

As an example using the data presented in Table 2, the total terrestrial ecological footprint associated with providing ten days of labour would be calculated as follows: (10 days ÷ 365 days/year) × 2.4 ha = 0.066 ha. Similarly, the marine ecological footprint associated with ten days of labour would be calculated as follows: (10 days ÷ 365 days/year) × 0.96 ha = 0.026 ha.

### *Footprinting Fossil Fuel Inputs*

Estimating the ecological footprint associated with the use of fossil fuels presents both conceptual and methodological challenges. Although fossil fuels have a biological origin, it is impossible to estimate the area of ecosystem that was required to produce the original biomass that ultimately becomes a given quantity of coal, oil or natural gas. Most ecological footprint analyses therefore employ one of two techniques when footprinting fossil fuel use. The first entails calculating the area of ecosystem required to produce a contemporary biologically sourced liquid fossil fuel substitute such as ethanol, methanol, soydiesel[96], or fish oil[97, 98]. The second, and the one that I have adopted, is to estimate the area of forest ecosystem required to sequester the $CO_2$ equivalent to the greenhouse gases that are produced through the production and combustion of fossil fuels.

The rationale underlying this technique is that if society is to avoid possible anthropogenic climate change then fossil fuel use should not exceed the assimilative capacity of the world's ecosystems[99]. Both marine and terrestrial ecosystems are believed to play an important role in anthropogenic $CO_2$

[96] Soydiesel is, as its name suggests, a diesel fuel-like product of the soybean that is produced through the esterification of soy oil. Ahmed et al (1994) provides an excellent review of the process and energetics of soydiesel production.

[97] Fish oil, a co-product along with fish meal of the fish reduction industry, has been used as a fuel source in Danish thermo-electric generating stations (Sandison 1995), and as a diesel fuel substitute on board fishing vessels and in fish processing plants in Alaska (Blythe 1996).

[98] For a review of this approach to footprinting fossil fuel use see Wackernagel and Rees (1996, p. 72).

[99] The major sources of anthropogenic $CO_2$ are fossil fuel combustion and through the oxidation of biomass due to disturbance of terrestrial ecosystems (e.g. deforestation, agriculture etc.).

assimilation[100]. However, because of the difficulty estimating a global average marine $CO_2$ sink rate and as terrestrial ecosystems are more readily manipulable than ocean ecosystems (e.g. carbon sink forests), most ecological footprint analyses to date have employed a notional $CO_2$ assimilation forest ecosystem as the basis for modelling the ecosystem support associated with fossil fuel use (for examples see Wada 1993, Larsson *et al.* 1994, Wackernagel and Rees 1996, Folke *et al.* 1997).

Practically, in modelling the ecological footprint associated with fossil fuel use, it was first necessary to quantify greenhouse gas emission intensities for each of the major fossil fuel inputs encountered in the analysis. This included $CO_2$ emissions that result directly from fuel combustion along with the total greenhouse gas emissions associated with providing the fossil fuels used. Table 3 summarises the emission intensity values that I used throughout this research for gasoline, diesel fuel, propane, and natural gas.

*Table 3. Assumed Greenhouse Gas Emission Intensities for Gasoline, Diesel Fuel, Natural Gas and Propane*

| Fossil Fuel | $CO_2$ Released Upon Combustion (g $CO_2$/MJ) | GHG Emissions from Production Through Fuel Dispensing (g $CO_2$ eq./MJ)[a] | Total GHG Emission Intensity (g $CO_2$ eq./MJ) |
|---|---|---|---|
| Gasoline | 70.2[b] | 22.4[c] | 92.6 |
| Diesel fuel | 73.9[d] | 14.0[c] | 87.9 |
| Natural Gas | 51[e] | 6.9[c] | 57.9 |
| Propane | 51[f] | 6.9[f] | 57.9 |

Notes: a. Includes gas leaks and flares from wells, feedstock recovery and transmission, and fuel refining, distribution and dispensing (see Delucchi 1997 for details).
b. Calculated from the results of a "real-world" automotive emissions study (Pierson, *et al.* 1996, Table 6, p. 2245).
c. Calculated from Delucchi 1997, Table 7, p. 191.
d. Calculated from the results of a "real-world" marine exhaust emission study of over 40 vessels (Lloyd's Register Engineering Services 1995, Table 5, p. 17).
e. From Weston 1996, Table 2, p. 2904.
f. I have assumed that propane releases the same amounts of $CO_2$ upon combustion and GHG's through the production cycle as does natural gas.

By multiplying the fossil fuel energy consumed, in MJ, by the appropriate total greenhouse gas emission intensity (from Table 3), I estimated the total resulting greenhouse gas emissions, expressed in terms of grams (or kilograms) of $CO_2$ equivalent, for each type of fossil fuel consumed.

[100] Models of the fate of anthropogenic $CO_2$ suggest that approximately 46% is accumulating in the atmosphere while another approximately 29% is being assimilated by the world's oceans with the remaining approximately 25% being assimilated by terrestrial ecosystems (see Longhurst 1991; Sarmiento and Sundquist 1992; Sundquist 1993).

Finally, in order to estimate the fossil fuel related ecological footprint, it was necessary to determine an appropriate carbon assimilation rate for a typical forest ecosystem. Not surprisingly, carbon assimilation rates by forests vary widely, depending on:

- the latitude, altitude and attitude of the forest,
- moisture availability and temperature, and
- species composition and the age of the stand.

In addition, while it may be most appropriate to use a global average carbon assimilation rate as all greenhouse gases released into the atmosphere enter the global "common pool", determining such a rate is difficult. As a result, previous ecological footprint analyses have employed either regionally-specific rates or estimates of the global average. For example Larsson *et al.* (1994) use a relatively high carbon assimilation value of 5 tonnes C/ha/yr, reflecting the re-conversion of tropical pasture to managed forest plantation while Folke *et al.* (1997) use an average value of 0.45 tonnes C/ha/yr that reflects the range of assimilation rates associated with newly growing temperate forests of the Baltic region. In contrast, Wackernagel and Rees (1996) employ an estimated global forest assimilation rate of 1.8 tonnes C/ha/yr.

In this analysis, I have chosen to use a carbon assimilation rate representative of British Columbia's forests primarily because a reasonably defensible value was available. As a result, the rate used throughout this research is 1 tonne C/ha/yr[101] which equates to a $CO_2$ assimilation rate of approximately 3.66 tonnes $CO_2$/ha/yr.

### *Footprinting Electricity Inputs*

The technique used to estimate the ecological footprint associated with the use of electricity depends, in part, upon the primary source of energy used to generate the electricity[102]. In this research, most of the electricity consumed by the two salmon production systems was provided by BC Hydro, the provincial electrical utility. Currently, approximately 90% of the electricity produced by BC Hydro is hydroelectric with the remaining 10% provided by a natural gas fired thermal generating station (Mr.

[101] After conferring with Dr. David Spittlehouse a research scientist with the B.C. Ministry of Forests, this value was determined by dividing, 55.21 Tg C/yr, the estimated average annual change in forest ecosystem carbon storage for all of British Columbia over the period from 1920 to 1989 (as determined by Kurz, *et al.* 1996, Table 3, p. 22), by 57.9 Mha, the total average forested area of British Columbia (Kurz, *et al.* 1996, Table 1, p. 3).

[102] For a review of the possible techniques that can be used to estimate the ecosystem support associated with the provision of electricity, see Wackernagel and Rees 1996, pp. 74-75.

John Rich, Senior Environmental Coordinator, BC Hydro, pers. comm. May, 1998). Given this mix of primary energy sources, I adopted an approach similar to that outlined above for estimating the ecological footprint associated with fossil fuel use. To wit, I estimated the average greenhouse gas emissions associated with generating a given quantity of electricity in British Columbia and then converted this into the area of typical British Columbia forest ecosystem that would be required to assimilate an equivalent quantity of carbon dioxide.

For hydroelectricity, I have used a greenhouse gas emission intensity value of 25 g $CO_2$/kWh generated. This is comprised of an estimated 5 g $CO_2$ equivalent per kWh that result from the inputs to dam and power plant construction[103] and 20 g $CO_2$ equivalent per kWh that result from the decay of biomass in flooded reservoirs[104]. With respect to the thermoelectric power, Delucchi (1997) reports that the "fuel cycle" greenhouse gas emissions associated with natural gas fueled, boiler-type generators is 735 g $CO_2$/kWh of electricity generated (p. 189, Table 6C). Using the current 90:10 mix of energy sources used by BC Hydro as the weighting factor, I estimate that the average greenhouse gas emissions associated with contemporary electricity generation[105] equals approximately 96 g $CO_2$/kWh or approximately 26.7 g $CO_2$/MJ of electricity delivered[106].

### *Footprinting Inorganic and Synthetic Organic Material Inputs*

As part of the analysis of both salmon production systems, I also estimated the ecological footprints associated with the major direct inorganic and synthetic organic[107] material inputs per tonne of salmon produced. The six inorganic and synthetic organic materials considered were aluminium, steel, all other metals combined[108], glass, concrete, and all plastics and related synthetic organic materials combined.

Most previous ecological footprint analyses that have accounted for such inputs have converted either the physical quantities (Wada 1993), or the monetary value (Larsson *et al.* 1994, Berg *et al.*

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[103] After reviewing analyses of the greenhouse gas emissions associated with the construction of hydro-electric dams and generating plants, Gagnon and van de Vate (1997) report that emissions typically fall within the range of 1 to 10 g $CO_2$ equivalent per kWh generated. I have used the middle of this range of values in this analysis.

[104] Greenhouse gases emissions through the process of biomass decay in reservoirs is influenced by a range of factors including: the types of soil and vegetation that is flooded, the area that is flooded, the depth of the reservoir, the latitude and altitude of the reservoir, annual duration of ice coverage of the reservoir and the age of the reservoir (Gagnon and van de Vate 1997). As a result, lifecycle emissions can vary widely between reservoirs. After reviewing a number of analyses of the emissions associated with hydropower reservoirs, Gagnon and van de Vate 1997, suggest that 20 g $CO_2$ equivalent per kWh generated is a reasonable worldwide average greenhouse gas emission intensity value associated with biomass decay from reservoirs.

[105] Estimated by adding the products of (735 x 0.1) and (25 x 0.9).

[106] Where 1kWh equals 3.6 MJ.

[107] The synthetic organic material inputs encountered in this research are primarily plastic derived.

1996) of the inputs into an embodied energy equivalent which is then treated as any other energy input. In this analysis, however, I adopted a more comprehensive approach. Instead of basing the estimate of ecosystem support on the greenhouse gases that result solely from the energy used (i.e. the embodied energy), I estimated the ecosystem support based on the total fuel- and non-fuel-origin greenhouse gases emitted through the provision of the material inputs[109]. Where possible, total greenhouse gas emission intensity values used in this research were based on representative contemporary Canadian values taken from the literature or from direct communication with researchers. In other instances, however, I had to rely on greenhouse gas emission intensity values from other countries.

Because I am using energy analysis in addition to ecological footprint analysis to evaluate the two salmon production systems, I have also quantified contemporary energy intensity estimates for the six major material inputs.

**Aluminium**

I have used a greenhouse gas emission intensity value of 8 kg $CO_2$ eq./kg and an energy intensity value of 140 MJ/kg for contemporary Canadian-produced primary aluminium. These values are based on the results of an extensive "cradle to gate" assessment of Alcan Aluminum Limited's Canadian facilities and their suppliers of raw materials (Mr. Steven Pomper, Director, Environment, Alcan Aluminum Limited, per. comm. April, 1998).

These values are comparable to, or lower than energy and emission intensity estimates for primary aluminium produced in other jurisdictions. For example, as part of the same analysis that provided the above estimates, Mr. Pomper reported that on a North American-wide basis, a greenhouse gas emission intensity value of 14.5 kg $CO_2$ eq./kg and an energy intensity value of 186 MJ/kg would apply (pers. comm., April, 1998). Similarly, Weston (1996) reports an emission intensity value of 13.6 kg $CO_2$ eq./kg and an energy intensity value of 130 MJ/kg for primary aluminium produced in the United States, while Moriguchi (1993) indicates that Japanese aluminium production results in emissions equivalent to 8.8 kg $CO_2$ eq./kg and van de Vate (1997), indicates that European primary aluminium production results in emissions that range between 13 and 34 kg $CO_2$ eq./kg. Finally,

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[108] Primarily comprised of lead and zinc.

[109] In many cases, embodied energy inputs account for the bulk of the greenhouse gas emissions associated with inorganic and synthetic organic materials. However, for some material inputs, such as concrete or aluminum, significant quantities of non-fuel origin greenhouse gases are emitted in their production.

Gielen, (1995) reports that contemporary Dutch primary aluminium production has an energy intensity of 175 MJ/kg.

### Steel

I was unable to identify any greenhouse gas emission and energy intensity estimates for contemporary Canadian steel production. After reviewing a range of emission and energy intensity estimates from around the world (Table 4), I have used a greenhouse gas emission intensity value of 2.5 kg CO2 eq./kg steel produced and an energy intensity value of 25 MJ/kg steel produced throughout this research.

*Table 4. Review of Energy and Greenhouse Gas Emission Intensity Values for Steel*

| Type of Steel Production | Country or Region | Time Period | Energy Intensity (MJ/kg) | Greenhouse gas Emissions (kg $CO_2$ eq./kg) | Source |
|---|---|---|---|---|---|
| Unspecified | Canada | mid 1970's | 25.7 | | Cole and Rousseau 1992 |
| Unspecified | U.S. | mid 1970's | 39.0 | | ibid. |
| Unspecified | N.Z. | mid 1970's | 32.0 | | ibid. |
| Unspecified | Switzerland | early 1980's | 27.7 | | ibid. |
| Unspecified | Sweden | 1988 | 24 | | Börjesson 1996 |
| Primary | Netherlands | 1990 | 23 | | Gielen 1995 |
| Recycled | Netherlands | 1990 | 5 | | ibid. |
| Unspecified | Brazil | 1991 | 31.7 | | Worrell *et al.* 1997 |
| Unspecified | China | 1991 | 42.4 | | ibid. |
| Unspecified | France | 1991 | 24.2 | | ibid. |
| Unspecified | Germany | 1991 | 18.3 | | ibid. |
| Unspecified | Japan | 1991 | 21.0 | | ibid. |
| Unspecified | Poland | 1991 | 28.0 | | ibid. |
| Unspecified | U.S. | 1991 | 26.5 | | ibid. |
| Unspecified | Japan | early 1990's | | 1.52 | Moriguchi 1993 |
| High alloy | Germany | early 1990's | | 7.21 | Frischknecht *et al.* 1994 in van de Vate 1997 |
| Low alloy | Germany | early 1990's | | 3.03 | ibid. |
| Unalloyed | Germany | early 1990's | | 2.44 | ibid. |
| Low alloy | Unspecified | Unspecified | | 2.0-2.2 | van de Vate 1995 in van de Vate 1997 |
| Low alloy | Europe | early 1990's | | 2.4 | EUR Commission 1995 in van de Vate 1997 |
| Low alloy | Germany | early 1990's | | 3 | Fritsche *et al.* 1995 in van de Vate 1997 |

### Other Metals

Relatively few references provided contemporary estimates of either greenhouse gas emission or energy intensity values associated with the production of metals other than steel and aluminium. All of the estimates identified, regardless of age, are summarised in Table 5.

*Table 5. Review of Energy and Greenhouse Gas Emission Intensity Values for Metals Other Than Steel and Aluminium*

| Metal | Country or Region | Time Period | Energy Intensity (MJ/kg) | Greenhouse gas Emissions (kg $CO_2$ eq./kg) | Source |
|---|---|---|---|---|---|
| Nickel | Canada | mid 1970's | 168.3 | | Cole and Rousseau 1992 |
| Nickel | U.S. | mid 1970's | 58.0 | | ibid. |
| Nickel | Finland | early 1980's | 468.0 | | ibid. |
| Zinc | Canada | mid 1970's | 64.1 | | ibid. |
| Zinc | N.Z. | mid 1970's | 68.4 | | ibid. |
| Zinc | Switzerland | early 1980's | 68.4 | | ibid. |
| Zinc | Finland | early 1980's | 43.2 | | ibid. |
| Copper –prim. | Netherlands | 1990 | 100 | | Gielen 1995 |
| Copper –recyc. | Netherlands | 1990 | 5 | | ibid. |
| Lead – primary | Netherlands | 1990 | 25 | | ibid. |
| Lead – recycled | Netherlands | 1990 | 4 | | ibid. |
| Zinc – primary | Netherlands | 1990 | 25 | | ibid. |
| Zinc – recycled | Netherlands | 1990 | 4 | | ibid. |
| Copper | Germany | early 1990's | | 5.4 | Frischknecht *et al.* 1994 in van de Vate 1997 |
| Copper | Europe | early 1990's | | 2.7 | EUR Commission 1995 in van de Vate 1997 |
| Copper | Germany | early 1990's | | 8.8 | Fritsche *et al.* 1995 in van de Vate 1997 |
| Copper | Unspecified | Unspecified | | 3.5 - 4.9 | van de Vate 1995 in van de Vate 1997 |

In this analysis, as lead and zinc were the most common metals encountered after steel and aluminium, and copper and nickel were, at most, minor inputs to the two systems being analysed, I adopted a conservative energy intensity value of 25 MJ/kg for all other metallic inputs. As no published greenhouse gas emission intensity values were identified for lead and zinc, I have simply assumed a value of 2.5 kg $CO_2$ eq./kg applies.

### Glass

No greenhouse gas emission or energy intensity estimates were found for contemporary Canadian glass production. Based on the published greenhouse gas emission and energy intensity values identified (Table 6), I have conservatively assumed that contemporary glass production has a greenhouse gas emission intensity of 1kg $CO_2$ eq./kg and an energy intensity of 10 MJ/kg.

*Table 6. Review of Energy and Greenhouse Gas Emission Intensity Values for Glass*

| Type of Glass | Country or Region | Time Period | Energy Intensity (MJ/kg) | Greenhouse gas Emissions (kg $CO_2$ eq./kg) | Source |
|---|---|---|---|---|---|
| Sheet | Canada | mid 1970's | 10.2 | | Cole and Rousseau 1992 |
| Sheet | U.S. | mid 1970's | 19.8 | | ibid. |
| Sheet | N.Z. | mid 1970's | 16.7 | | ibid. |
| Sheet | Switzerland | early 1980's | 21.6 | | ibid. |
| Sheet | Finland | early 1980's | 16.5 | | ibid. |
| Wool | Canada | mid 1970's | 22.3 | | ibid. |
| Wool | U.S. | mid 1970's | 14.0 | | ibid. |
| Wool | Switzerland | early 1980's | 18.0 | | ibid. |
| Wool | Finland | early 1980's | 23.4 | | ibid. |
| Primary | Netherlands | 1990 | 7 | | Gielen 1995 |
| Recycled | Netherlands | 1990 | 6 | | ibid. |
| Automobile | Japan | early 1990's | | 1.76 | Moriguchi 1993 |
| Unspecified | Germany | early 1990's | | 1.2 | Frischknecht *et al.* 1994 in van de Vate 1997 |
| Unspecified | Germany | early 1990's | | 1.9 | Fritsche *et al.* 1995 in van de Vate 1997 |
| Unspecified | Unspecified | Unspecified | | 0.9 – 1.2 | van de Vate 1995 in van de Vate 1997 |

**Concrete**

Once again, I was unable to find any greenhouse gas emission or energy intensity values for contemporary Canadian concrete production. As a result, in this analysis I have assumed a greenhouse gas emission intensity of 0.15 kg $CO_2$ eq./kg and an energy intensity value of 1 MJ/kg for contemporary Canadian concrete production. These values were selected as they lie at the conservative end of the range of published values available (Table 7).

*Table 7. Review of Energy and Greenhouse Gas Emission Intensity Values for Concrete*

| Country or Region | Time Period | Energy Intensity (MJ/kg) | Greenhouse gas Emissions (kg $CO_2$ eq./kg) | Source |
|---|---|---|---|---|
| Canada | mid 1970's | 1.2 | | Cole and Rousseau 1992 |
| U.S. | mid 1970's | 1.3 | | ibid. |
| N.Z. | mid 1970's | 2.0 | | ibid. |
| Switzerland | early 1980's | 0.9 | | ibid. |
| Germany | early 1990's | | 0.14 | Frischknecht *et al.* 1994 in van de Vate 1997 |
| Germany | early 1990's | | 0.16 | EUR Commission 1995 in van de Vate 1997 |
| Unspecified | Unspecified | | 0.16 | van de Vate 1995 in van de Vate 1997 |

### Plastics

A variety of plastics and related synthetic organic materials are used in both salmon production systems being studied. However, the data available on the material inputs to the two systems are generally not detailed enough to permit an analysis based on the specific types of synthetic organic materials used. As a result, I combined all plastics and related synthetic organic material inputs and treated them as non-specific plastics. Table 8 summarises the range of emission and energy intensity values for plastics available from the literature.

*Table 8. Review of Energy and Greenhouse Gas Emission Intensity Values for Plastics*

| Type of Plastic | Country or Region | Time Period | Energy Intensity (MJ/kg) | Greenhouse gas Emissions (kg $CO_2$ eq./kg) | Source |
|---|---|---|---|---|---|
| Polyethylene | Canada | mid 1970's | 87.0 | | Cole and Rousseau 1992 |
| Polyethylene | Switzerland | early 1980's | 49.3 | | ibid. |
| Polystyrene | Canada | mid 1970's | 105.0 | | ibid. |
| Polystyrene | Switzerland | early 1980's | 122.8 | | ibid. |
| Polystyrene | Finland | early 1980's | 118.8 | | ibid. |
| Polystyrene | Netherlands | 1990 | 35[a] | | Gielen 1995 |
| PVC | Netherlands | 1990 | 35[a] | | ibid. |
| Other | Netherlands | 1990 | 40[a] | | ibid. |
| Syn. Rubber | Sweden | 1988 | 96 | | Börjesson 1996 |
| Syn. Rubber | Japan | early 1990's | | 1.28 | Moriguchi 1993 |
| Resin | Japan | early 1990's | | 1.61 | ibid. |
| Unspecified | Germany | early 1990's | | 1.37 – 5.45 | Frischknecht *et al.* 1994 in van de Vate 1997 |
| Unspecified | Europe | early 1990's | | 2.4 | EUR Commission 1995 in van de Vate 1997 |
| Unspecified | Germany | early 1990's | | 6 | Fritsche *et al.* 1995 in van de Vate 1997 |
| Unspecified | Unspecified | Unspecified | | 2.0 – 7.9 | van de Vate 1995 in van de Vate 1997 |

Note: a. Values exclude the provision of feedstock.

Selecting values that fall to the conservative end of the range of values reported in the literature (Table 8), I have assigned a greenhouse gas emission intensity value of 3 kg $CO_2$ eq./kg and an energy intensity value of 75 MJ/kg to the generic plastics encountered in this study.

Table 9 summarises the emission and energy intensity values that I used throughout this research for the six major types of inorganic and synthetic organic material inputs encountered.

*Table 9. Summary of Greenhouse Gas Emission and Energy Intensity Values Used*

| Material Input | Energy Intensity (MJ/kg) | Greenhouse Gas Emissions (kg $CO_2$ eq./kg) |
|---|---|---|
| Aluminium | 140 | 8 |
| Steel | 25 | 2.5 |
| Other Metals | 25 | 2.5 |
| Glass | 10 | 1 |
| Concrete | 1 | 0.15 |
| Plastics | 75 | 3 |

## Energy Analysis

Using data compiled as part of the ecological footprint analysis, I conducted an energy analysis of the two salmon production systems. This analysis focussed exclusively on the industrial energy (i.e. fossil fuels, and electricity) dissipated both directly and indirectly in the process of producing salmon.

### The Energy Quality Problem

A methodological issue that arose when conducting this analysis is typically referred to as the energy quality problem (Patterson 1983, 1996, Kåberger 1991). The energy quality problem occurs because standard enthalpic measures of energy (for example MJ or kcal) only measure the heat content of the energy form and not its relative ability to do work, or, in other words, it relative quality[110]. Therefore, in analysing a system that incorporates two or more qualitatively different forms of energy, "[b]efore any efficiency calculations can be made, these energy forms need to be commensurated or adjusted in terms of energy quality" (Patterson 1996, p. 383). In this research, because fossils fuels and electricity differ in their ability to do work, I converted the electrical energy inputs to the two systems into fossil fuel equivalents by assuming a 35% fossil fuel to electricity conversion efficiency[111].

### Energy Return on Investment

The results of an energy analysis can be expressed in any one of a variety of ways. Frequently, energy inputs are expressed relative to the physical quantities of outputs produced or services provided (e.g. MJ/litre of orange juice, MJ/tonne•kilometre of transport service provided) (Patterson

[110] For a more complete review of the energy quality problem see Patterson 1996.
[111] For example, 1 MJ of electricity would be equivalent to approximately 2.86 MJ of fossil fuel energy (1/0.35 = 2.86).

1996). In the case of the current research, I expressed the results in terms of the MJ of fossil fuel equivalent energy required to yield a round tonne of salmon.

However, because the two systems analysed can also be thought of as food energy producing systems, I calculated their energy efficiency using energy return on investment (EROI) ratios Cleveland 1992, Mitchell and Cleveland 1993). EROI ratios were calculated by dividing the useful energy output, in terms of both the gross edible and edible protein energy produced, by the total industrial energy input. In calculating the gross and edible protein output, I assumed that the total edible yield from a round salmon carcass is 65%[112] and that the average protein content of the edible portion is 20%[113] for all species of salmon produced. Furthermore, I assumed that the average gross wet weight energy content of salmon flesh, regardless of species, is 7.6 MJ/kg[114] and that the gross energy content of protein is 23.6 MJ/kg[115].

To permit ease of comparison with published EROI ratios for other food production systems, EROI ratios for both salmon production systems were calculated using both gross edible energy and edible protein energy.

[112] As part of his analysis of the energy efficiency of two forms of salmon culture in Sweden, Folke (1988) assumed that the average edible yield from an Atlantic salmon carcass was 65%. Similarly, Crapo *et al.* (1993) report that for most species of Pacific salmon, the average canned yield from a round weight carcass is between 65 and 67%. This can be contrasted with the average yield of steaks from a round weight carcass, between 57 and 62%, while the yield of skinless/boneless fillets typically vary between 42 and 51% (Crapo *et al.* 1993).

[113] The 20% protein content of salmon flesh value is based on the range of values for Pacific salmon reported by Higgs *et al.* (1995, Table 4.15, pp. 270-271).

[114] The gross energy content of salmon flesh can vary widely reflecting a variety of factors including lifestage, diet, and activity level. The gross wet weight energy content value of 7.6 MJ/kg for salmon flesh is based on the range of values reported for the flesh of wild and cultured Pacific salmon by Higgs *et al.* (1995, Table 4.15, pp. 270-271). Furthermore, in his analysis of the energy efficiency of Atlantic salmon culture systems in Sweden, Folke (1988) also employed a gross wet weight energy value of 7.6 MJ/kg for salmon flesh.

[115] The gross energy content of protein is taken from the notes to Table 4.15, p. 271 in Higgs *et al.* (1995).

# *Chapter 4: Analysis of the Intensive Salmon Culture Industry*

The intensive salmon culture industry in British Columbia employs essentially the same technology whether producing Atlantic, chinook or coho salmon. However, because of interspecific differences in behaviour and survival patterns under farming conditions, the ecological footprint associated with producing a tonne of Atlantic and a tonne of chinook salmon was estimated separately where data were available to support such a distinction. Coho salmon were not analysed, as coho production has represented less than 10% of the total annual farmed production in British Columbia for most of the last decade (Figure 9). Furthermore, I assumed that the ecological footprint associated with farmed coho production would closely resemble that of farmed chinook.

In estimating the ecological footprints of farmed Atlantic and chinook salmon, I focused on four primary and one secondary aspect of their production cycle. The primary aspects analysed were:

1. the direct operating material, labour and energy inputs associated with the production of salmon smolts in hatcheries and lake-pen operations,
2. the direct operating material, labour and energy inputs associated with the saltwater production phase of both chinook and Atlantic salmon until harvest,
3. the direct operating labour and energy inputs required to transport adult fish from sea-cage sites to processing plants, and
4. the direct material and energy inputs and indirect energy inputs required to build and maintain the capital infrastructure of the sea-cage rearing systems.

Because feed represents, after water, the largest single physical input to salmon farming, I also conducted a detailed analysis of the direct and indirect material and energy inputs associated with the production, processing and transportation of salmon feed.

## Quantifying the Direct Material, Labour and Energy Inputs to the Freshwater Phase of Salmon Farming

Four companies that together operate a total of 5 hatcheries, were surveyed to determine the material, labour and energy inputs associated with producing smolts ready to enter saltwater. In addition to

operating hatcheries, two of the four surveyed companies also used lake-pen rearing sites to "finish" a portion of their Atlantic salmon smolts prior to entering saltwater.

The total 1996 production from these four companies combined was approximately 4.6 million smolts, representing approximately 50% of the total industry-wide production. The hatcheries operated by the companies surveyed range in size from the very small, under 100,000 smolts produced annually, to the very large, over 2.5 million smolts produced annually. One of the hatcheries for which data was obtained produced only chinook smolts, three hatcheries produced only Atlantic salmon smolts and one produced Atlantic, chinook, coho and steelhead trout smolts during the period for which data were provided. However, because the hatchery that produced a variety of smolts could only provide aggregated data (i.e. not broken down on a species-specific basis), and because the dedicated chinook hatchery is an unusually small facility, it was decided that material and energy inputs to smolt production would not be determined on a species-specific basis.

Each company was asked to provide the following information regarding their freshwater operations for a recent representative year[116]:

1. for each species cultured, the total number, total weight and average weight of the smolts produced,
2. the type and mass of feed used for all freshwater operations,
3. the total amount of electricity used in kWh,
4. the types and quantities of fossil fuels used for all hatchery and lake-pen related activities including fuel used to accelerate smolt growth, power vehicles, heat buildings etc., and
5. the amount of labour required to sustain the hatchery and, if applicable, the lake-pen rearing operations.

A summary of the material, labour and energy input and smolt output data supplied by the four companies appears in Appendix B. All of the companies surveyed provided detailed information on all of the inputs and outputs of interest with the following two exceptions. One company was unable to provide data on their consumption of fossil fuels. However, as this company only used fossil fuels to power hatchery support vehicles, this data gap should have a negligible impact on the overall analysis. The second data gap exists with respect to the labour, fossil fuel and electricity inputs

[116] All companies provided data for either a calendar year or a fiscal year whichever was more convenient.

associated with the lake-pen rearing phase of one company's smolt production. A full set of material, labour and energy input data were available from this company's hatchery operations. However, during the lake-pen rearing phase, only data on the feed consumed by their smolts were available. Once again, it is believed that this data gap would have a negligible effect on the overall analysis as labour, fuel and electricity consumption is relatively small during lake-pen rearing.

Because companies reported information differently, it was necessary to convert the data provided into a consistent form. The types and methods of data conversion used is discussed in Appendix B. Table 10 provides a standardised summary of the material, labour and energy inputs and smolt production for the four participating companies.

*Table 10. Summary of Inputs To and Smolt Production From Four Companies' Freshwater Operations*

| Inputs | Company 1 | Company 2 | Company 3 | Company 4 | Totals |
|---|---|---|---|---|---|
| Labour (person-days) | 556 | 1,440 | 4,320 | 4,400 | 10,716 |
| "Dry" feed (kg) | 3,703 | 31,225 | 145,000 | 368,015 | 547,943 |
| Gasoline (MJ) | n/a | 224,621 | 451,500 | 420,379 | 1,096,500 |
| Diesel (MJ) | n/a | 119,581 | 72,080 | 2,622,919 | 2,814,580 |
| Propane (MJ) | not used | 2,458,935 | not used | 1,554,349 | 4,013,284 |
| Electricity (MJ) | 324,767 | 2,722,637 | 7,812,000 | not used | 10,859,404 |
| | | | | | |
| Smolt Output (kg) | 685 | 21,204 | 104,000 | 203,644 | 329,533 |

From the combined input and smolt production totals (Table 10), I estimated the weighted average inputs required to yield a tonne of smolts using the mass of smolts produced by each company as the weighting factor (Table 11).

*Table 11. Operating Inputs Required to Produce an Average Tonne of Salmon Smolts*

| Inputs per tonne of smolts produced | |
|---|---|
| Labour (person-days) | 32.5 |
| "Dry" feed (kg) | 1,663 |
| Gasoline (MJ) | 3,327 |
| Diesel (MJ) | 8,541 |
| Propane (MJ) | 12,179 |
| Electricity (MJ) | 32,954 |

Source: Appendix B.

However, as the objective of the research was to estimate the biophysical costs of an average tonne of harvested adult chinook or Atlantic salmon, it was necessary to quantify the mass of smolts that must enter saltwater, which upon harvesting will yield one tonne, while accounting for typical

mortality losses during the entire saltwater rearing phase. Using data supplied by the C.A.S.H. program (Appendix A), I determined that, on average, approximately 20.6 kg of Atlantic salmon smolts are required to yield a harvested round tonne of adults while approximately 13.7 kg of chinook smolts are required to yield a harvested tonne of adults. Combining these values with the average inputs from Table 11, estimates were made of the operating material, labour and energy inputs associated with the freshwater phase of salmon farming per harvested tonne of Atlantic and chinook salmon produced (Table 12).

*Table 12. Average Operating Inputs to Smolt Production to Yield a Final Harvested Tonne of Salmon*

| Inputs to Smolt Production per Final Harvested Tonne | Atlantic | Chinook |
|---|---|---|
| Labour (person-days) | 0.67 | 0.45 |
| "Dry" feed (kg) | 34 | 23 |
| Gasoline (MJ) | 69 | 45 |
| Diesel (MJ) | 176 | 117 |
| Propane (MJ) | 251 | 166 |
| Electricity (MJ) | 679 | 450 |

## Quantifying the Direct Material, Labour and Energy Inputs to the Saltwater Phase of Salmon Farming

In 1996, a total of 16 companies operated saltwater based net-cage grow-out sites for salmon in British Columbian waters. Their combined production that year was approximately 800 round tonnes of coho, 8,450 round tonnes of chinook and 19,300 round tonnes of Atlantic salmon from a total of approximately 80 active grow-out sites (Figure 9). Not surprisingly, the annual production from the 16 companies operating grow-out sites varied widely. For example, four companies each produced under 500 tonnes, three produced between 500 and 1,000 tonnes, another three produced between 1,000 and 2,000 tonnes and six produced over 2,000 tonnes each annually (British Columbia Environmental Assessment Office 1997).

To quantify the operating material, labour, and energy inputs associated with the saltwater based grow-out phase of salmon farming, I surveyed four companies. Two of these were dedicated chinook producers and two were dedicated Atlantic salmon producers. Over the time period for which these companies provided data, they operated a total of 21 saltwater based grow-out sites. Individually, their annual harvest ranged from under 100 round tonnes to over 3,300 round tonnes. On a species-specific basis, the two chinook producers harvested a total of 556 round tonnes or approximately

6.5% of the industry-wide chinook production in 1996 while the two Atlantic salmon producers harvested over 5,076 tonnes, representing the equivalent of approximately 26% of the total 1996 industry-wide Atlantic salmon production.

All companies surveyed were asked to provide the following information regarding their material, labour and energy inputs to saltwater based grow-out operations for a given representative time period:

1. the total number, and total round weight of all salmon harvested, along with an estimate of the total salmon "standing stock"[117] biomass change in the water from the start to the end of the period over which data were provided,
2. the type and total mass of feed used,
3. the amount, if any, of electricity used in kWh,
4. the types and quantities of fossil fuels used for all grow-out site related activities including heating, feed transport, personnel changes, etc., and
5. the amount of labour required for all grow-out site related activities.

The data provided by the four companies along with the analysis of the average inputs per tonne of salmon produced appears in Appendix D.

The primary difference between the information sought from saltwater-based and freshwater-based operations was that for marine grow-out operations, it was potentially important to determine the change in the standing stock biomass in the water over the period for which data were provided. This was particularly important in any situation in which a company was either actively increasing or decreasing its stock size. By not accounting for such changes, inputs normalised per tonne of salmon harvested could be inadvertently inflated or deflated. However, in situations in which a company was essentially operating in steady-state, it could be assumed that the standing stock biomass change over a year would be negligible, all other things, such as mortality and escape losses, being equal[118].

[117] In this context, I use the term "standing stock" to refer to the total living biomass of farmed salmon in a given company's grow-out sites at a given point in time.

[118] It is worth noting that by taking into account changes in the standing stock biomass, however, a bias is introduced which will consistently have the effect of underestimating the quantities of various inputs that are required to yield a harvested tonne of salmon. This occurs because when the stock of salmon is being built up, not all of the increased "production" will ultimately be harvested. A certain proportion can be expected to die or escape prior to harvesting. Similarly, in the situation where the standing stock has been reduced over the time period for which data were provided, not all of the

All four companies canvassed provided me with all the information that I had requested regarding their salmon production and material, labour and energy inputs, in more or less detail, with the following exceptions. The largest producer surveyed was unable to provide me with data regarding the change in their standing stock of salmon. As a result, I had to assume that there was no change in the standing stock over the time for which data were provided. In addition, the same company only provided data regarding their total expenditure on gasoline and diesel fuel combined. Without any additional guidance from the company's representatives, I assumed that half of the fuel expenditure was made on gasoline and half was made on diesel fuel.

Because of the internal record keeping practices used by most of the surveyed companies, the electricity, fuel and labour inputs associated with the operation of their head offices were included as part of the inputs to their grow-out site operations. And while inputs to running an office are not, strictly speaking, grow-out site related, these inputs are likely to be relatively small when compared to true grow-out site operating inputs. Furthermore, I would argue that ultimately the operating inputs associated with office activities are part and parcel of the overall process of producing farmed salmon.

As was the case with respect to the inputs to freshwater operations (Appendix B), it was sometimes necessary with respect to marine grow-out data to either standardise certain inputs, such as labour, into a common unit of measure and to convert inputs recorded as monetary expenditures into physical units (see Appendix D for details).

From the input data in Appendix D and by using the total weight of salmon produced by each company over the period for which data were provided, I calculated the weighted average operating material, labour and energy inputs associated with saltwater based grow-out operations for both chinook and Atlantic salmon (Table 13).

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change in biomass in the water is necessarily the result of accelerated harvest. A reduction in the standing stock biomass can also result from increased mortality or escape losses.

*Table 13. Average Direct Operating Inputs Associated with the Saltwater based Grow-Out Phase of Salmon Farming per Round Tonne of Salmon Produced*

| Inputs per Tonne of Salmon Produced | Atlantic | Chinook |
|---|---|---|
| Labour (person-days) | 3.3 | 10.9 |
| "Dry" feed (kg) | 1,736 | 2,183 |
| Gasoline (MJ) | 1,171 | 1,842 |
| Diesel (MJ) | 1,037 | 1,290 |
| Propane (MJ) | 239 | 0 |
| Electricity (MJ) | 0 | 463 |

From Appendix D.

From the data in Table 13, the material, labour and aggregate energy inputs associated with chinook production are generally higher than the inputs to Atlantic salmon production. Specifically, labour inputs are over 300% higher, while the feed inputs are approximately 25% higher and aggregate energy inputs are about 46% higher. There are several possible reasons for this difference. Contemporary strains of farmed chinook salmon may be inherently poorer performers than contemporary strains of Atlantic salmon under intensive cultivation. For example, Jones (1997) found that due to differences in swimming speed and basic morphology, contemporary strains of chinook farmed in British Columbia experience drag forces 40% higher than farmed Atlantic salmon[119]. As a result, chinook use significantly greater energy for propulsion leaving consequently less energy available for growth when compared with Atlantic salmon. Anecdotal evidence from salmon farmers supports the view that contemporary domesticated strains of Atlantic salmon are much more docile and less energetic in the net-cage environment than are contemporary strains of domesticated chinook salmon.

At the same time, because the two companies that supplied data on Atlantic salmon production are both much larger than the two companies that supplied data on chinook production, their lower inputs per unit of production may reflect certain economies of scale. As a result, there may be a consistent bias towards lower inputs per unit Atlantic salmon production compared with chinook salmon production.

One way to test whether the differences in the inputs reflect biological differences or data artefacts, is to compare the results with those of an independent analysis. The data provided by the C.A.S.H. program (Appendix A), provides just such an opportunity. Comparing the feed used during saltwater grow-out for the 23 Atlantic and the 13 chinook salmon groups represented, shows that on average 1,460 kg and 2,020 kg of feed were required to yield a round tonne of Atlantic and chinook salmon

respectively. Therefore, from the C.A.S.H. program data, chinook would appear to require approximately 38% more feed per unit mass of salmon produced than do Atlantic salmon. This would appear to support the hypothesis that there is indeed an inherent difference between contemporary domesticated chinook and Atlantic salmon.

It is also worth noting that the feed input requirements from the C.A.S.H. program data are lower for both Atlantic and chinook salmon than the estimates of feed inputs determined by my survey. Specifically, my results indicate a feed consumption rate that is approximately 15% higher in Atlantic salmon and 7% higher in the case of chinook when compared to the C.A.S.H. program data. These differences, while fairly small, are relatively important because, as we shall see below, the overall biophysical costs associated with intensive salmon farming are very sensitive to total feed use.

When considering whether my data or the C.A.S.H. program results better reflect reality, there are two factors that should be kept in mind. First, my survey data reflect a much larger total production tonnage than the C.A.S.H. program data set. The total tonnage of Atlantic salmon produced by the two companies that provided me with data is three orders of magnitude larger that the total Atlantic salmon production reflected in the C.A.S.H. program data. Likewise, the total chinook production from the two companies that I surveyed is two orders of magnitude larger than the chinook production upon which the C.A.S.H. program analysis is based. Perhaps more importantly, however, the C.A.S.H. program data that was provided to me explicitly excluded fish groups which experienced greater than 50% mortality. Thus the results of the analysis of the C.A.S.H. program data underestimate the actual average amount of feed required to produce a given quantity of salmon, given that occasional high mortality events are part of contemporary intensive salmon culture.

## Quantifying the Direct Labour and Energy Inputs to Salmon Transport

As discussed previously, I did not attempt to quantify the inputs associated with the transport of smolts. I did, however, quantify the operational labour and energy inputs associated with the transport of adult salmon from marine grow-out sites to shore-based processing facilities.

[119] Chinook were found to swim approximately 20% faster on average than Atlantic salmon while morphologically, chinook were consistently taller, thicker and shorter than Atlantic salmon of the same mass (Jones 1997).

One of the specialised salmon transport companies, Transmar Shipping Ltd. (hereafter referred to as Transmar), was surveyed to determine the labour and energy inputs associated with hauling salmon from grow-out sites to processing plants (see Appendix E). In 1996, using three converted purse seine vessels, Transmar transported approximately 7,692 round tonnes of farmed Atlantic salmon (Mr. Don Millerd, Transmar Shipping Ltd., pers. comm., April, 1997). This represented approximately 40% of total industry-wide Atlantic salmon production in 1996 or about 26% of the total industry-wide production of all species.

Transmar provided details of its operating expenses associated with salmon haulage activities for three years; 1994, 1995 and 1996. From these data, I calculated average fuel and labour inputs per tonne of salmon transported for each year and for all three years combined using the mass of salmon hauled as the weighting factor (Appendix E). The analysis revealed that during transport, the average tonne of farmed salmon required the direct combustion of approximately 86.5 litres of diesel fuel, with a net energy content of 3,119 MJ, and the expenditure of 0.51 person-days of labour. Finally, although Transmar only transported Atlantic salmon, I assumed that the estimated labour and energy inputs apply equally to chinook transport.

## Sum of Direct Inputs to Farmed Salmon Production

Based on the analyses above, Table 14 and Table 15 summarise the estimates of the average direct operating material, labour and energy inputs to intensive salmon culture in British Columbia, for Atlantic and chinook salmon respectively.

*Table 14. Summary of Average Direct Operating Material, Labour and Energy Inputs to Intensive Atlantic Salmon Culture*

| | Operating Inputs per Round Tonne Atlantic Salmon Harvested | | | |
|---|---|---|---|---|
| | To Smolt Production | To Marine Grow-Out | To Adult Transport | Total |
| Labour (person-days) | 0.67 | 3.3 | 0.51 | 4.5 |
| "Dry" feed (kg) | 34 | 1,736 | | 1,770 |
| Gasoline (MJ) | 69 | 1,171 | | 1,240 |
| Diesel (MJ) | 176 | 1,037 | 3,119 | 4,332 |
| Propane (MJ) | 251 | 239 | | 490 |
| Electricity (MJ) | 679 | 0 | | 679 |

*Table 15. Summary of Average Direct Operating Material, Labour and Energy Inputs to Intensive Chinook Salmon Culture*

| | Operating Inputs per Round Tonne Chinook Salmon Harvested | | | |
|---|---|---|---|---|
| | To Smolt Production | To Marine Grow-Out | To Adult Transport | Total |
| Labour (person-days) | 0.45 | 10.9 | 0.51 | 11.9 |
| "Dry" feed (kg) | 23 | 2,183 | | 2,206 |
| Gasoline (MJ) | 45 | 1,842 | | 1,887 |
| Diesel (MJ) | 117 | 1,290 | 3,119 | 4,526 |
| Propane (MJ) | 166 | 0 | | 166 |
| Electricity (MJ) | 450 | 463 | | 913 |

It was possible to partially corroborate or "ground-truth" the above estimates using industry workforce data as a guide. As part of the provincial Salmon Aquaculture Review process, the 1996 total direct employment in the salmon farming industry was quantified (Table 16).

*Table 16. Total 1996 Direct Employment in the British Columbia Salmon Farming Industry*

| Activity | Fulltime Equivalent Positions |
|---|---|
| Hatchery | 124 |
| Grow-Out Sites | 496 |
| Transport | 78 |
| Selling and Administrative | 87 |
| Other | 25 |
| Processing | 332 |
| Total | 1,142 |

Source: British Columbia Environmental Assessment Office 1997, vol. 4, p. A-17

Excluding the jobs in the processing side of the industry, there were a total of 810 full-time equivalent positions in the industry as a whole in 1996 (Table 16). Given that a total of 28,550 round tonnes of farmed Atlantic, chinook and coho salmon were harvested in British Columbia that year and assuming that there are 240 days of labour associated with each full-time position, we can say that, industry-wide, an average of 6.8 person-days of labour were required per round tonne of salmon harvested[120].

This can be compared with the average number of direct person-days of labour that were required to yield a round tonne of salmon based on my data. In Tables 14 and 15 above, I estimated that a round tonne of Atlantic and chinook salmon required 4.5 and 11.9 person-days of direct labour respectively to reach the dock immediately prior to processing. Multiplying these numbers by the round tonnes of

[120] Calculated as follows: (810 fulltime positions x 240 days per fulltime position) ÷ 28,550 tonnes of salmon = 6.8 person-days/tonne.

Atlantic and chinook salmon harvested in 1996, or 8,450 tonnes and 19,300 tonnes, respectively, summing the result and dividing by the total tonnage of Atlantic and chinook salmon harvested, I arrive at a weighted average of 6.8 person days of labour required per tonne of salmon harvested. Thus my estimates may be considered a reasonable proximate for true average inputs to farmed salmon production in British Columbia.

## Quantifying the Inputs, and Ecosystem Support Areas to Contemporary Salmon Feed

There are several reasons why I undertook a detailed analysis of the biophysical costs of salmon feed for the contemporary British Columbia salmon farming industry. As noted above, feed is the largest single physical input, after water, to salmon farming. Moreover, previous energy analyses of intensive fish culture systems (Mathews *et al.* 1976, Pitcher 1977, Rawitscher 1978, Folke 1988, Berg *et al.* 1996) indicate that the energy inputs to feed typically represent over 90% of the total energy inputs to the culture system being analysed.

In addition, as feed represents the largest single cost sector to contemporary salmon farmers (Forster 1995, Asche 1997), there is continuing interest amongst salmon feed formulators to reduce the cost of their product while maintaining or improving feeding performance (Kaushik 1990, Higgs *et al.* 1995, Higgs *et al.* 1996, Higgs 1997). Coupled with this economic incentive, there is also interest within the industry in reducing the dependence on some inputs, particularly fish-sourced ingredients, for political/environmental reasons. For this reason, I believe that there is an opportunity to provide salmon feed manufacturers with a benchmark by which they can evaluate the biophysical costs associated with the use of alternative ingredients as they strive to reduce the economic cost of salmon feed.

The following analysis of the inputs to salmon feed production and the ecosystem support areas required to sustain the biological inputs is based on the production of an average tonne of contemporary salmon feed. The inputs per tonne of feed produced were then incorporated into the larger model of the biophysical costs associated with the production of a tonne of farmed chinook and Atlantic salmon using the estimates of total feed inputs required as outlined in Tables 14 and 15.

Broadly speaking, feeds used in the intensive culture of fish can be classified into four general types reflecting their relative water content. Wet, moist, semi-moist and dry feeds typically contain approximately 75%, 30%, 15% and 8% moisture by weight respectively. And while moist, and semi-

moist feeds have been used historically in the British Columbia salmon farming industry, dry feeds are currently used almost exclusively (Mr. Jason Mann, EWOS Canada Limited, pers. comm. 1998).

Since the first dry extruded diet was developed for salmon in 1971[121], a great deal of research has gone into improving the production and formulation of dry feeds to meet the specific nutritional needs of the various life-stages of salmon, to improve the palatability and availability of the feeds to the fish, to improve the palatability and aesthetic appeal of the resulting salmon flesh to consumers, and to reduce the costs of feed production itself. As a result, contemporary dry salmon feeds can vary considerably, particularly with respect to gross composition, the size of the individual feed pellets, and, most importantly to this research, the range of ingredients used in their formulation.

When contemplating this analysis I briefly considered using published formulations but rejected this approach for three reasons. First, as published feed formulations are invariably more than a few years old, it is unlikely that they reflect the latest advances in fish nutrition or the relative availability, quality, and price of potential ingredients. Second, any analysis based on a single published formulation cannot reflect the breadth of feeds currently in use. And finally, published formulations typically indicate only the generic type of most constituents. This is of limited value when trying to quantify the biophysical cost of using specific inputs. For example, while fish oil is a significant component of most published salmon diets, the specific type and source of the fish oil used is seldom reported. It was therefore important that detailed, reasonably current, feed formulation data along with data regarding the labour and energy input to feed milling be used in the analysis.

When this analysis was undertaken in 1998, two companies, EWOS Canada Limited (hereafter referred to simply as EWOS) and Moore-Clark Co. (Canada) Incorporated, together supplied over 90% of the dry feed used by the intensive salmon culture industry in British Columbia and the US Pacific Northwest. The two companies have approximately equal market share and each operate one feed milling plant in the Lower Mainland region of British Columbia (Mr. Jason Mann, EWOS Canada Limited, pers. comm. 1998).

[121] For a brief review of the development history of artificial salmonid diets see Hardy (1987).

## *Quantifying the Direct Material, Labour and Energy Inputs to the Formulation of Salmon Feed Pellets*

EWOS was approached to provide data on the material, labour and energy inputs associated with the production of an average or typical tonne of salmon feed. Specifically I requested the following information:

1. the type, quantities and sources of ingredients from which contemporary salmon feeds are made,
2. the types and quantities of energy required to process the various ingredients into a final product, and
3. the amount of labour required to process the various ingredients into a final product.

EWOS was an ideal source of data on the inputs to salmon feed because, as of mid-July 1997, their feed mill in Surrey became a dedicated fish feed only production facility in which over 95% of total production is salmon feeds for the local market[122].

Because of the highly competitive nature of the salmon feed industry, EWOS was reluctant to provide detailed formulation information regarding any of their specific salmon feeds. They were, however, willing to provide composite or aggregate formulation data reflecting the complete range of salmon feeds that they produce (Table 17). In other words, EWOS provided information on the amount of various ingredients used in salmon feeds, normalised per tonne of "average" feed produced. This was ideal for the purposes of this study as the results should better reflect average industry-wide inputs to contemporary salmon feed manufacturing.

[122] Prior to this, EWOS's operations had included poultry feed production.

*Table 17. Average Direct Material, Labour and Energy Inputs to Salmon Feeds*

| Input[a] | Average quantity per tonne feed produced (kg) |
|---|---|
| Prime or Superprime South American fish meal[b] | 323 |
| B.C. herring meal[c] | 57 |
| Gulf of Mexico Menhaden oil[d] | 144 |
| B.C. mixed fish oil[e] | 36 |
| Wheat (whole kernel) | 150 |
| Corn Gluten meal (60% protein) | 80 |
| Canola meal[f] | 40 |
| Soybean meal (de-hulled, solvent extracted)[f] | 40 |
| Blood meal | 40 |
| Feather meal[g] | 40 |
| Meat meal[g] | 40 |
| Premixes[h] | 10 |
| | |
| Labour in person-days | 0.05 |
| Natural gas in MJ[I] | 1,534 |
| Electricity in kWh | 140.72 |

Source: Mr. Jason Mann, EWOS Canada Limited, pers. comm. 1998

Notes: a. The material inputs were determined based on the 1998 projection of all ingredient purchases divided by the total projected sales tonnage for the year while labour and energy inputs were based on actual usage data for the five month period from August to December, 1997 inclusive divided by the total tonnage of salmon feed produced during that interval.

b. Chilean and Peruvian Prime and Superprime meals are largely interchangeable. The fisheries which provide the inputs to these meals are dedicated industrial fisheries which target primarily the Peruvian anchovy (*Engraulis ringens*), the South Pacific sardine (*Sardinops sagax sagax*), the Araucanian herring (*Strangomera bentincki*), the Inca scad (*Trachurus murphyi*) and the Chub mackerel (*Scomber japonicus*) (Polushin 1994).

c. British Columbia herring meal provided by West Coast Reductions of Vancouver, the last fish reduction plant operating in British Columbia. The meal is derived almost entirely from carcasses of Pacific herring (*Clupea pallasii*) which result from the roe herring fishery (Mr. Russ Mitchellson, West Coast Reductions Ltd. pers. comm. 1997).

d. Gulf of Mexico menhaden oil can be supplied by any one of a number of companies that operate fish reduction plants along the US gulf coast. It is the product of a dedicated industrial fishery which targets primarily the Gulf menhaden (*Brevoortia patronus*).

e. British Columbia mixed fish oil is supplied by West Coast Reductions of Vancouver, This fish oil is derived entirely from fish processing wastes derived from a wide range of species including Pacific herring (*Clupea pallasii*), Pacific hake (*Merluccius productus*)and various Pacific salmon (*Oncorhynchus sp.*) (Mr. Russ Mitchellson, West Coast Reductions Ltd. pers. comm. 1997).

f. Canola meal and soybean meal are used interchangeably in salmon feed (Mr. Jason Mann, EWOS Canada Ltd. pers. comm. 1998) so each was assumed to contribute equally to the feed modelled.

g. Feather meal and meat meal are used interchangeably in salmon feed (Mr. Jason Mann, EWOS Canada Ltd. pers. comm. 1998) so each was assumed to contribute equally to the feed modelled.

h. Premixes include vitamins, carotenoid colouring agents, etc.

i. Natural gas represents over 99% of the total fossil energy used in EWOS' plant (Mr. Jason Mann, EWOS Canada Ltd. pers. comm. 1998).

Most of the inputs to salmon feed used by EWOS and outlined in Table 17 are widely traded feedstuffs[123].

## The Direct Industrial Energy Inputs to Salmon Feed Milling

The direct industrial energy inputs required to mill, pelletise, and dry one tonne of salmon feed amount to approximately 507 MJ of electricity[124] and 1,534 MJ of natural gas (Table 17). Expressed as fossil fuel equivalents, this amounts to a total direct industrial energy input of approximately 2,980 MJ per tonne of salmon feed[125]. This can be compared with previous estimates of direct industrial energy inputs to feed milling of 900 MJ/tonne for trout feed (Pitcher 1977) and 3,270 MJ/tonne for catfish feed (Rawitscher 1978).

## The Gross Nutritional Energy Content of Contemporary Salmon Feed

Using the component proportions outlined in Table 17 and estimates of the unit gross nutritional energy content of the individual feedstuffs, I estimate that the gross nutritional energy content of an average tonne of contemporary salmon feed is approximately 22,400 MJ (Table 18).

[123] For descriptions of: a) the processes involved in reducing whole fish and/or fish processing wastes into fish meal and oil see FAO, Fisheries Industry Division (1986), Bimbo (1990) or Hardy (1992), b) the rendering process used to produce meat meal and the range of processes used to process blood into blood meal see Fernando (1992), c) the process used to make feather meal see Polin (1992), d) the corn wet milling process from which corn gluten meal results see Corn Refiners Association (1989), e) various soybean processing options and products see Considine and Considine (1982), and f) the canola milling process that yields canola meal see Hickling (1993).

[124] 140.72kWh of electricity multiplied by 3.6 MJ/kWh

[125] To convert the 507 MJ of electricity into fossil fuel equivalents, I divided by 0.35.

*Table 18. Estimated Gross Nutritional Energy Content of an Average Tonne of Contemporary Salmon Feed*

| Input | Average quantity per tonne feed (kg) | Unit gross energy content (MJ/kg) | Total gross energy content (MJ) |
|---|---|---|---|
| Total fish meal | 380 | 20.2[a] | 7,676 |
| Total fish oil | 180 | 36.4[b] | 6,552 |
| Wheat | 150 | 16.8[c] | 2,520 |
| Corn Gluten meal | 80 | 18.0[d] | 1,440 |
| Canola meal | 40 | 18.1[e] | 724 |
| Soybean meal | 40 | 17.9[e] | 716 |
| Blood meal | 40 | 23.7[e] | 948 |
| Feather meal | 40 | 22.6[e] | 904 |
| Meat meal | 40 | 22.5[f] | 900 |
| | | Total: | 22,380 |

Notes:
a. I have applied the unit gross energy content value for Peruvian anchovy meal as reported in Hajen *et al.* (1993, Table 2, p. 336).
b. I have applied a unit gross energy content of 36.4 MJ/kg for fish oil based on the gross energy content of lipids generally as noted in Higgs *et al.* (1995).
c. Hajen *et al.* 1993, Table 2, p. 336.
d. I have applied a unit gross energy content value of 18.0 MJ/kg for corn gluten meal with a protein content of 60%.
e. Hajen *et al.* 1993, Table 2, p. 336.
f. I have applied the unit gross energy content value for poultry by-product meal produced in British Columbia as reported in Hajen *et al.* (1993, Table 2, p. 336).

## Ecological Footprint of Biological Material Inputs to Feed

Approximately 56% by weight of the inputs to the salmon feed being modelled are derived from fish, 31% are derived directly from agricultural crops and 12% are derived from livestock (Table 17). All of these inputs were analysed to determine the area of ecosystem required to produce them as well as the types and quantities of industrial energy inputs required to produce, harvest, process and transport them. Because the remaining 1% of the input to salmon feeds, the premixes, are such a small component and because of their complex composition, their contribution to the biophysical costs of salmon feeds was not analysed in this research.

### Ecosystem Support Area to Provide Fish Meals and Oils

As described in the previous chapter, the first step in estimating the marine ecological footprint associated with producing a given quantity of fish or other marine organism involved using Equation 1 to quantify the primary productivity required to ultimately yield the mass of marine organisms of interest. Re-stated here, Equation 1 appears as:

$$P = (M/9) \times 10^{(T-1)}$$

In using Equation 1 to estimate the primary productivity required to provide the fish meal and oil inputs to salmon feed, it was first necessary to convert each into their wet weight of fish equivalents. As the yield rate from whole fish to fish meal and oil can vary considerably depending on:

- the species being reduced,
- the season and hence the condition of the fish at the time of capture,
- whether round fish or fish wastes are being reduced,
- the freshness of the fish upon processing, and
- the efficiency of the reduction plant,

it was important to use representative yield rates, specific to the fish source and processing plants used. Table 19 summarises the applicable yield rates and wet fish equivalents for each of the fish meal and oil inputs to the feed modelled.

*Table 19. Yield Rates and Wet Weight of Fish Required for Fish Meal and Oil for One Tonne of Salmon Feed*

| Input | Mass of Fish meal or Oil Required (kg) | Yield Rate | Wet Weight of Whole Fish Required (kg) |
|---|---|---|---|
| Prime or Superprime S. American fish meal | 323 | 22%[a] | 1,468 |
| British Columbia herring meal | 57 | 16%[b] | 356 |
| Gulf of Mexico menhaden oil | 144 | 12%[c] | 1,200 |
| British Columbia mixed fish oil | 36 | 2%[d] | 1,800 |

Notes: a. Fish meal yield rates for newer South American plants producing Prime and Superprime meals typically vary between 20% and 25% with 22% representing a reasonable year-round average (Mr. Tony Bimbo, a fish meal and oil manufacturing consultant, pers. comm. March, 1998).
b. Mr. Russ Mitchelson, West Coast Reductions Ltd. pers. comm. 1997.
c. Fish oil yield rates for Gulf of Mexico menhaden oil typically vary between 6% and 20% with 12% being an representative year-round average (Mr. Glen Speakman, Vice President, Daybrook Fisheries of New Jersey, pers. comm., March 5, 1998).
d. An oil yield rate of 2% for fish processing wastes is typical for the British Columbia fish reduction industry (Mr. Russ Mitchelson, West Coast Reductions Limited, pers. comm., October, 1997).

The equivalent of approximately 1,800 kg of whole fish are required to supply fish meal, and 3,000 kg of whole fish are required for fish oil for each tonne of contemporary salmon feed (Table 19). Only the industrial energy inputs required to capture and reduce 3,000 kg of whole fish is included in the analysis below so as to avoid double-counting the energy required to provide both meals and oils.

The double-counting issue also applies with respect to the area of ecosystem support required. However, because the ecosystem support areas associated with the fish meals and oils is only partially dependent upon the wet weight mass of fish, it was necessary to continue the analysis for all four of the meals and oils used. Therefore, the next step in the analysis was to estimate the average trophic level for each of the fish derived inputs.

At least five species of fish, including Peruvian anchovy (*Engraulis ringens*), South Pacific sardine (*Sardinops sagax sagax*), Araucanian herring[126] (*Strangomera bentincki*), Inca scad[127] (*Trachurus murphyi*), and Chub mackerel[128] (*Scomber japonicus*), are used to produce South American fish meals and oils[129]. Using landings data from the Chilean industrial fishery for 1990 to 1993 inclusive, and estimates of the mean trophic level for each of the species used for reduction to meal and oil, in Appendix F I have estimated that the overall mean trophic level for the industrial fisheries of Chile is 2.9.

As its name indicates, British Columbia herring meal is derived almost entirely from Pacific herring (*Clupea pallasii*) carcasses that result from the roe herring fishery[130]. Based on the results of several trophic models of marine ecosystems around the margin of the northeast Pacific (Pauly and Christensen 1996), I assigned a mean trophic level of 3.0 to Pacific herring.

Gulf of Mexico menhaden oil is derived almost entirely from Gulf menhaden (*Brevoortia patronus*) that are fished specifically for reduction to meal and oil along the Mississippi, Louisiana and Texas Gulf coasts[131]. According to Ahrenholz (1991), Gulf menhaden, along with the other menhaden species native to the Atlantic and Gulf coasts of the United States and Mexico, are filter feeding omnivorous planktivores. While I was unable to find any published trophic models that included Gulf menhaden, I was able to estimate their average trophic level from published quantitative stomach content analyses. In one analysis, the stomachs of five mature Gulf menhaden taken from coastal bays in Texas were found to contain only phytoplankton (Matlock and Garcia 1983). However, a more recent analysis, in which the stomachs of 100 mature Gulf menhaden were examined, found that approximately 72% of their diet was phytoplankton and the remaining approximately 28% was

[126] Another common names for the Araucanian herring is the South Pacific herring.
[127] Other common names for the Inca scad are Jack mackerel and Horse Mackerel.
[128] Another common name for the chub mackerel is the Pacific mackerel.
[129] Based on data from the Chilean fishing industry for 1990 to 1993 inclusive presented in Polushin (1994).
[130] Small quantities of other fish processing wastes may find their way into herring meal but these are considered to be trivial when compared to the mass of herring carcasses used.

zooplankton[132] (Castillo-Rivera *et al.* 1996). Given the much larger number of specimens examined as part of the second analysis described, I have used it as the basis of my estimate of the average trophic level of Gulf menhaden. As a result, they are assigned a mean trophic level of 2.3.

As the inputs to the British Columbia mixed fish oil are fish processing wastes from several different fisheries that vary widely in their output from season to season and from year to year, it was difficult to estimate a representative average trophic level for these inputs. I therefore assumed that the input to this locally produced fish oil is derived entirely from Pacific herring with a mean trophic level of 3.0[133].

Using Equation 1, the wet weight mass of fish required to yield each fish meal and oil (Table 19), and the mean trophic levels described above, I estimated the primary productivity required to provide the four fish meal and oil inputs per tonne of salmon feed.

*Table 20. Primary Productivity Required to Provide the Fish Biomass for Fish Meal and Oil Inputs to One Tonne of Contemporary Salmon Feed*

| Input | Wet Weight of Whole Fish Required (kg)[a] | Mean Trophic Level[b] | PPR (kg C)[c] |
|---|---|---|---|
| Superprime South American fish meal | 1,468 | 2.9 | 12,956 |
| B.C. herring meal | 356 | 3.0 | 3,956 |
| Gulf of Mexico menhaden oil | 1,200 | 2.3 | 2,660 |
| B.C. mixed fish oil | 1,800 | 3.0 | 20,000 |

Notes: a. Values from Table 19.
b. See text above.
c. Calculated using Equation 1.

Finally, using net primary productivity estimates from Longhurst *et al.* (1995) for the parts of the world's oceans that conform most closely to the areas that supply fish destined for reduction, I calculated the area of marine ecosystem required to produce the four fish meal and oil inputs (Table 21).

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[131] The Gulf menhaden and Atlantic menhaden (*Brevoortia tyrannus*) reduction fisheries are two of the largest and oldest commercial fisheries in the United States with combined landings totaling between 600,000 and 1.2 million tonnes annually in recent decades (Smith 1991).

[132] The zooplankton identified included tintinnids, a number of species of copepods, ostracods and cladocerans (Castillo-Rivera 1996, Table 1, p. 1105).

[133] I believe that this is a reasonable assumption to make, as in recent years herring carcasses from the roe herring fishery make up large proportion of fish processing wastes handled by West Coast Reductions (Mr. Russ Mitchelson, West Coast Reductions Ltd., pers. comm. 1997). Furthermore, any error which results from making this assumption will tend to have the effect of underestimating the ecosystem support area required, as herring occupy a lower average trophic level than most, if not all, of the other fish species, such as hake or salmon, whose processing wastes are also used for reduction purposes (Pauly and Christensen 1996).

*Table 21. Marine Ecosystem Support Areas Required to Produce the Fish Biomass for Fish Meal and Oil Inputs to a Tonne of Contemporary Salmon Feed*

| Input to Salmon Feed | PPR (kg C) | Net Primary Productivity (g C/m$^2$ /year) | Marine Ecosystem Support Area (ha) |
|---|---|---|---|
| Superprime South American fish meal | 12,956 | 269[a] | 4.8 |
| B.C. herring meal | 3,956 | 525[b] | 0.75 |
| Gulf of Mexico menhaden oil | 2,660 | 190[c] | 1.4 |
| B.C. mixed fish oil | 20,000 | 525[b] | 3.8 |

Notes: a. The region of the Pacific ocean which supports the industrial fisheries of Chile and Peru falls entirely within the Chile-Peru Coastal Current province as defined by Longhurst *et al.* (1995). The average net primary productivity of the Chile-Peru Coastal Current is estimated to be 269 gC/m$^2$/yr by Longhurst *et al.* (1995).

b. Pacific herring spend the majority of their life history in coastal waters on the landward side of the continental shelf margin (Taylor 1984). This portion of the northeastern Pacific ocean conforms most closely to the Alaska Downwelling province and the California Upwelling province as defined by Longhurst *et al.* (1995), who estimated the average net primary productivities of these two regions as 661 and 388 g C/m$^2$/yr respectively. A straight average of these net primary productivity values, or 525 g C/m$^2$/yr, was used for the purposes of the current model.

c. The marine ecosystem that sustains the Gulf menhaden fishery falls entirely within the Caribbean domain as defined by Longhurst *et al.* (1995). Longhurst *et al.* (1995) estimate that the average net primary productivity of the Caribbean domain is 190 g C/m$^2$/yr.

The combined ecosystem support area required to sustain the fish meal inputs to a tonne of salmon feed is approximately 5.6 ha while the area required to provide the fish oil inputs amounts to approximately 5.2 ha (Table 21). So as to not double-count, only the larger of these two is incorporated into the overall model of the inputs to farmed salmon production.

## Ecosystem Support Area to Provide the Livestock By-Product Meals

Livestock by-product meals account for 12% of the mass of the generic salmon feed being modelled (Table 17). As these meals are largely interchangeable for each other (Mr. Jason Mann, EWOS Canada Ltd., pers. comm. 1997), it was assumed that, on average, 40 kg of each of the three meals used - blood meal, meat meal and feather meal - is incorporated in an average tonne of salmon feed.

To simplify this part of the analysis, I assumed that all by-product meals are derived from chicken. I believe this is a reasonable simplifying assumption as chicken by-products make up a significant proportion of the inputs to meat and blood meals produced locally at the West Coast Reduction plant in Vancouver (Mr. Russ Mitchelson, pers. comm. 1997). Moreover, any error that is introduced into the analysis by adopting this assumption should underestimate the biophysical costs of salmon feed

production. This is because chicken typically have higher feed conversion rates than cattle and similar feed conversion rates to swine when fed the same diet[134].

As blood meal, feather meal and meat meal are all co-products of the meat, egg and dairy industries, the accounting convention used to address the partitioning problem has its greatest potential impact in this part of the model. As previously discussed, in the base case model I have apportioned all biophysical costs associated with producing a given live weight quantity of livestock at slaughter in direct proportion to the mass of the various co-products that result.

Using appropriate yield rates, the wet weight quantities of chicken co-products required to yield 40 kg each of blood meal, feather meal and meat meal are presented in Table 22.

*Table 22. Yield Rate and Wet Weight of Chicken By-Products Required to Provide By-Product Meal Inputs to Salmon Feed*

| By-Product Meal | Quantity Required per tonne of Salmon Feed (kg) | Yield Rate from Wet Weight of Chicken By-Products | Wet Weight of Chicken By-Products Required (kg) |
|---|---|---|---|
| Blood meal | 40 | 10.75%[a] | 372 |
| Feather meal | 40 | 100%[b] | 40 |
| Meat meal | 40 | 25%[c] | 160 |
| | | | Total: 572 |

Note: a. The blood meal yield rate of 10.75% was determined using the average dry matter content of blood meal at 93% (from Polin 1992, p. 187) and the average dry matter content of whole chicken blood at 10% (from Polin 1992, p. 186) and the following logic: 40 kg of blood meal contains 37.2 kg of dry matter (i.e. 40 x 0.93) and 372 kg of whole blood is required to yield 37.2 kg of dry matter (i.e. 372 x 0.1). Therefore, the yield rate from whole blood to blood meal equals 40/372 or 10.75%.
b. The feather meal yield rate was deemed to be 100% as the average crude protein content of feather meal at 86.4% (from Polin 1992, p. 182) is approximately equal to the total protein content of whole feathers at 87% (Polin 1992, p. 178).
c. Mr. Russ Mitchelson of West Coast Reductions, pers. comm. October, 1997.

A total of 572 kg of wet weight chicken by-products are required to yield the livestock meal inputs to a tonne of contemporary salmon feed (Table 22). The associated ecological footprint was then quantified by estimating the area of agricultural ecosystem required to produce the feed to grow the equivalent of 572 kg of chicken.

Although almost all contemporary chicken production employs specially formulated composite feeds that result in relatively high feed-to-chicken biomass conversion rates, I did not base the analysis of ecosystem support area on such feeds. Instead, I assumed that the required mass of chicken was fed

[134] For example, Smil *et al.* (1983) report that it takes between 5.4 and 6.75 kg of grain corn for broilers to gain a kilogram of weight while swine require between 5.2 and 6.6kg per kilogram of weight gain and cattle require between 9.98 and 15.39kg of grain corn per kilogram of weight gain. See also Ostrander (1980, p. 391) for a comparison of the relative efficiency with which different livestock species convert dietary energy into protein.

entirely on grain corn. I made this assumption for three reasons. First, by basing the analysis on unprocessed grain corn, I eliminate the potentially large "hidden" processing energy costs associated with composite feeds. Second, as corn has one of the highest yields per hectare of all grain crops, basing the model on grain corn alone will minimise the resulting agricultural land ecological footprint. And finally, the overall analysis is simplified considerably.

Smil *et al.* (1983) indicate that broiler chickens typically require between 5.4 kg and 6.75 kg of grain corn to gain one kilogram in weight. Using the low end of this range as the conversion rate for the model, I estimated that 3,089 kg of grain corn is required to produce the wet weight of chicken equivalent to the livestock by-product meal inputs[135]. Using the Canadian five-year average yield rate of grain corn, 6,780 kg per hectare (Appendix G), I estimate that 0.456 hectares of agricultural ecosystem is needed to provide the livestock by-product meal inputs per tonne of contemporary salmon feed produced.

### Ecosystem Support Area to Provide Agricultural Crop Inputs

An average tonne of contemporary salmon feed includes 150 kg of wheat, 80 kg of corn gluten meal and 80 kg of a combination of de-hulled solvent-extracted soybean meal and canola meal (Table 17). As canola and soybean meals are highly interchangeable in the feed formula (Mr. Jason Mann, EWOS Canada Limited, pers. comm. 1997), for the purposes of this analysis I assumed that they contribute equally. Therefore 40 kg of each is incorporated into the diet being modelled.

As corn gluten, soybean and canola meals are each co-products of their respective milling processes, the partitioning problem arises once again. However, under the convention used throughout the base model I simply treated the three protein meals as whole oilseed/grain equivalents in determining the ecosystem support areas and energy inputs required to produce them.

The areas of agricultural ecosystem associated with producing the direct crop inputs to an average tonne of salmon feed were determined (see Table 23) using the five-year Canadian average yields of the four crops as presented in Appendix G.

[135] Calculated by multiplying 572 kg of chicken by 5.4 kg grain/kg chicken.

*Table 23. Agricultural Ecosystem Support Area Required to Provide the Direct Crop Inputs to Contemporary Salmon Feed*

| Input | Mass required (kg) | Canadian 5 year Average Yield (kg/ha)[a] | Agricultural Ecosystem area required (ha) |
|---|---|---|---|
| Wheat | 150 | 2,200 | 0.068 |
| Corn (for gluten meal) | 80 | 6,780 | 0.012 |
| Canola (for meal) | 40 | 1,300 | 0.031 |
| Soybean (for meal) | 40 | 2,580 | 0.016 |
| | | | Total: 0.127 |

Notes a: All agricultural crop yield rates from Appendix G.

A total of 0.127 ha of agricultural ecosystem support is required to provide the four crop-derived inputs to a tonne of contemporary salmon feed (Table 23).

### Sum of Ecosystem Support Areas to Supply Material Inputs per Tonne of Salmon Feed Produced

Combining the results of the three sections immediately above, the average tonne of salmon feed produced in British Columbia requires the dedicated support of approximately 5.6 ha[136] of marine ecosystem and 0.58 ha[137] of agricultural ecosystem.

## *Energy Inputs to Fish Harvesting, Processing and Transportation for Fish Meal and Oil*

### Energy to Capture Fish for Conversion to Fish Meal and Oil

As discussed above, only the energy required to capture the 3,000 kg of fish destined for fish oil was included in the model to avoid double counting.

Energy analyses of fisheries from different parts of the world consistently show that energy intensities (e.g. the energy inputs per mass of fish landed) can vary by as much as an order of magnitude between different fishing gears (Leach 1976, Lorentzen 1978, Rawitscher 1978, Nomura 1980). Therefore, when modelling the energy inputs required to catch a given quantity of fish, it is important to base the model on the appropriate fishing technology. Many of the world's largest reduction fisheries, including the fisheries that provide the South American fish meal and the Gulf of Mexico menhaden oil used in salmon feeds, employ purse seine technology almost exclusively (Smith 1991, Polushin 1994, Arancibia *et al.* 1995). In addition, the majority of the herring that end

[136] This is the marine ecosystem support required to provide the fish meal inputs only (see Table 21 and accompanying text).
[137] This is the sum of the 0.456 ha of agricultural ecosystem required to sustain the provision of the livestock by-product meal inputs and the 0.127 ha of agricultural ecosystem that is required to sustain the provision of the direct grain and oilseed derived inputs.

up being used to make mixed fish oil here in British Columbia are also caught by purse seiners. Hence, I used this fishing technology to model the energy inputs required to catch the fish destined for reduction.

Previous estimates of the energy inputs to purse seine fisheries for small pelagic species have ranged from lows of:

- 680 MJ [138] per tonne of capelin landed by Icelandic vessels during the mid-1970's (recalculated from Ágústsson *et al.* 1978),
- 2,200 MJ [139] per tonne of herring landed in Maine in the early 1970's (recalculated from Rawitscher 1978, Table A-2),
- 2,355 MJ [140] per tonne of fish landed by the Norwegian herring reduction fishery of the mid-1970's (re-calculated from Lorentzen 1978, Table 4), and
- 3,500 MJ per tonne of herring landed by Scottish purse-seiners in the early 1970's (Searle and Windsor 1982)

to highs of 10,000 MJ per tonne of fish landed by both the South African pilchard fishery of the early 1970's (Pitcher 1977) and for Japanese purse seiners catching small pelagics in the mid-1970's (Nomura 1980, Table 1). I was reluctant, however, to use any of these results or an average of them in my model because they are all based on data which are at least 20 years old. Over that period, the energy efficiency associated with a given fishery or fishing technology can vary as a result of changes in relative resource abundance and/or technology, in particular changes in vessel size and horsepower (Brown and Lugo 1981, Watanabe and Uchida 1984, Sato *et al.* 1989, Mitchell and Cleveland 1993)[141].

Fortunately data were available from which I could generate contemporary energy input estimates for both the British Columbia purse seine herring fishery and the Gulf of Mexico purse seine menhaden fishery.

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[138] Only included fuel inputs.
[139] Included both direct and indirect energy inputs.
[140] Ibid.
[141] The twin effects of resource depletion and technological change over time on energy efficiency in a fishery is particularly well documented by Mitchell and Cleveland (1993). In their analysis they show that the energy used to harvest seafood increased from approximately 6 to 36 kcal of fuel for each kilocalorie of edible fish protein landed in the New Bedford, Massachusetts fishery from 1968 to 1988.

### *Fuel Energy Inputs to the British Columbia Purse Seine Herring Fishery*[142]

Table 24 presents the analysis of the fuel energy inputs to the British Columbia purse seine roe herring fishery for 1991 and 1994.

*Table 24. Estimates of Direct Diesel Fuel Consumed by the British Columbia Purse Seine Herring Fishery, 1991 and 1994*

| Year | Total herring landings by B.C. purse seiners (tonnes) [a] | Total fuel expenditures by fleet while herring fishing[b] | Provincial average price of commercial diesel fuel ($/l) [c] | Fuel consumption per tonne herring landed | |
|---|---|---|---|---|---|
| | | | | (litres)[d] | (MJ) [e] |
| 1991 | 23,330 | $1,170,000 | $0.313 | 160 | 5,766 |
| 1994 | 23,572 | $830,000 | $0.307 | 115 | 4,144 |
| | | | **Averages:** | **137.5** | **4,955** |

Notes: a. Landing data from the Department of Fisheries and Oceans' annual British Columbia Commercial Catch Statistics, 1991 and 1994.
b. Data includes all purse seine vessels licensed to fish herring. 1991 data from Exhibit C.1 and 1994 data from Exhibit D.1 of Gislason 1997.
c. From Appendix C.
d. Calculated by first dividing the total expenditures made on fuel (third column) by the average price of diesel fuel (fourth column). This was then divided by the total tonnes of herring landed by seiners (second column).
e. Calculated based on the energy content of diesel fuel of 36.036 MJ/litre (Rose and Cooper 1977).

Over the two years for which data were available, 1991 and 1994, the British Columbia purse seine fleet burned, on average, approximately 137.5 litres of diesel fuel (Table 24), with a net energy content of approximately 4,956 MJ[143]. Therefore, 8,921 MJ of diesel fuel are required to harvest the 1,800 kg of herring (Table 19) which must be caught to supply the British Columbia mixed fish oil component of the salmon feed being modelled.

### *Indirect Energy Inputs to the British Columbia Purse Seine Herring Fishery*

As most, if not all, of the purse seine vessels that are used to fish for herring in British Columbia are also used to fish for salmon, the results of my analysis in Chapter 5, of the inputs to build and maintain a typical 18m long aluminium-hulled salmon purse seiner, can be used to estimate the indirect inputs associated with landing a tonne of herring[144]. From that analysis (see Table 56 and the accompanying text), I made the following estimates of the inputs required, on an annual basis, to build and maintain a typical 18m long aluminium-hulled purse seiner:

[142] The vast majority of the herring caught by the British Columbia purse seine fleet are taken as part of the roe herring fishery when the herring are highly aggregated just prior to spawning. As a result, the fishery should be relatively energetically efficient because the exact location of the pre-spawning aggregations of herring are very well know to fishers and therefore very little extra fuel is burned in the search for fish. In addition, unlike reduction fisheries that are conducted in warmer waters, purse seiners operating in British Columbia do not incur the additional energetic expense of refrigerating their catch while on board in order to avoid spoilage prior to processing.

[143] Based on the net energy content of diesel fuel of 36.04MJ/l as derived from Rose and Cooper 1977, p. 281.

[144] Complete details of the analysis of the material, labour and energy inputs associated with building and maintaining a typical salmon purse seiner appears as part of the analysis of the inputs to the commercial salmon fishery in Chapter 5.

- 1,725 kg of aluminium,
- 1,380 kg of steel,
- 180 kg of mixed metals and other materials,
- 54,000 MJ of electricity, and
- 52 person-days of labour.

To transform these total annual inputs into average inputs per tonne of herring landed, a two-step conversion was required[145]. The first factor to account for is that herring fishing is not the only activity in which a typical purse seiner engages. To address this issue, I used income data for the entire British Columbia purse seine fleet, as reported by Gislason (1997, Table A.1), to calculate the herring fishing income to total income ratio for the five year period from 1990 to 1994 inclusive. The result, that herring fishing accounts for approximately 26% of the total seine fleet's income, was used to determine the proportion of the total inputs to build and maintain a typical purse seiner that are attributable to herring fishing.

Next it was necessary to calculate the average annual tonnage of herring landed by a single seiner in British Columbia (Table 25).

*Table 25. Average Herring Catch per Licensed Purse Seiner in British Columbia, 1990-1994*

| Year | Total tonnes of herring landed by purse seiners[a] | Number of seiners with herring licenses[b] | Average landings per vessel (t) |
|---|---|---|---|
| 1990 | 24,372 | 252 | 97 |
| 1991 | 23,330 | 252 | 93 |
| 1992 | 19,937 | 252 | 79 |
| 1993 | 25,797 | 252 | 102 |
| 1994 | 23,572 | 252 | 94 |
| | | Average: | 93 |

Notes: a. Annual herring landings by purse seiners from Department of Fisheries and Oceans, annual British Columbia Commercial Catch Statistics, 1990 through 1994 inclusive.
b. The number of herring seine licenses issued was taken from the Fisheries and Oceans Canada web site at: http://www.nrc.dfo.ca/communic/statistics/LICENSES/pacific/lic_e90.htm.

By first multiplying the annual material, energy and labour inputs to build and maintain a typical aluminium hulled purse seiner outlined above (and in Table 56), by the proportion that is attributable

[145] This is the same process that I employ in the analysis of the vessel related inputs per tonne of salmon landed.

to herring fishing, and then dividing the result by the average number of tonnes of herring landed per vessel (Table 25), I calculated the material and associated indirect energy inputs per tonne of herring landed (Table 26).

*Table 26. Estimated Material, Energy and Labour Inputs Required to Build and Maintain a Typical 18m Seiner per Tonne of Herring Landed*

| Inputs | Annual inputs to a typical 18m seiner[a] | Inputs per tonne of herring landed[b] | Energy Intensity (MJ/kg)[c] | Indirect energy inputs per tonne herring landed (MJ) |
|---|---|---|---|---|
| Aluminum (kg) | 1,725 | 4.8 | 140 | 675 |
| Steel (kg) | 1,380 | 3.9 | 25 | 96 |
| Mixed metals, etc. (kg) | 180 | 0.5 | 25 | 13 |
| Electricity (MJ) | 54,000 | 151 | | |
| Labour (person-days) | 52 | 0.1 | | |

Notes: a. From Table 56.
b. Values in this column calculated by multiplying the values in the first column by 0.26, the average ratio of herring fishing income to total income of seiners in British Columbia, and then dividing by 93, the average annual herring landings per vessel for the British Columbia seine fleet from 1990 to 1994.
c. Energy intensity values used throughout this research are outlined in Table 9.

As a result, 151 MJ of direct electricity and 784 MJ of indirect energy, which for simplicity I have assumed is entirely derived from natural gas, is required to build and maintain the purse seine vessels themselves per tonne of herring landed. Therefore, a total of 271 MJ of electricity and 1,411 MJ of natural gas are required to produce and maintain the vessels used to harvest the 1,800 kg of herring that end up as British Columbia mixed fish oil.

### *Energy Inputs to the Gulf of Mexico Purse Seine Menhaden Fishery*

Omega Protein Limited, the largest menhaden fishing company in the United States[146] provided me with data on the fuel consumed by their 37 purse seiners, based along the US Gulf coast, during the 1998 and 1999 seasons (Table 27).

[146] Over the 1990's, Omega Protein Limited 's fleet of 50 purse seiners, based out of five ports on the Gulf and Atlantic coasts, landed an average of slightly over a half a million tonnes annually and accounted for about two thirds of all US menhaden landings.

*Table 27. Summary of Catch and Fuel Consumed by Omega Protein's Gulf Menhaden Fleet: 1998 & 1999*

| Year | Home Port | No. of Vessels | Catch (tonnes) | Total Diesel Fuel Consumption (litres) | Energy Intensity (litres/tonne) | (MJ/tonne) |
|---|---|---|---|---|---|---|
| 1998 | Moss Point | 9 | 82,824 | 4,239,854 | 51 | 1,845 |
| 1998 | Morgan City | 6 | 64,171 | 2,468,986 | 38 | 1,386 |
| 1998 | Cameron | 12 | 100,204 | 4,173,174 | 42 | 1,501 |
| 1998 | Abbeville | 10 | 93,866 | 4,179,110 | 45 | 1,604 |
| 1999 | Moss Point | 9 | 108,539 | 4,028,643 | 37 | 1,338 |
| 1999 | Morgan City | 7 | 94,637 | 3,060,888 | 32 | 1,166 |
| 1999 | Cameron | 11 | 139,415 | 4,661,038 | 33 | 1,205 |
| 1999 | Abbeville | 11 | 149,405 | 4,866,749 | 33 | 1,174 |
| | Totals/Average: | | 833,062 | 31,678,442 | **38** | **1,370** |

Data provided by Mr. Mike Wilson, VP Marine Operations, Omega Protein Limited, pers. comm., January, 2000.

From the data provided by Omega Protein, the average direct fuel energy inputs to the Gulf of Mexico menhaden fishery is 1,370 MJ/tonne of fish landed (Table 27). Therefore, a total of 1,644 MJ of diesel fuel are required to harvest the 1,200 kg of menhaden which must be caught to supply the menhaden oil component of the salmon feed modelled.

I did not undertake a detailed analysis of the indirect energy inputs associated with building and maintaining a typical menhaden purse seiner. Instead, based on the results of other fisheries energy analyses (Rochereau 1976, Leach 1976, Rawitscher 1978, Lorentzen 1978, and my analysis in Chapter 5 of the energy inputs to salmon fishing vessels) I have conservatively estimated that the indirect energy required to build and maintain the menhaden fishing vessels is equivalent to 10% of their direct fuel energy inputs. This amounts to approximately 140 MJ/tonne, of which I have assumed 15% would be electricity while the remainder would be derived from natural gas. On this basis, a total 25 MJ of electricity and 143 MJ of natural gas are needed to produce and maintain the vessels used to harvest the 1,200 kg of menhaden destined for fish oil.

Combining the direct and indirect energy inputs to both the British Columbia herring fishery and the Gulf menhaden fishery I estimated that a total of 10,565 MJ of diesel fuel, 296 MJ of electricity and 1,554 MJ of natural gas are required to provide the 3,000 kg of wet fish for the fish oil inputs to salmon feed.

## Energy to Process Raw Fish to Fish Meal and Oil

Many factors can influence the amount of energy required to process a given quantity of raw fish into meal and oil. These include the type of reduction process used and, in particular, the type of dryer

employed[147], the capacity of the plant[148], the age of the plant's equipment, and the degree to which waste heat is recovered within the plant for use in pre-heating the raw fish and in multiple-effect stickwater evaporators (FAO, Fisheries Industry Division 1986).

As no energy use data were available from plants that currently supply the specific fish meal and oil inputs being modelled, I had to rely on published energy use estimates and on data provided by a supplier of fish meal reduction plant equipment (Table 28).

*Table 28. Summary of Estimates of Energy Inputs to the Reduction of Fish to Fish Meal and Oil*

| Plant capacity (wet tonnes/day) | Meal Type | Total direct energy input (MJ/wet tonne) | Total direct energy input (MJ/tonne meal) | Comments | Source |
|---|---|---|---|---|---|
| n/a | n/a | | 10,500 | | a |
| n/a | n/a | 2,122 | | | b |
| n/a | n/a | | 21,740 | | c |
| n/a | n/a | 2,245 | | | d |
| 10 to 60 | whole meal | 2,370 | | no waste heat recovery | e |
| 100 to 200 | whole meal | 2,159 | | no waste heat recovery | e |
| 250 to 500 | whole meal | 2,070 | | no waste heat recovery | e |
| over 500 | whole meal | 1,944 | | no waste heat recovery | e |
| 100 to 200 | whole meal | 1,914 | | waste heat recovered | e |
| 250 to 500 | whole meal | 1,784 | | waste heat recovered | e |
| over 500 | whole meal | 1,658 | | waste heat recovered | e |
| n/a | whole meal | 2,600 | | | f |
| 60 | whole meal | 3,305 | | Con-Kix air dryer | g |
| 150 | whole meal | 2,949 | | Con-Kix air dryer | g |

Source notes:
a. Edwardson 1976 as reported in Searle and Windsor 1981.
b. Pitcher 1977.
c. Rawitscher 1978.
d. Lorentzen 1978.
e. FAO, Fishery Industries Division 1986.
f. Canadian Fishery Consultants Limited 1994.
g. Mr. Chris Pook, regional manager, Alpha Laval Inc. pers. comm. November, 1997.

While the direct energy inputs to process fish into fish meal and oil vary from approximately 1,660 MJ to 3,300 MJ per tonne of wet fish processed (Table 28) [149], for the purposes of the current model, I chose to use the lowest, most conservative energy input value of 1,660 MJ [150] per tonne[151].

[147] At least five different types of dryers are currently in use in different fish meal plants, direct hot air or "flame" dryers, direct fired rotary dryers, indirect steam dryers, indirect tube dryers and indirect hot air dryers. (FAO Fishery Industry Division 1986).

[148] The capacity of fish meal and oil plants can vary from under 10 wet tonnes of fish processed per day to over 3600 wet tonnes of fish per day (FAO Fishery Industry Division 1986).

[149] Interestingly, the two highest energy input values are associated with the most modern fish meal plants for which data were available. The Con-Kix fish reduction plant by Alpha Laval, which uses a hot air dryer, is designed specifically to produce very high quality fish meals and oil. (Mr. Chris Pook, Alpha Laval Inc., pers. comm., November, 1997).

[150] This is the energy input value associated with a large capacity reduction plant operating with full waste heat recovery as described by the FAO, Fishery Industries Division (1986).

Therefore, a total of 4,980 MJ of energy is required to process 3,000 kg of wet fish represented by the fish oil components in an average tonne of salmon feed. Of this, approximately 95%, or 4,730 MJ, is derived directly from fossil fuels[152], while the remaining 5%, or 250 MJ is represented by electricity[153]. Finally, it is assumed that the fossil energy inputs are entirely natural gas derived[154].

## Energy to Transport Fish Meal and Oil to Vancouver

Average energy consumption data associated with transporting freight by truck, rail and ship were unavailable for Canada and for the international carriage of freight by ships. I therefore relied on 1996 average American transportation energy input values for hauling freight by ship, train and transport truck as reported in the *18th edition* of the *Transportation Energy Data Book* (Davis 1998).

Table 29 summarises the estimated transportation distances required to haul fish meal and oil inputs, the assumed modes of transport, average energy intensities for the various modes of transport, and the final transportation energy inputs required to deliver the four fish meal and oil inputs to the EWOS plant in Surrey, British Columbia.

*Table 29. Summary of Transportation Distance, Mode and Energy Input for the Fish Meal and Oil Components of Salmon Feed*

| Component | Mass (kg) | Assumed Mode of Transport | Transport Distance (km) | Average Energy Intensity (KJ/tonne-km)[a] | Transport Energy (MJ) |
|---|---|---|---|---|---|
| S. American fish meal | 323 | Ship | 10,000[b] | 298 | 963 |
| B.C. herring meal | 57 | Truck | 20 | 2,015 | 2 |
| G. of Mexico menhaden oil | 144 | Rail | 4,600[c] | 266 | 176 |
| B.C. mixed fish oil | 36 | Truck | 20 | 2,015 | 1 |
| | | | | | Total: 1,142 |

Notes: a. All energy intensity values from Davis 1998.
b. Estimated distance to transport South American fish meal based on the distance from Antofagasta, Chile to Vancouver, Canada, a straight line distance of 9,580 km as calculated on the web site http://www.indo.com/distance
c. Estimated distance to transport Gulf of Mexico menhaden oil based on the railroad mileage from New Orleans, Louisiana to Seattle, Washington as calculated from the web site http://my.uprr.com/pub/mileage/index.cfm

[151] I believe that employing this value will underestimate the actual processing energy inputs associated with producing the fish meals and oils used because the high quality fish meals and oils demanded by the salmon feed industry are often produced using reduction technologies which are not the most energy efficient available. (Mr. Richard Carrol of Atlas-Stord, pers. comm., March, 1998; Mr. Chris Pook, Alpha Laval Inc., pers. comm., November, 1997).

[152] Used primarily to raise steam and in some cases to provide direct heating to dryers.

[153] The 95:5 ratio of fossil fuel energy to electrical energy inputs associated with fish reduction plants is from FAO, Fisheries Industries Division 1986.

[154] Natural gas is the primary fuel used in the West Coast Reduction plant in Vancouver (Mr. Russ Mitchellson, West Coast Reductions Ltd. pers comm. 1997) and in the plants that provide the Gulf of Mexico menhaden oil. However, the majority of Chilean and Peruvian fish reduction plants use heavy fuel oil (Mr. Tony Bimbo, fish reduction industry consultant, pers. comm., March, 1998).

A total of 1,142 MJ of fuel are required to transport the fish meal and oil components of an average tonne of salmon feed from their sources to the EWOS plant. Although ships and trains may burn heavier fuel oils, for simplicity, I have assumed that all of the transportation energy is derived from diesel fuel for the purposes of modelling $CO_2$ emissions.

## *Energy Inputs to Livestock Rearing and By-Product Processing and Transportation*

### Energy to Rear Chicken Biomass for By-Product Meals

No data were available on the energy inputs associated with chicken rearing in Canada. However, Ostrander (1980) provides a detailed breakdown of the average direct and indirect energy requirements of broiler chicken production in northern US states for 1974 (Table 30).

*Table 30. Average Direct and Indirect Industrial Energy Inputs, Excluding Feed, to Chicken Production*

| Inputs | Energy input per tonne of chicken produced (MJ)[a] | Proportion of the Total Energy Input Required |
|---|---|---|
| Buildings | 4,940 | 35.3% |
| Equipment | 206 | 1.5% |
| Propane of brooding | 4,295 | 30.7% |
| Electricity | 2,300 | 16.4% |
| Transportation | 2,244 | 16.0% |
| | Total: 13,985 | |

Notes: a. All values are recalculated from data presented by Ostrander (1980) based on the assumption that at slaughter an average broiler weighs 1.59 kg (3.5 lb.).

From the data presented in Ostrander (1980), I estimated that the production of a tonne of chicken requires a total of 13,985 MJ of energy for non-feed related purposes (Table 30). Therefore, approximately 8,000 MJ of energy is required to rear the 572 kg of chicken biomass (Table 22) represented by the three livestock by-product meal inputs to an average tonne of salmon feed. Of this, 1,315 MJ is derived from electricity[155], and 2,457 MJ is derived from natural gas for brooding[156]. I assume that the remaining 4,228 MJ required for buildings, equipment and transportation is derived from diesel fuel.

[155] Calculated by multiplying 8,000 MJ by 0.164, the electrical energy proportion of the total energy inputs in Table 30.
[156] Calculated by multiplying 8,000 MJ by 0.307, the brooding energy proportion of the total energy inputs in Table 30.

## Energy to Process Livestock By-Products into Meals

Relatively little published information was found regarding the energy inputs associated with processing livestock by-products into their respective meals.

As part of her review of the process technologies used to produce blood meal, Fernando (1992) uses a graph to illustrate the range of energy inputs required to evaporate water from blood for several technologies (Fernando 1992, p. 88). In order to err on the conservative side, I chose to use the mid-range energy input value, 2.8 MJ/kg of water evaporated, associated with the most energy efficient process for which she provides data. As approximately 332 kg of water must be evaporated from whole blood in order to yield 40 kg of blood meal (Table 22), approximately 930 MJ of energy is required for processing the blood meal component of an average tonne of salmon feed.

No published estimates were found of the energy required to process meat scraps and feathers into their respective meals. I therefore applied the same unit process energy input of 1,660 MJ/wet tonne that was used to model the energy required to reduce raw fish to fish meal and oil[157]. Therefore, 332 MJ of energy is required to process the 160 kg of meat and scraps and 40 kg of raw feathers to yield the required quantities of their respective meals in an average tonne of salmon feed.

As Fernando (1992) did not provide information regarding the sources of primary energy used to process blood, I have assumed that the energy inputs to livestock by-product processing mirror the primary energy breakdown associated with fish meal processing. Therefore, of the 1,262 MJ total energy required to process by-products, I assume that 95%, or about 1,200 MJ is derived from natural gas and the remaining 5% ,or 62 MJ, is electrical energy.

## Energy to Transport By-Products and the Resulting Meals

I assumed that the entire 572 wet weight kg of livestock by-products required for by-product meals are sourced in the Fraser Valley and are transported 50 km by truck to the West Coast Reduction Ltd. plant in downtown Vancouver for processing. I also assumed that the resulting 120 kg of meal are transported by truck a distance of 20 km from the reduction plant to EWOS' feed mill in Surrey. Given an energy intensity of 2,015 kJ/tonne-km for truck transport (Davis 1998), a total of 62 MJ of diesel fuel is required to transport the raw livestock by-products and the resulting meal components of an average tonne of salmon feed.

[157] I believe that this is a reasonable assumption given that the average moisture content and consistency of scrap meat is similar to raw fish and fish wastes. It may, however, underestimate the energy requirements associated with feather meal

## *Energy to Harvest, Process and Transport the Direct and Indirect Crop Inputs*

### Energy to Produce/Harvest Agricultural Crops

A great many energy analyses of agricultural systems have been conducted since the first oil price shock of 1973. For the purposes of this work, however, I only reviewed analyses which assessed one or more of the crops incorporated into salmon feed, namely wheat, grain corn, canola and soybeans. After reviewing seven works that provide estimates of the energy inputs associated with wheat production (Briggle 1980, Stout *et al.* 1984, Zentner *et al.* 1989, Smith *et al.* 1995, Coxworth *et al.* 1996, Börjesson 1996, Sonntag 1997), six that provide estimates of the energy inputs to corn production (Pimentel and Terhune 1977, Smil, *et al.* 1983, Stout *et al.* 1984, Pimentel *et al.* 1985, Swanton *et al.* 1996, Coxworth *et al.* 1996), five that provide estimates of the energy inputs to soybean production (Scott and Krummel 1980, Stout *et al.* 1984, Ahmed *et al.* 1994, Swanton *et al.* 1996, Coxworth *et al.* 1996), and two that provide estimates of the energy inputs to canola/rape seed production (Börjesson 1996, Sonntag 1997), I decided to use the estimates of the energy inputs to wheat[158], grain corn and soybean production from Coxworth *et al.* (1996) because:

- the data from which their estimates are based reflect typical contemporary (1990's) Canadian agricultural productivities and practices for the three crops of interest,
- their estimates, while encompassing the same suite of inputs[159] as most contemporary agricultural energy analyses, tended to be on the conservative (low) side of other recent estimates, and
- by using a single source reference for three of the four crops of interest, variation that can result from differences in the assumptions and methodology used is minimised.

As Coxworth *et al*'s work did not include an estimate of the energy inputs associated with canola production, I relied on the results of a Canadian speciality crop management study (Sonntag 1997)[160].

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processing, as raw feathers must first be cooked under pressure with steam for up to an hour, in order to hydrolyse the keratin present in raw feathers, before they are dried to their original moisture content (Polin 1992).

[158] The energy input values which I use reflect a continuous wheat cropping system.

[159] The analysis by Coxworth *et al.* (1996) included the energy inputs associated with seed, fuel for all machinery including trucks engaged in farm related activities, machinery manufacture, depreciation and repair, fertilizers, and pesticides.

[160] The data presented in Sonntag (1997) is based on a detailed study undertaken in Saskatchewan from 1992 to 1995 which examined the effects of variations of crop rotation and tillage method on the economics and energy performance of canaryseed, canola, lentil, mustard, peas and wheat.

Table 31 summarises the unit and total energy input estimates for the four direct crop components of salmon feed, along with an estimate of the energy inputs to produce the grain corn required for livestock by-product meal production.

*Table 31. Estimates of Unit and Total Industrial Energy Requirements to Produce and Harvest the Direct and Indirect Crop Inputs to Salmon Feed*

| Direct and indirect crop inputs to salmon feed | Quantity required per tonne of salmon feed (kg) | Unit Energy Inputs (MJ/tonne harvested) | Energy Inputs (MJ) |
|---|---|---|---|
| Wheat | 150 | 4,120[a] | 618 |
| Corn (for gluten meal) | 80 | 3,180[b] | 254 |
| Soybean (for meal) | 40 | 1,870[b] | 75 |
| Canola (for meal) | 40 | 6,370[c] | 255 |
| Grain corn used as fodder to sustain by-product meal inputs | 3,089 | 3,180[b] | 9,823 |

Notes: a. Unit energy input value for continuous wheat cultivation from Coxworth *et al.* 1996, Table 1, p. 168.
b. Unit energy input values for grain corn and soybeans from Coxworth *et al.* 1996, Table 4, p. 171.
c. Unit energy input value for canola calculated from data presented in Sonntag 1997, Table 6, p. 13, Table 24, p. 32 and Table 28, p. 34.

A total of 1,202 MJ of energy is required to produce the quantities of grain and oilseed-derived feedstuffs that are *directly* incorporated into an average tonne of salmon feed. An additional 9,823 MJ of energy is needed to produce the grain corn required to grow the livestock by-product meal inputs to an average tonne of salmon feed (Table 31). Although several forms of industrial energy are used in crop production, to simplify the analysis, I assumed that all of it is derived from diesel fuel.

## Energy to Process Oilseed and Grain Corn into Protein Meals

As the wheat component of the salmon diet modelled is composed of unprocessed whole grains, and for reasons discussed above I have assumed that the fodder required to sustain the livestock by-product meal components is derived entirely from unprocessed grain corn, it was only necessary to estimate the energy required to process 80 kg of corn gluten meal, 40 kg of soybean meal, and 40 kg of canola meal[161].

Under the partitioning problem accounting convention used throughout the analysis (that energy inputs follow mass of outputs) it was not necessary to estimate the whole grain or oilseed mass that must be processed to yield the quantities of the three protein meals. I simply estimated the energy to process 80 kg of corn, 40 kg of canola and 40 kg of soybeans.

[161] For a description of the corn wet milling process from which corn gluten meal results, see Corn Refiners Association 1989. For a description of various soybean processing options and products see Considine and Considine 1982. For a description of the canola milling process that yields canola meal see Hickling 1993.

Once again, there was a paucity of published data on the energy associated with processing grains and oilseeds into their various component products. Fortunately, one publication (Ahmed *et al.* 1994) provided a detailed breakdown of the energy inputs to contemporary American soybean processing using conventional solvent extraction technology (Table 32).

*Table 32. Estimated Average Energy Inputs to Soybean Processing using Solvent Extraction*

| Input | Industry Average Energy Input (MJ/tonne of seed)[a] |
|---|---|
| Electricity | 120 |
| Fuel to raise steam | 1,300 |
| Solvent loss[b] | 86 |
| | Total: 1,506 |

Notes: a. All energy input values have been recalculated from data in Ahmed *et al.* 1994, Table 4, p. 7.
b. Conventional oilseed processing uses n-hexane as a solvent to maximize the extraction of the oil fraction of the seed. As n-hexane is highly volatile, it is inevitable that some is lost as part of the extraction process. Ahmed *et al.* (1994) estimate that on average the equivalent of approximately 2.9 litres of hexane is lost per tonne of oilseed processed. In assigning an energy value to the loss of hexane I have simply used its straight fuel energy value of approximately 29.7 MJ/l (Ahmed *et al.* 1994).

From the data presented by Ahmed *et al.* (1994), a total of 1,506 MJ of energy is required to process a tonne of soybeans into its meal and oil fractions. Of this total, 120 MJ, or approximately 8%, is electricity and I made the conservative simplifying assumption that all of the remaining energy needed is derived from natural gas for the purposes of modelling greenhouse gas emissions[162].

As no data were available regarding the energy inputs to canola seed processing and corn wet milling, I assumed that the unit energy inputs to these processes are the same as those for soybean processing. Therefore, a total of 240 MJ is required to process the 80 kg of corn and 40 kg of both canola and soybeans into their respective meals. Of this, approximately 19 MJ is electricity while the remainder is assumed to be derived from natural gas.

## Energy to Transport Agricultural Inputs

Table 33 summarises the estimates of the energy to transport the quantities of the three plant protein meals, the whole grain wheat and the grain corn required as fodder to produce the livestock by-

[162] While the energy associated with hexane losses during the extraction process are clearly not derived from natural gas, it is a reasonable assumption that natural gas is used as the fuel to raise steam. As the energy input associated with raising steam represents the vast majority of the non-electrical energy inputs to soybean processing, I have simplified the analysis by assuming that all non-electrical energy inputs are natural gas derived.

product meals, from their respective major production regions in Canada to the Lower Mainland region of British Columbia[163].

*Table 33. Estimates of the Transportation Energy Required for Direct and Indirect Crop Inputs to an Average Tonne of Salmon Feed*

| Input | Mass to transport (kg) | Assumed Source Region[a] | Transport Distance (km) | Transportation Energy Intensity (kJ/t-km)[b] | Transportation Energy Required (MJ) |
|---|---|---|---|---|---|
| Wheat | 150 | Alberta | 1,000 | 266 | 40 |
| Canola meal | 40 | Alberta | 1,000 | 266 | 11 |
| Corn gluten meal | 80 | Manitoba | 2,300 | 266 | 49 |
| Soybean meal | 40 | Manitoba | 2,300 | 266 | 24 |
| Grain corn for fodder | 3,089 | Manitoba | 2,300 | 266 | 1,890 |
| | | | | | Total: 2,014 |

Notes: a. The closest major Canadian production region for wheat and canola was assumed to be Alberta while for corn and soybeans, it was assumed to be Manitoba.
b. It was assumed that all of the agricultural inputs were transported by rail from their source region to the Lower mainland of British Columbia. The average energy intensity value of 266 kJ/t-km for transporting freight by rail was taken from Davis 1998.

A total of 2,014 MJ of diesel fuel derived energy is needed to transport the direct and indirect crop inputs per tonne of salmon feed produced (Table 33).

## Energy to Transport Finished Salmon Feeds

The final energy input associated with providing salmon feed that I quantified is that required to transport the finished feed from the feed mill to its location of final use. The modes of transportation used to deliver feed and the transport distances can vary widely. In instances where the hatchery or net-cage site is directly accessible by road, feed is often moved exclusively by truck. However, when there is no road access, or if truck transportation is prohibitively expensive, feed is delivered by barge or other vessel from some central location with good road access.

To simplify the estimation of the transport energy, I assumed that the average tonne is hauled by truck 175 km, the approximate road distance from the feed mills in the Lower Mainland to Campbell River, the community that serves a large portion of the British Columbia salmon farming industry. Using an average energy intensity value of 2,015 kJ/tonne-km for truck transportation (Davis 1998), approximately 353 MJ of diesel fuel energy is needed to transport a tonne of salmon feed to its location of final use.

[163] I did not estimate the energy required to transport the raw grain corn, canola and soybeans which go into the three plant protein meal components as I assumed that the processing mills are located in close proximity to the agricultural areas that provide the raw grain corn and oilseeds.

## *Summary of the Ecosystem Support and Total Energy Inputs to Supply a Tonne of Salmon Feed*

From the analysis above, an average tonne of salmon feed used by the intensive salmon culture industry in British Columbia requires the dedicated support of approximately:

- 5.6 ha of marine ecosystem to produce of fish-derived components,
- 0.456 ha of agricultural ecosystem to produce livestock byproduct meal-derived components, and
- 0.127 ha of agricultural ecosystem to produce crop-derived components.

Table 34 summarises the direct and indirect industrial energy inputs required to harvest, process, and transport a tonne of salmon feed and its components. It also provides an estimate of the total energy inputs, expressed in terms of fossil fuel equivalents, along with estimates of the total resulting greenhouse gas emissions.

*Table 34. Direct and Indirect Industrial Energy Inputs to Produce a Tonne of Salmon Feed and Resulting Greenhouse Gas Emissions*

| Process | Diesel Fuel (MJ) | Natural Gas (MJ) | Electricity (MJ) | Total Energy Inputs in Fossil Fuel Equivalents (MJ)[a] |
|---|---|---|---|---|
| Indirect Inputs | | | | |
| - Direct fuel input to fish capture | 10,565 | | | 10,565 |
| - Indirect inputs to fish capture | | 1,554 | 296 | 2,400 |
| - Fish reduction | | 4,730 | 250 | 5,444 |
| - Fish meal/oil transport | 1,142 | | | 1,131 |
| - Chicken rearing | 4,228 | 2,457 | 1,315 | 10,442 |
| - By-product processing | | 1,200 | 62 | 1,377 |
| - By-product meal transport | 62 | | | 62 |
| - Production of direct crop inputs | 1,202 | | | 1,202 |
| - Production of corn for fodder | 9,823 | | | 9,823 |
| - Crop processing | | 221 | 19 | 275 |
| - Crop transport | 2,014 | | | 2,014 |
| Direct Inputs | | | | |
| - Salmon feed milling | | 1,534 | 507 | 2,983 |
| - Salmon feed transport | 353 | | | 353 |
| **Total (MJ):** | **29,389** | **11,696** | **2,449** | **48,082** |
| GHG emission intensities (kg $CO_2$ equiv./MJ)[b]: | 0.0879 | 0.0579 | 0.0267 | Total Greenhouse Gas Emissions |
| **GHG emissions (kg $CO_2$ equiv.):** | **2,583** | **677** | **65** | **3,325** |

Notes: a. Total energy inputs, expressed in terms of fossil fuel equivalents are calculated by assuming a 35% conversion efficiency from fossil fuels to electrical energy.
b. Greenhouse gas emission intensity values from Table 3.

An average tonne of salmon feed used by the intensive salmon culture industry in British Columbia requires the fossil fuel equivalent energy input of approximately 48,100 MJ of industrial energy (Table 34). The greenhouse gas emissions that result from the various forms of energy inputs amount to the equivalent of 3,300 kg of $CO_2$ per tonne of salmon feed produced (Table 34).

## Quantifying the Material Inputs and Associated Embodied Energy and Greenhouse Gas Emissions to Build and Maintain Saltwater Grow-Out Site Infrastructure

I did not undertake an exhaustive analysis of the material, labour and energy inputs to build and maintain all forms of capital infrastructure associated with intensive salmon culture in British Columbia. I did, however, quantify the material inputs and related embodied energy and greenhouse gas emissions associated with building and maintaining marine grow-out site infrastructure. Specifically, I quantified the inputs to build and maintain a galvanised steel cage system with a

complete set of containment and predator nets, anchoring system and an associated floating combination bunkhouse/feedshed building.

It is possible to gauge the relative importance of grow-out site infrastructure by examining the total capital expenditures made by the 13 member companies of the British Columbia Salmon Farmers Association in 1996 (Table 35).

*Table 35. Capital Expenditures made by British Columbia Salmon Farmers Association Member Companies in 1996*

| Forms of Capital | Amount Invested in 1996 |
|---|---|
| Nets | $3,347,000 |
| Cages | $3,750,000 |
| Barges | $1,173,000 |
| Boats | $1,091,000 |
| Trucks | $77,000 |
| Equipment | $3,729,000 |
| Buildings | $1,627,000 |
| Other | $1,579,000 |
| Total | $16,373,000 |

Source: Coopers and Lybrand 1997

In combination, cages, nets and buildings together represent over 50% of the capital expenditures made by the industry in 1996 (Table 35).

A variety of styles, sizes and configurations of net-cage systems are used by the British Columbia salmon farming industry. The main structural members of a cage system may be composed of steel, aluminium, plastic or wood, depending upon the age, size and type of cage system being used. However, based on discussions with individuals within the industry, it was determined that a galvanised steel framed system of ten cages, with each cage measuring 30 metres by 30 metres by 20 metres deep could be considered a fairly typical, large-volume system, and one which would likely characterise many new systems that might be built in the foreseeable future. By modelling the inputs associated with such a relatively large-volume system, the results will tend to err on the conservative side, as the inputs per tonne of salmon produced decreases with increasing net-cage volume. Other attributes of the net-cage system modelled included: a predator net surrounding the entire system, bird netting covering all cages, a floating combination feedshed/bunkhouse building, all required floatation and a complete anchoring system.

Given the above described characteristics, Mr. Doug Louvier, president of Wavemaster Canada Limited, a fabricator of galvanised steel net-cage systems in British Columbia, provided detailed data on the physical quantities of material inputs to build such a system, along with estimates of the expected working life of the various components. The data provided by Mr. Louvier, along with the analysis of the input materials required to build and maintain a marine grow-out site per tonne of salmon produced appears in Appendix H.

From the analysis in Appendix H, Table 36 presents the input quantities of steel, zinc, plastics, concrete and wood associated with the production of a tonne of Atlantic and chinook salmon along with the total "embodied" energy and greenhouse gas emissions.

*Table 36. Material Inputs and Associated Embodied Energy and Greenhouse Gas Emissions to Build and Maintain Marine Grow-Out Site Infrastructure per tonne of Salmon Produced*

| | Inputs in kg/tonne salmon produced | | Energy Intensities | Embodied energy in MJ per tonne salmon | | GHG Emission Intensities | GHG emissions/tonne salmon (kg $CO_2$ equiv.) | |
|---|---|---|---|---|---|---|---|---|
| Inputs | Atlantics | Chinook | (MJ/kg)[a] | Atlantics | Chinook | (kg $CO_2$ eq./kg)[b] | Atlantics | Chinook |
| Steel | 4.5 | 7.8 | 25 | 113 | 196 | 2.5 | 11 | 20 |
| Zinc | 0.26 | 0.44 | 25 | 6 | 11 | 2.5 | 1 | 1 |
| All plastics | 9.9 | 17.1 | 75 | 739 | 1,281 | 3.0 | 30 | 51 |
| Concrete | 9.9 | 17.1 | 1 | 10 | 17 | 0.15 | 1 | 3 |
| Wood | 1.1 | 1.9 | n/a | | | n/a | | |
| | | | **Totals:** | **869** | **1,505** | | **43** | **75** |

Notes: a. Energy intensities from Table 9.
b. Greenhouse gas emission intensities from Table 9.

For each tonne of Atlantic salmon produced by the contemporary salmon farming industry in British Columbia, approximately 869 MJ of energy is "embodied" in the material inputs to build and maintain marine grow-out infrastructure and the equivalent of approximately 43 kg of $CO_2$ were released to provide these materials. Similarly, for each tonne of chinook salmon produced, approximately 1,505 MJ of energy is embodied in the material inputs and the equivalent of 75 kg of $CO_2$ were released to provide those inputs.

# Chapter 5: Analysis of the Commercial Salmon Fishery

The ecological footprint analysis of the commercial salmon fishery in British Columbia is comprised of six components. I evaluated the ecosystem support area required to sustain:

1. the prey consumed by an average population of wild foraging salmon which will yield one tonne of harvested adults,
2. the direct operating material, labour and energy inputs to the artificial production of juvenile chinook and coho salmon in hatcheries for release into the wild,
3. the fuel consumed directly in the process of catching a tonne of salmon for each of the three fishing gears used,
4. the labour required directly in the process of catching a tonne of salmon for each of the three fishing gears used,
5. the material and energy inputs associated with providing the fishing gear "consumed" per tonne of salmon landed for each gear type, and
6. the material, labour and energy inputs associated with building and maintaining the capital infrastructure of the fishing vessels themselves, per tonne of salmon landed for each of the three fishing gears.

The first component of the analysis was undertaken on a species-specific basis for each of the five salmon species caught by the commercial fleet. The second component was also undertaken on a species-specific basis but only for chinook and coho salmon[164].

A different analytical approach was necessary for the last four components listed above in that at first instance, I had to determine the inputs to land a generic tonne of salmon on a gear-specific basis. This is because all three gear sectors of the British Columbia salmon fleet harvest all five species of salmon to a greater or lesser extent. However, by using the proportion of the catch of each species contributed by each gear sector, I converted gear-dependent inputs into inputs on a species-specific basis.

[164] The rationale for limiting the analysis to the inputs associated with the artificial production of chinook and coho smolts is presented as part of the analysis below of the inputs to artificial enhancement.

## Quantifying the Ecosystem Support Area to Grow a Tonne of Salmon Foraging in the Wild

In quantifying the area of ecosystem required to grow a tonne of each of the five species of Pacific salmon when foraging in the wild, I made three major simplifying assumptions. First, while hundreds of distinct stocks contribute to the British Columbia commercial salmon fishery, I modelled only the ecosystem support required to grow an "average" tonne of chinook, coho, sockeye, chum and pink salmon.

Second, I assumed that the food required to grow an average tonne of salmon is derived exclusively from marine ecosystems. Although all Pacific salmon begin life in freshwater, for those salmon that do migrate to the ocean[165] and survive to a harvestable size, over 99% of their total biomass is acquired while foraging in marine ecosystems. This can be illustrated using coho salmon, a species that tends to have, on average, one of the longest periods of freshwater residence of the five Pacific salmon species native to British Columbia and typically achieves a relatively large average size upon smoltification. If an average coho weighs 20 grams when leaving fresh water[166], and upon harvesting has a mass of 2,700 grams[167], 99.3% of its final mass has been derived from marine ecosystems.

Finally, I also assumed that the basic physiological requirements, and hence the life-cycle energy budgets of chinook, coho, chum and pink salmon mirror that of sockeye salmon. This assumption was necessary because almost all of the available literature on the bioenergetics of Pacific salmon is derived from studies of sockeye salmon.

To maintain parallelism with the analysis of the feed inputs required to yield a tonne of farmed salmon, the first step in this analysis was to estimate the quantity of prey that an average population of Pacific salmon would consume in order to yield a harvestable tonne of salmon. In other words, what is the average population growth efficiency of Pacific salmon, taking into account the consumption by all members of the population regardless of whether they reach maturity. Fortunately, Brett (1986) generated such an estimate for a typical wild population of Babine Lake sockeye based upon his earlier detailed model of the life-cycle energetics of a typical individual 4-

[165] Note some populations of Pacific salmon remain in freshwater throughout their life. The most prominent example of this life history pattern in British Columbia is provided by the kokanee salmon, the freshwater resident form of the sockeye salmon.

[166] While coho smolts can range widely in size both within a given population and between populations (see Sandercock 1991), an average of 20 grams per smolt is reasonable.

[167] Using data on the total tonnage and number of coho landed by the entire British Columbia commercial fleet for the ten years from 1985 to 1994, I have calculated that the average coho weighs approximately 2.69 kg.

year-old Babine Lake sockeye (Brett 1983). He estimated that a typical cohort of Babine Lake sockeye experience a population growth efficiency of 22.8%, just 3.5% lower than the growth efficiency experienced by an individual fish (Brett 1986).

In estimating the ecosystem area required to grow a tonne of salmon foraging in the wild, I applied Brett's population growth efficiency of 22.8% to chinook, coho, chum and pink salmon in addition to sockeye salmon. As a result, a total of 4,386 kg of prey (wet weight) is consumed by the average population of salmon that ultimately yields one harvestable tonne[168]. The next step in the analysis was to estimate the primary productivity required to sustain the production of 4,386 kg of prey. This was done using the analytical approach outlined in Equation 1, for each of the five species of salmon, taking into account interspecific differences in the average trophic level of their respective prey.

The average trophic level of the prey of the five salmon species was estimated using published stomach content analyses reflecting a range of marine life stages for each species, drawn from several locations around the north Pacific basin. For each diet composition analysis used, a mean trophic level for the diet as a whole was estimated by assigning trophic level values, to one decimal place, to each of the major prey types encountered. Finally, for each species of salmon, I averaged the results of all of the diet composition trophic level means to produce an estimate of their overall prey base trophic level. Details of the stomach content analyses used and the calculation of the mean trophic level of salmon prey appear in Appendix I.

From the trophic level estimates generated in Appendix I, Table 37 presents the primary productivity required to sustain the production of a harvested tonne of each species of Pacific salmon.

*Table 37. Primary Productivity Required to Yield One Harvested Tonne of Pink, Chum, Sockeye, Coho and Chinook Salmon*

| Salmon species | Wet weight mass of prey required (kg) | Mean Trophic Level of Prey [a] | Primary Productivity Required (kg C) [b] |
|---|---|---|---|
| Pink | 4,386 | 2.50 | 15,411 |
| Chum | 4,386 | 2.51 | 15,770 |
| Sockeye | 4,386 | 2.54 | 16,898 |
| Coho | 4,386 | 2.81 | 31,465 |
| Chinook | 4,386 | 2.90 | 38,710 |

Notes: a. Mean trophic level of prey values are estimated in Appendix I
b. Primary productivity required was estimated using Equation 1.

[168] This was calculated by dividing 1000 kg of harvested salmon by 0.228, the population growth efficiency estimated by Brett (1986).

Finally, the marine ecological footprint associated with growing a tonne of each of the five salmon species was calculated by dividing the estimates of primary productivity required (Table 37) by appropriate net primary productivity values. As before, Longhurst *et al.* (1995) was used to estimate average net primary productivity values for the regions of the north Pacific ocean that conform most closely to the areas utilised by Pacific salmon originating from British Columbia and the Pacific Northwest (Table 38)[169].

*Table 38. Ecological Footprint to Sustain the Production of Prey Consumed by One Tonne of Pink, Chum, Sockeye, Coho and Chinook Salmon*

| Salmon species | PPR (kg C) | Net primary productivity (g C/m$^2$/year) | Marine Ecosystem Support Area (ha) |
|---|---|---|---|
| Pink | 15,411 | 341[a] | 4.5 |
| Chum | 15,770 | 341[a] | 4.6 |
| Sockeye | 16,898 | 341[a] | 5.0 |
| Coho | 31,465 | 341[a] | 9.2 |
| Chinook | 38,710 | 388[b] | 10 |

Notes: a. The stocks of pink, chum, sockeye and coho salmon that are most likely to be harvested by commercial fishers in British Columbia originate primarily from British Columbian and Pacific Northwest rivers. These stocks utilise coastal and offshore portions of the northeast Pacific ocean (see Burgner 1991, Heard 1991, Salo 1991, Sandercock 1991 and Hart 1973). These areas conform most closely with Longhurst *et al.*'s (1995) California Upwelling Coastal province, Alaska Downwelling Coastal province, East Pacific Subarctic Gyre province (also known as the Alaskan Gyre), and Offshore California Current province. Longhurst *et al.*'s estimates of the net primary productivity for each of these four provinces is 388, 661, 199, and 117 g C/m$^2$/year, respectively. I have used the average of these four net primary productivity values.

b. Chinook stocks that are most likely to be harvested by commercial fishers in British Columbia originate primarily in British Columbian and Pacific Northwest rivers. The majority of chinook stocks from these regions tend to remain on the landward side of the continental shelf margin throughout their time in marine waters (Healey 1991, Hart 1973). These areas conform most closely with Longhurst *et al.*'s (1995) California Upwelling Coastal province, Alaska Downwelling Coastal province, and the Offshore California Current province. Longhurst *et al.*'s estimates of the net primary productivity for these three regions is 388, 661, and 117 g C/m$^2$/year respectively. I have used an average of these three net primary productivity values in the current model.

## Quantifying the Direct Material, Labour, and Energy Inputs to the Artificial Rearing of Chinook and Coho Smolts

In this analysis, I only quantified the biophysical costs associated with producing juvenile chinook and coho salmon from SEP-operated hatcheries. This decision was based on the belief that the inputs associated with producing salmon in hatcheries are very much greater than the inputs associated with producing them through all other artificial enhancement activities. This was confirmed by an analysis

[169] Relatively few salmon of Asian or Alaskan origin are caught by commercial fisheries in British Columbia.

that I undertook of feed consumption by fish throughout the SEP program (Appendix J). The results indicate that the production of juvenile chinook and coho in combination account for approximately 84% of the total inputs to all SEP facilities. Juvenile chum production accounts for about 15% of the inputs and pink and sockeye combined account for only about 1%. As the vast majority of SEP produced chinook and coho originate in hatcheries, they became the focus of this part of the analysis.

Managers of two SEP hatcheries (Tenderfoot Creek hatchery and Robertson Creek hatchery) were contacted to determine the average operating material, labour and energy inputs associated with juvenile chinook and coho production from their facilities. Tenderfoot Creek hatchery is located on a tributary of the Cheakamus River in the Squamish River watershed, and produces approximately 1,600,000 chinook, and about 300,000 coho smolts per annum. Robertson Creek hatchery is located on a tributary of the Stamp River on Vancouver Island and produces approximately 8,370,000 chinook, 890,000 coho, and 125,000 steelhead smolts per year[170]. Together, these two hatcheries account for approximately 18% of the total annual SEP production of chinook smolts and about 6% of the total annual SEP production of coho smolts.

Each hatchery manager was asked to provide the following information regarding their hatchery's operation for a recent representative year:

1. the total number and total mass of smolts produced of each species,
2. the types and quantities of feed used,
3. the amount of electricity, in kWh, used by the hatchery and an estimate of the proportion attributable to the production of the various species produced,
4. the types and quantities of fossil fuels used for all hatchery-related activities, including fuel to heat buildings, power vehicles, etc., and an estimate of the proportion attributable to the production of the various species produced, and
5. the amount of labour required to run the hatchery, and an estimate of the proportion attributable to the production of the various species produced.

A summary of the data provided appears in Appendix K. Table 39 presents the resulting estimates of the average material, labour and energy inputs associated with producing one million chinook and

[170] Although I was provided with data on the biophysical inputs associated with steelhead smolt production from the Robertson Creek hatchery, it is not included as part of this research.

one million coho smolts from SEP hatcheries based on the data from the Tenderfoot Creek and Robertson Creek hatcheries.

*Table 39. Estimated Direct Material, Labour and Energy Inputs Required to Produce Chinook and Coho Smolts from SEP Hatcheries*

| Inputs | Inputs Required to Produce | | | |
|---|---|---|---|---|
| | Chinook Smolts | | Coho Smolts | |
| | per $10^6$ pieces | per tonne | per $10^6$ pieces | per tonne |
| "Dry" Feed (kg) | 3,843 | 690 | 19,442 | 971 |
| Labour (pers-days) | 332 | 60 | 550 | 28 |
| Electricity (MJ) | 166,439 | 29,845 | 2,765,090 | 138,255 |
| Gasoline (MJ) | 26,179 | 4,694 | 106,347 | 5,317 |
| Furnace Oil (MJ) | 47,585 | 8,533 | 49,843 | 2,492 |
| Propane (MJ) | 9,637 | 1,728 | 0 | 0 |

Source: see Appendix K.

Upon release, coho smolts require much greater inputs of feed, and energy than do chinook smolts (Table 39). This is largely because coho are typically reared in the hatchery environment for a much longer period of time, and to a much larger size[171], than are chinook smolts.

As SEP-origin fish only make up a fraction[172] of the total adult salmon population available to commercial fishers and because SEP activities are undertaken to meet a variety of objectives in addition to producing fish for the commercial fishery[173],it was necessary to convert the data in Table 39 into inputs per tonne of salmon landed by the commercial fleet. This conversion involved three steps. First, an estimate was made of the inputs required to support the total average annual production of chinook and coho smolts from all SEP facilities. This was done by multiplying the inputs per million smolts released (Table 39) by the average annual total number of chinook and coho smolts released from SEP facilities. Using data provided by the SEP, I estimate that an average of approximately 57.692 million chinook and 20.907 million coho smolts were released annually between 1985 and 1994 (Appendix L).

Next, the SEP-related inputs to the total average annual commercial harvest of chinook and coho salmon was calculated by multiplying the total annual inputs to all SEP chinook and coho smolt production by the average proportion of SEP-origin returning adult chinook and coho that are

[171] For example, the average coho smolt released from the Robertson Creek hatchery weighs approximately 20 grams while the average chinook smolt weighs about 5.5 grams on release.

[172] Of variable size depending on species of salmon, the year, etc.

[173] Other beneficiaries of the Salmon Enhancement Program include the recreational fishery, the aboriginal fishery, and various American fisheries. In addition, the SEP is used to bolster the numbers of some weak or threatened stocks, in effect, meeting a conservation objective.

harvested by commercial fishers in British Columbia. Again, using data provided by the SEP, I calculated that over the period from 1985 to 1994, 27% of SEP-origin adult chinook and 40% of SEP-origin adult coho were harvested by the B.C. commercial fleet (Appendix L).

Finally, the SEP-related inputs per average tonne of commercially caught chinook and coho were estimated by dividing the total SEP inputs to the entire annual commercial harvest of chinook and coho by the average total annual tonnage of commercially harvested chinook and coho for the period 1985 to 1994 (Appendix M).

Table 40 presents the resulting SEP-related feed, labour and energy inputs to artificial chinook and coho smolt production per average tonne of chinook and coho landed by the commercial fleet.

*Table 40. SEP-Related Inputs to the Average Commercially Harvested Tonne of Chinook and Coho Salmon*

| Inputs | SEP Related Inputs per Tonne of Commercially Harvested Salmon | |
|---|---|---|
| | Chinook | Coho |
| "Dry" Feed (kg) | 11.9 | 18.8 |
| Labour (pers-days) | 1.0 | 0.53 |
| Electricity (MJ) | 514 | 2,670 |
| Gasoline (MJ) | 81 | 103 |
| Furnace Oil (MJ) | 147 | 48 |
| Propane (MJ) | 30 | 0 |

## Quantifying the Inputs of Fuel, Labour and Gear to Land a Tonne of Commercially Caught Salmon

I quantified four inputs associated with the commercial harvest of salmon from the wild for each of the three fishing gears used (troll, purse seine and gillnet):

1. the fuel consumed directly in the process of salmon fishing,
2. the direct labour to salmon fishing,
3. the direct material and related indirect energy inputs to fishing gear, and
4. the direct energy, labour and material inputs and associated indirect energy inputs to build and maintain fishing vessels.

The first three were quantified using a similar technique and are considered in sequence immediately below. The inputs associated with building and maintaining salmon fishing vessels, however, were quantified using a different technique and, as such, is considered separately.

As mentioned previously, each of the five species of salmon are caught, to a greater or lesser extent, by all three fishing gears. It was therefore not possible to directly quantify the fuel, labour and gear inputs associated with landing a tonne of salmon on a species by species basis. I first had to quantify these inputs in terms of a generic tonne of salmon landed by each of the three gears. These were then converted into inputs on a species-specific basis using the share that each gear sector contributes to the average landed tonne of each species of salmon as a weighting factor. Appendix M presents the total British Columbia commercial catch, and proportion of the total catch taken by each gear sector for the five species of salmon, for the ten year period from 1985 to 1994 inclusive.

In addition, as the inputs associated with harvesting a given quantity of fish depends, in part, on stock abundance, which in the case of salmon can vary markedly from year to year, an estimate of the average inputs associated with landing a round tonne of salmon would ideally be based upon an extended time series of data. The most extensive data set available results from costs and earnings surveys of the salmon fleet for the years 1985, '88, '91 and '94[174]. These surveys were undertaken by Fisheries and Oceans Canada (previously known as the Department of Fisheries and Oceans) as a means to assess the financial performance of the salmon fleet over time. For a randomly selected sample set for each of up to 50 stratified segments of the fleet, in-person interviews were conducted to elicit detailed information from skippers or fishing boat owners on a variety of financial parameters related to their fishing activities[175]. Amongst other things, the data collected through the surveys included:

- total monetary expenditures made while engaged in fishing and related activities for a variety of fixed and variable costs, including expenditures made on fuel and fishing gear,
- gross income earned by the vessel through fishing for each of the various species for which the vessel is licensed and through other activities, and
- crew size and the total number of weeks that were spent fishing.

[174] In Appendix M, I have calculated the average British Columbia commercial salmon harvest by species and gear type for both the years in which costs and earnings surveys have been conducted (1985, '88, '91, and '94) and for the entire decade from 1985 to 1994. By comparing these averages, it would appears as if the four years for which costs and earnings survey data are available are generally representative of the average British Columbia commercial salmon fishery over the decade.

[175] Detailed descriptions of the methodology employed in surveying the fleet appear in reports prepared by the DPA Group (1988) and Department of Fisheries and Oceans (1992).

From the raw survey results, income statements were prepared, either by Fisheries and Oceans staff or by economic analysts contracted to the department, for the entire salmon fleet and for each of four subsets of the fleet: the purse seiners, the gillnetters, the trollers and the hybrid gillnet-trollers.

These fleet-wide income statements appear in a series of three reports on the financial performance of the salmon fleet as a whole (DPA Group 1988, Department of Fisheries and Oceans 1992, and Gislason; 1997). However, Mr. Stuart Kerr of the Program Planning and Economics Branch of Fisheries and Oceans Canada, who prepared the second report, and who oversaw the production of the third report by Gislason (1997), indicated to me that the income statements presented in Gislason's report should be considered the best, or most accurate, to date for all four survey years (pers. comm., October, 1997). Therefore, I only used data presented in the income statements prepared by Gislason (1997) to estimate the fuel, gear and labour inputs to salmon fishing.

In using these income statements, I was faced with two challenges. First, although there are only three gear types employed in salmon fishing (purse seine, gillnet and troll), and all salmon landings are reported in these terms, the income statements are prepared for four fleet subsets: the dedicated seiners, gillnetters, and trollers and the hybrid gillnet-trollers. This last group of vessels possess licenses and equipment to harvest salmon using either gillnet or trolling methods. In order to incorporate the data for these hybrid vessels into my analysis, and without any hard data regarding the proportions of this fleet's catch taken when gillnetting or trolling, I simply reapportioned the inputs of interest to these vessels evenly between the dedicated gillnet fleet and the dedicated troll fleet.

The second challenge is that in some cases, the inputs of interest are reported in a disaggregated form while in other instances, they are reported as aggregates. For example, the income statements for all fleet segments for 1991 and 1994 (Gislason 1997, Appendices C and D) report fuel expenditures and labour inputs specifically in terms of those incurred while engaged in salmon fishing, herring fishing and other fishing activities. However, the income statements for 1985 and 1988 (Gislason 1997, Appendix A) only report fuel expenditures and labour inputs on the basis of all activities undertaken by each fleet segment. Similarly, the income statements for all four survey years only report the expenditures made on fishing gear by each fleet segment in an aggregate form. In other words, gear expenditures are not "broken out" on the basis of that required to go salmon fishing, herring fishing, etc. In order to not over-estimate the fuel, labour and gear related inputs specifically associated with salmon fishing, it was therefore necessary to estimate a "salmon fishing specific fraction" for each of

the aggregated inputs reported. This was done using the salmon fishing to total fishing income ratio for each fleet segment for each survey year.

## Quantifying the Direct Fuel Energy Inputs Associated with Harvesting a Tonne of Salmon

Applying the above described data manipulations to the fuel expenditure data presented in Appendices A, C and D of Gislason (1997), estimates were made of the total money spent on fuel by the entire British Columbia commercial seine, gillnet, and troll fleets for the four years in which costs and earnings surveys were conducted (Table 41).

*Table 41. Total Fuel Expenditures Made While Salmon Fishing by the B.C. Commercial Seine, Gillnet, and Troll Fleets, 1985, '88, '91, and '94*

| Year | Seine Fleet | Gillnet Fleet[a] | Troll Fleet[a] |
|---|---|---|---|
| 1985[b] | $6,287,000 | $5,842,000 | $6,651,000 |
| 1988[b] | $4,386,000 | $5,355,000 | $4,265,000 |
| 1991 | $4,080,000 | $5,095,000 | $5,525,000 |
| 1994 | $4,340,000 | $6,615,000 | $4,975,000 |

Source: Gislason 1997, Appendices A, C and D.

Notes: a. The estimates of the total fuel expenditures made by the gillnet and troll fleets each includes 50% of the fuel expenditures made by the hybrid gillnet-troll fleet.
b. The estimates of the fuel expenditures made while salmon fishing in 1985 and 1988 were made by multiplying the total fuel expenditure for each fleet segment by that fleet segment's salmon fishing income to total fishing income ratio.

To convert the fuel expenditure estimates (Table 41) into physical quantities of fuel consumed it was necessary to estimate the diesel fuel to gasoline use mix ratio for each of the three fleets. This is because the average unit prices of commercial diesel fuel and commercial gasoline are quite distinct in most years. The fuel mix ratio for each of the fleet sectors was calculated from an electronic data file of the physical characteristics of each vessel holding a valid salmon license as of May, 1998[176]. From this data file, approximately 95% of seiners, 93% of trollers and 62% of gillnetters used diesel fuel for propulsion, with the remaining vessels in each gear sector using gasoline. Using these fuel use proportions and the average fuel prices for commercial diesel and gasoline outlined in Appendix C, I estimated the hybrid or blended fuel prices per litre for the three gear sectors for 1985, '88, '91, and '94 (Table 42)[177].

[176] This data file was provided to be by Mr. Brian Moore of the Program Planning and Economics Branch of Fisheries and Oceans Canada, May, 1998. It contained the following information for most of the licensed salmon fishing vessels at that time: type of salmon fishing license held (eg. seine, gillnet or troll), gross tonnage of the vessel, net tonnage of the vessel, length of vessel, primary hull material, propulsive fuel, year that the vessel was built, and year of re-build (if applicable).

[177] This of course assumes that the fuel type mix ratios have remained reasonably constant from 1985 to 1997 and that within each gear sector, there is no difference in the average fishing pattern of gasoline and diesel fueled vessels.

*Table 42. Estimated Average Blended Fuel Price Paid by Seiners, Gillnetters and Trollers in 1985, '88, '91, and '94*

| Year | Estimated Average Blended Fuel Price (cents/litre) | | |
|---|---|---|---|
| | Seine Fleet | Gillnet Fleet | Troll Fleet |
| 1985 | 34.7 | 35.7 | 34.8 |
| 1988 | 27.5 | 28.3 | 27.5 |
| 1991 | 31.6 | 33.4 | 31.7 |
| 1994 | 30.8 | 31.7 | 30.9 |

From the data presented in Table 41, Table 42 and Table M-3 of Appendix M, I estimated the average number of litres of fuel burned per tonne of salmon landed by each gear sector, for each of the four years in which costs and earnings surveys were conducted[178] as well as an average of the four years (Table 43).

*Table 43. Estimated Average Fuel Consumption, in litres and MJ, per Tonne of Salmon Landed by Seiners, Gillnetters and Trollers*

| Year | Blended Fuel Consumption per Tonne of Salmon Landed | | |
|---|---|---|---|
| | Seine Fleet (litres) | Gillnet Fleet (litres) | Troll Fleet (litres) |
| 1985 | 308 | 650 | 808 |
| 1988 | 317 | 981 | 868 |
| 1991 | 304 | 785 | 735 |
| 1994 | 513 | 986 | 935 |
| **Average:** | **361** | **850** | **836** |
| Diesel:Gasoline Use Ratio[a] | 95:5 | 62:38 | 93:7 |
| Energy Content of Fuel (MJ/l)[b] | 35.85 | 34.60 | 35.77 |
| Energy Content of Fuel (MJ) | **12,900** | **29,400** | **29,900** |

Notes: a. See text above for an explanation of the diesel fuel to gasoline use ratios for each of the gear sectors.
b. The average energy content of the fuel burned by each gear sector was estimated by taking a weighted average of 36.04 MJ/l (the energy content of diesel fuel) and 32.04 MJ/l (the energy content of gasoline) using the diesel to gasoline use ratios (fuel energy content data from Rose and Cooper 1977).

On average, purse sieners consume approximately 360 litres of fuel, gillnetters approximately 850 litres of fuel, and trollers approximately 840 litres of fuel per tonne of salmon landed (Table 43). In energetic terms, these fuel inputs equate to approximately 12,900 MJ, 29,400 MJ and 29,900 MJ per tonne of salmon landed by seiners, gillnetters and trollers respectively (Table 43).

[178] This was done by first dividing the estimated total expenditure on fuel while salmon fishing (from Table 41) by the average price of blended fuel (from Table 42) for each gear sector in each survey year. This yielded an estimate of the total number of litres of fuel consumed while salmon fishing by each sector in each of the four years. These values were then divided by the corresponding total tonnage of salmon landed as reported in Table M-3 of Appendix M.

The final step in this part of the analysis entailed converting the inputs per tonne of salmon landed by each gear sector into average inputs on a species-specific basis, and for all salmon combined. This was done using the average proportion that each gear sector contributes to an average tonne of chinook, coho, sockeye, pink, and chum salmon landed in British Columbia for the years 1985, '88, '91 and '94 (see Appendix M) as the weighting factor (Table 44)[179].

*Table 44. Average Fuel Consumption per Tonne of Chinook, Coho, Sockeye, Pink and Chum Salmon Landed in B.C.*

| Species of Salmon | Average Fuel Consumption per Tonne of Salmon Landed | |
|---|---|---|
| | litres | MJ |
| Chinook | 800 | 28,500 |
| Coho | 790 | 28,100 |
| Sockeye | 650 | 22,800 |
| Chum | 560 | 19,600 |
| Pink | 510 | 18,000 |
| Average of all salmon | 600 | 21,200 |

Although the fuel inputs per tonne of salmon landed are a combination of diesel fuel and gasoline, I simplified the estimation of the greenhouse gas emissions that result by assuming that the emissions intensity of the diesel/gasoline combination is 0.090 kg $CO_2$ equivalent/MJ of fuel burned.

## Quantifying the Direct Labour Inputs Associated with Harvesting a Tonne of Salmon

The income statements prepared by Gislason (1997) for the British Columbia salmon fleet provide estimates of the:

- average crew size,
- average number of weeks fished[180], and
- total number of licensed vessels,

[179] By way of example, the calculation of the energy input to an average tonne of chinook salmon landed would appear as follows: (12,900 MJ x 0.080) + (29,400 MJ x 0.116) + (29,900 MJ x 0.804) = 28,482 that I have rounded to 28,500.

[180] While the income statements prepared by Gislason (1997) for 1991 and 1994 provide estimates of the average number of weeks spent specifically fishing for salmon, the 1985 and 1988 income statements only provide estimates of the average total number of weeks spent fishing. Once again, I have attempted to "back out" an estimate of the average number of weeks spent salmon fishing by each gear sector in 1985 and 1988 by multiplying the salmon fishing income to total fishing income ratio, by the total number of weeks fished for each gear sector.

for each of the four sub-sets of the salmon fleet for 1985, '88, '91 and '94. By assuming five working days per week, and by re-allocating half of the labour inputs associated with the hybrid gillnet-troll fleet to the dedicated gillnet fleet and half to the dedicated troll fleet, I estimated the total labour input to the commercial fleets while salmon fishing for 1985, '88, '91, and '94 (Table 45).

*Table 45. Labour Inputs to Salmon Fishing by the B.C. Commercial Seine, Gillnet, and Troll Fleets, 1985, '88, '91, and '94*

| Year | Total Labour Inputs (person-days) | | |
|---|---|---|---|
| | Seine Fleet | Gillnet Fleet[a] | Troll Fleet[a] |
| 1985[b] | 162,788 | 208,712 | 234,851 |
| 1988[b] | 149,782 | 232,413 | 185,315 |
| 1991 | 140,029 | 205,435 | 227,641 |
| 1994 | 164,175 | 301,053 | 213,455 |

Source: Gislason 1997, Appendices A, C, and D

Notes: a. Labour inputs to the gillnet and troll fleets while salmon fishing each include 50% of the labour input to the hybrid gillnet-troll fleet while salmon fishing.
b. The estimates of labour inputs to salmon fishing in 1985 and 1988 were made by multiplying the total number of weeks spent fishing for each fleet segment by that fleet segment's salmon fishing income to total fishing income ratio.

Dividing the total labour input estimates (Table 45) by the corresponding total tonnage of salmon landed by each gear sector (Table M-3 in Appendix M), I generated estimates of the average labour inputs associated with landing a tonne of salmon by seiners, gillnetters and trollers (Table 46).

*Table 46. Labour Inputs per Tonne of Salmon Landed by the B.C. Commercial Seine, Gillnet, and Troll Fleets, 1985, '88, '91, and '94*

| Year | Labour Inputs (in person-days) per Tonne of Salmon Landed by the: | | |
|---|---|---|---|
| | Seine Fleet | Gillnet Fleet | Troll Fleet |
| 1985 | 2.8 | 8.3 | 9.9 |
| 1988 | 3.0 | 12.1 | 10.4 |
| 1991 | 3.3 | 10.6 | 9.6 |
| 1994 | 6.0 | 14.2 | 12.4 |
| **Average:** | **3.8** | **11.3** | **10.6** |

Once again, it was necessary to convert the gear-specific labour inputs per tonne of salmon landed into average species-specific inputs and for all salmon combined. As before, this was done using the average proportions that each gear sector contributes to an average tonne of chinook, coho, sockeye, pink, and chum salmon landed in British Columbia, for the years 1985, '88, '91 and '94 (determined in Appendix M), as the weighting factor (Table 47)[181].

[181] By way of example, the calculation of the labour input to an average tonne of sockeye salmon landed would appear as follows: (3.8 pers.-days x 0.407) + (11.3 pers.-days x 0.452) + (10.6 pers.-days x 0.141) = 8.1 person-days.

*Table 47. Labour Inputs per Tonne of Chinook, Coho, Sockeye, Chum and Pink Salmon Landed in B.C.*

| Species of Salmon | Average Labour Input per Tonne of Salmon Landed (person-days) |
|---|---|
| Chinook | 10.1 |
| Coho | 9.3 |
| Sockeye | 8.1 |
| Chum | 6.8 |
| Pink | 5.9 |
| Average of all salmon | 7.3 |

## Quantifying the Indirect Energy and Greenhouse Gas Emissions Associated with Providing the Fishing Gear "Consumed" per Tonne of Salmon Landed

In the process of fishing, it is inevitable that fishing gear is lost, damaged or worn beyond repair. In this section, I have quantified the average material inputs of fishing gear, in terms of steel, plastics, lead, etc., that are "consumed" in the process of salmon fishing, along with the associated embodied energy inputs and greenhouse gas emissions, per tonne of salmon landed.

The income statements prepared by Gislason (1997) provide estimates of the total amount of money spent on *all* fishing gear by each of the seine, gillnet, troll and hybrid gillnet-troll fleets. For these fleet sub-sets, I estimated the amount spent specifically on *salmon* fishing gear by multiplying the total fishing gear expenditures by the corresponding ratio of salmon fishing income to total fishing income. As was the case in the analyses of the inputs of fuel and labour, I re-allocated half of the gear expenditures made by the hybrid gillnet/troll vessels to the dedicated gillnet fleet and half to the dedicated troll fleet[182]. Finally, in order to facilitate the conversion of the expenditures on gear into corresponding physical quantities of material goods, I converted all of the monetary values into their 1998 dollar equivalents using the Canadian industrial product price index for miscellaneous manufactured chemical products for sporting, fishing and hunting equipment (Appendix N). Table 48 presents the resulting estimates of the total expenditures, expressed in 1998 dollars, made on salmon fishing gear by seiners, gillnetters and trollers in 1985, '88, '91 and '94.

[182] Once again, this re-allocation of the inputs to the hybrid gillnet-troll fleet is based on the assumption that 50% of this fleet's salmon catch is made while gillnetting and 50% is made when trolling.

*Table 48. Total Expenditures Made by Seiners, Gillnetters and Trollers in 1985, '88, '91, and '94 on Salmon Fishing Gear (expressed in 1998 dollars)*

| Year | Amount of Money Spent, in 1998$[a], on Salmon Fishing Gear by the: | | |
|---|---|---|---|
| | Seine Fleet | Gillnet Fleet[b] | Troll Fleet[b] |
| 1985[c] | $5,086,855 | $8,240,533 | $6,993,310 |
| 1988[c] | $4,626,619 | $8,229,086 | $6,166,876 |
| 1991[c] | $3,795,013 | $5,839,342 | $6,547,644 |
| 1994[c] | $5,313,916 | $6,925,391 | $5,471,616 |

Source: Gislason 1997, Appendices A, C and D.

Notes: a. All dollar values were converted into their 1998 dollar equivalents using the industrial product price index for miscellaneous manufactured chemical products for sporting, fishing and hunting equipment (see Appendix N).

b. The estimates of the expenditures on gear made by the gillnet and troll fleets each includes 50% of the gear expenditures made by the hybrid gillnet-troll fleet.

c. For all four years, estimates of the salmon fishing related gear expenditures were made by multiplying the total expenditures on gear for each fleet segment by that fleet segment's salmon fishing income to total fishing income ratio.

By dividing the total expenditures made on salmon fishing gear (Table 48) by the corresponding total tonnage of salmon landed by each gear sector for each of the four years (Appendix M), I estimated the average expenditures on fishing gear, expressed in 1998 dollars, per tonne of salmon landed by seiners, gillnetters and trollers (Table 49).

*Table 49. Average Expenditures on Salmon Fishing Gear per Tonne of Salmon Landed by Gear Type (expressed in 1998 dollars)*

| Year | Amount of Money Spent, in 1998$, on Salmon Fishing Gear per Tonne of Salmon Landed: | | |
|---|---|---|---|
| | Seine Fleet | Gillnet Fleet | Troll Fleet |
| 1985 | $87 | $327 | $295 |
| 1988 | $92 | $427 | $345 |
| 1991 | $89 | $301 | $276 |
| 1994 | $194 | $327 | $318 |
| **Average:** | **$115** | **$345** | **$309** |

On average, purse seiners spent $115, gillnetters $345, and trollers $309 (all expressed in 1998 dollars) on fishing gear per tonne of salmon landed (Table 49). The expenditures were converted into their corresponding quantities of material inputs using data provided by two companies.

The Canadian Fishing Company Limited, owners of one of the largest purse seine fleets in British Columbia, and fabricators of purse seine nets for their own vessels and for outside sale to other vessel owners, provided detailed data on the 1998 costs, and quantities of material and labour inputs

required to fabricate a standard 575 mesh deep by 220 fathom long "inside"[183] salmon seine net complete with two release bunts (Table 50).

*Table 50. Inputs to Fabricate a Standard Inside Salmon Seine Net*

| Inputs | Quantity of Inputs | Input Cost (in 1998 $) | Ratio of Input Cost to Total Cost of Net[a] |
|---|---|---|---|
| Plastic derived components | | | |
| - braided nylon and polyester salmon netting for bunts, pre-bunt, body and borders | 2,360 kg | $23,400 | |
| - netline | 205 kg | $3,150 | |
| - purselines | 250 kg | $3,575 | |
| - other ropes and twines | 240 kg | $3,400 | |
| - floats (plastic shelled, foam cored) | 340 kg | $7,200 | |
| Sub-total of all plastic inputs: | 3,395 kg | $33,525 | 0.65 |
| Lead in the form of leadcore leadline[b] | 1,545 kg | $11,050 | 0.18 |
| Steel in the form of miscell. hardware | 135 kg | $2,010 | 0.03 |
| Fabrication labour | 230 hours | $9,200 | 0.15 |
| | Total: | $62,985 | |

Source: Mr. Chris Cue, seine fleet operations manager, Canadian Fishing Company, pers. comm., September 8, 1998.

Notes: a. Values in this column represent the proportion of the total costs of a seine net that each of the major component categories (eg. plastics, lead, steel and labour) represent. For example, the ratio for plastic derived inputs is calculated by dividing $33,525 by $62,985.
b. Although leadline is a composite of a lead cord, encased in a sheath of nylon or polyester, for the purposes of this analysis, I have assumed that it is entirely composed of lead.

By assuming that the inputs associated with fabricating a complete standard seine net reflect the average inputs associated with the routine expenditures made on fishing gear by seiners, then, using Equation 2 below, and the data presented in Table 50, I estimated that approximately 6.2 kg of plastics, 2.8 kg of lead, 0.2 kg of steel, and 0.4 person-hours of labour are required to provide the fishing gear "consumed" per tonne of salmon landed by seiners.

$$(Q_i / C_i) \times (R_i \times GC_{seine}) \qquad \text{Equation 2.}$$

where: $Q_i$ is the physical quantity of input i, in kilograms or hours, to a standard seine net (as presented in the second column of Table 50),
$C_i$ is the cost of input i to a standard seine net (as presented in the third column of Table 50),

[183] One of the ways in which the catching capacity of purse seiners is regulated in British Columbia is through limitations on the size of their nets. Salmon seine nets used on waters that lie between Vancouver Island and the mainland (i.e. to the "inside" of Vancouver Island), including the Strait of Georgia and Johnstone Strait, can be a maximum of 220 fathoms long by 575 mesh deep. On the other hand, salmon seine nets used on waters to the west or "outside" of Vancouver Island can be up to 225 fathoms long by 875 mesh deep in size.

$R_i$ is the ratio of the cost of input i to total seine net cost (as presented in the forth column of Table 50), and
$GC_{seine}$ is the gear cost per tonne of salmon landed by seiners, which I have previously estimated to be $115.

For the analysis of the inputs to gillnet and troll fishing gear, I accessed information that reflects the routine pattern of gear purchases made by gillnet and troll fishermen. Pacific Net and Twine Limited, a major supplier of gillnet[184] and troll fishing gear in British Columbia, provided me with estimates of the following, based on their sales of gillnet and troll fishing gear separately:

- estimates of the proportions of their total sales of fishing gear that are comprised of various materials such as plastics, steel, and lead, and
- for each of the broad material types (e.g. plastics, steel, and lead) estimates of the average 1998 retail price per kilogram.

Table 51 summarises the data provided by Pacific Net and Twine Limited.

[184] Pacific Net and Twine supplies over 30% of the gillnet fishing gear used in British Columbia (Mr. Gary Nakashima, owner, Pacific Net and Twine, pers. comm. October 1998).

*Table 51. Breakdown of Commercial Gillnet and Troll Fishing Gear Sales Made by Pacific Net and Twine Ltd. in 1998*

| Material Inputs to Gillnet Fishing Gear | Proportion of Their Total Gillnet Gear Sales[a] | Estimated Average Retail Price per kg |
|---|---|---|
| All plastic derived components[b] | 98% | $60[c] |
| Lead[d] | 2% | $2 |
| **Material Inputs to Troll Fishing Gear** | **Proportion of Their Total Troll Gear Sales[a]** | **Estimated Average Retail Price per kg** |
| All plastic derived components[e] | 55% | $50[f] |
| All steel components[g] | 40% | $50[h] |
| Lead and miscellaneous[i] | 5% | $2 |

Source: Mr. Gary Nakashima, owner, Pacific Net and Twine Limited, pers. comm., October 20, 1998

Notes: a. The proportions of Pacific Net and Twine's total sales of gillnet and troll gear are estimated on a dollar value basis.
b. The plastic derived components of salmon gillnet fishing gear represent the gillnet mesh material itself, various nylon and polyester ropes and twines and plastic shelled, foam filled floats.
c. The various plastic derived inputs to gillnet gear range widely in their price per kilogram (from approximately $38/kg to over $200/kg). The average price of $60/kg represents Mr. Nakashima's estimate of the average price based on average sales of various items.
d. The lead used in gillnet gear is almost entirely represented by leadline.
e. Plastic derived inputs to troll fishing gear include a variety of lures, wet weather clothing, etc.
f. The average price of plastic derived inputs to troll fishing gear was estimated by Mr. Nakashima by taking a weighted average price of four plastic derived products that they sell.
g. Steel inputs to salmon troll fishing gear include steel cable, hooks, snaps, swivels, knives, etc.
h. The average price of steel components of troll fishing gear was estimated by Mr. Nakashima by taking the weighted average price of eight troll fishing related steel products that they sell.
i. Lead "cannon balls", used as weighs represent the majority of inputs to this category. However, other inputs include wooden lures.

Using Equation 3 below and the data presented in Tables 49 and 51, I estimated that per tonne of salmon landed, gillnetters use approximately 5.6 kg of plastics and 3.4 kg of lead while trollers use approximately 3.4 kg of plastics, 2.5 kg of steel and 7.7 kg of lead.

$$(1 / AP_i) \times (P_i \times GC) \qquad \text{Equation 3.}$$

where: $AP_i$ is the estimated average retail price of material input i, to either gillnet or troll fishing gear (from the third column of Table 51),
Pi is the proportion of total gillnet or troll gear sales that a material input i represents (from the second column of Table 51), and
GC is the estimated average expenditure on salmon fishing gear made by gillnetters ($345) or trollers ($309) per tonne of salmon landed.

The penultimate step in this part of the analysis entailed the conversion of the estimated material inputs to fishing gear, per tonne of salmon landed, by seiners, gillnetters and trollers, into corresponding embodied energy inputs, and greenhouse gas emissions (Table 52).

*Table 52. Estimates of Average Energy Inputs and Greenhouse Gas Emissions Associated with Providing the Fishing Gear Inputs to Seiners, Gillnetters and Trollers per Tonne of Salmon Landed*

| Gear Sector and Material Input | Material Input per tonne of salmon landed (kg) | Energy Intensity (MJ/kg)[a] | Energy Input per tonne of salmon landed (MJ) | GHG Emission Intensity (kg $CO_2$ eq/kg)[b] | GHG Emissions per tonne of salmon landed (kg $CO_2$ eq) |
|---|---|---|---|---|---|
| Seiner Inputs | | | | | |
| - plastics | 6.2 | 75 | 465 | 3.0 | 19 |
| - steel | 2.8 | 25 | 70 | 2.5 | 7 |
| - lead | 0.2 | 25 | 5 | 2.5 | 1 |
| **Totals:** | | | **540** | | **27** |
| Gillnet Inputs | | | | | |
| - plastics | 5.6 | 75 | 420 | 3.0 | 17 |
| - lead | 3.4 | 25 | 85 | 2.5 | 9 |
| **Totals:** | | | **505** | | **26** |
| Troll Inputs | | | | | |
| - plastics | 3.4 | 75 | 255 | 3.0 | 10 |
| - steel | 2.5 | 25 | 63 | 2.5 | 6 |
| - lead | 7.7 | 25 | 193 | 2.5 | 19 |
| **Totals:** | | | **511** | | **35** |

Notes: a. Energy intensities used in this research are outlined in Table 9.
b. Greenhouse gas emission intensities used in this research are outlined in Table 9.

As before, I converted the gear-related energy inputs and greenhouse gas emissions per tonne of salmon landed by each gear sector (Table 52), on a species-specific basis using the proportion that each gear sector contributes to a tonne of chinook, coho, sockeye, pink, and chum salmon landed in British Columbia as the weighting factor (Appendix M)[185]. The results of these calculations, for all five species of salmon considered separately and for all salmon combined appear in Table 53.

*Table 53. Estimated Energy Inputs and Greenhouse Gas Emissions to Provide the Fishing Gear Inputs per Tonne of Chinook, Coho, Sockeye, Pink and Chum Salmon Landed in B.C.*

| Species of Salmon | Energy Input to Provide Fishing Gear per Tonne of Salmon Landed (MJ) | Greenhouse Gas Emissions to Provide Fishing Gear per Tonne of Salmon Landed (kg $CO_2$ equiv.) |
|---|---|---|
| Chinook | 510 | 33 |
| Coho | 510 | 33 |
| Sockeye | 520 | 28 |
| Chum | 530 | 27 |
| Pink | 530 | 28 |
| Average of all salmon | 520 | 28 |

Note: All values rounded to two significant figures.

[185] By way of example, the calculation of the energy input to provide the fishing gear used to land an average tonne of pink salmon would appear as follows: (540 MJ x 0.70) + (505 MJ x 0.114) + (511 MJ x 0.186) = 531 MJ.

## Quantifying the Material, Labour and Energy Inputs to Build and Maintain Fishing Vessels per Tonne of Salmon Landed

I encountered several challenges when trying to estimate the inputs, per tonne of salmon landed, that go into building and maintaining the capital infrastructure of the fishing vessels themselves. The problems arose largely because:

- fishing vessels are compositionally complex,
- the British Columbia salmon fishing fleet is highly heterogeneous particularly with respect to vessel age[186], size, and primary hull material[187], and
- detailed information regarding the inputs required to construct salmon fishing vessels was only available for purse seiners and gillnetters.

In addition to the differences between salmon fishing vessels that result from their use of different fishing gears, within each gear specific sub-set of the fleet, there is tremendous diversity. For example, the physical size of salmon fishing vessels can range widely. This is evident using vessel length as an indicator of vessel size (Figure 11)[188].

[186] As of 1998, licensed salmon fishing vessels in British Columbia ranged in age from 1 to over 90 years old (from data provided by Mr. Brian Moore, Program Planning and Economics Branch, Fisheries and Oceans Canada, May, 1998)

[187] By primary hull material, I am referring to the main material from which the vessel's hull, holds and decks are fabricated.

[188] While there are a wide range of physical characteristics that can be used to describe the size and/or power of a fishing vessel, vessel length is one of the few characteristics that are carefully measured and recorded by Fisheries and Oceans Canada (pers. comm, Mr. Brian Moore, Fisheries and Oceans Canada, May, 1998). This is because vessel length, along with the net tonnage, is used as the "replacement rule" when new vessels are built to replace vessels retiring from the fleet (Technical Advisory Committee on Replacement Rules 1993).

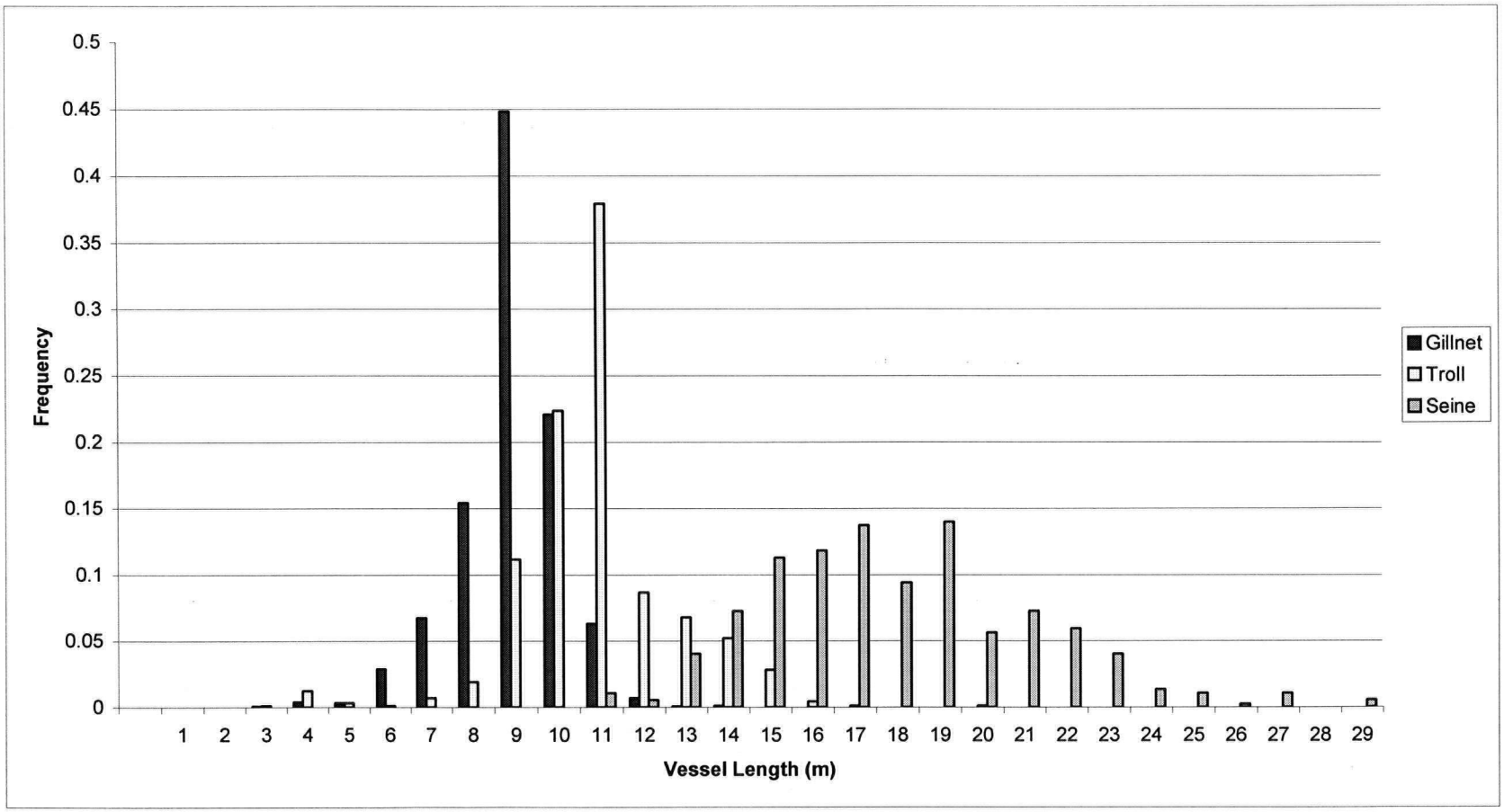


*Figure 11. Length Distributions of British Columbia's Commercial Salmon Gillnet, Troll and Seine Vessels in 1998*

Source: Data from Mr. Brian Moore, Program Planning and Economics Branch, Fisheries and Oceans Canada, May, 1998. Data represents 1,734 gillnet vessels, 886 troll vessels and 372 purse seine vessels.

Purse seiners, which tend to be the largest, highest volume vessels in the salmon fleet, range in length from approximately 12.5 m to 31 m and average 19.4 m. Next in size are the trollers which range in length from about 5 m to 19 m with an average of 12.4 m. And finally gillnetters, which are, on average, the smallest salmon fishing boats, range in length from 4 m to 15 m and average 10.4 m (Figure 11)[189].

In addition to the fleet's heterogeneity with respect to size, a variety of materials have been used to build salmon fishing boats over time. For example, as of 1998, the British Columbia salmon fleet included vessels constructed using at least four different primary hull materials: wood, steel, aluminium, and fibreglass[190]. For those vessels for which primary hull material information is available[191], Table 54 presents the proportions of each sub-set of the British Columbia salmon fleet that are built of wood, steel, fibreglass and aluminium.

*Table 54. Proportion of Salmon Fishing Vessels Constructed Primarily from Wood, Steel, Fibreglass and Aluminium*

| Vessel Type | Primary Hull Material | | | |
|---|---|---|---|---|
| | Wood | Steel | Fibreglass | Aluminium |
| Purse seiners[a] | 32% | 29% | 9% | 30% |
| Gillnetters[b] | 16% | 0% | 62% | 22% |
| Trollers[c] | 62% | 4% | 33% | 1% |

Source: Data file provided by Mr. Brian Moore, Program Planning and Economics Branch, Fisheries and Oceans Canada, May, 1998.

Notes: a. Data represents 258 of the 372 licensed salmon seine vessels in 1998
b. Data represents 1,320 of the 1,734 licensed salmon gillnet vessels in 1998
c. Data represents 699 of the 886 licensed salmon troll vessels in 1998

This wide range of primary hull material use reflects changes over time in materials availability, fabrication technology, and the relative cost of various factors of production. Figures 12, 13, and 14 illustrate the changes in primary hull material use over time along with the age distribution of vessels in each of the three main sub-sets of the salmon fleet, the seiners, gillnetters and trollers.

[189] From an electronic data file of the fleet's physical characteristics provided to me by Mr. Brian Moore of the Program Planning and Economics Branch of Fisheries and Oceans Canada, May, 1998.

[190] Ibid.

[191] The database, maintained by Fisheries and Oceans Canada, on the physical characteristics of the licensed salmon fishing vessels is incomplete with respect to the primary hull material used in some vessels.

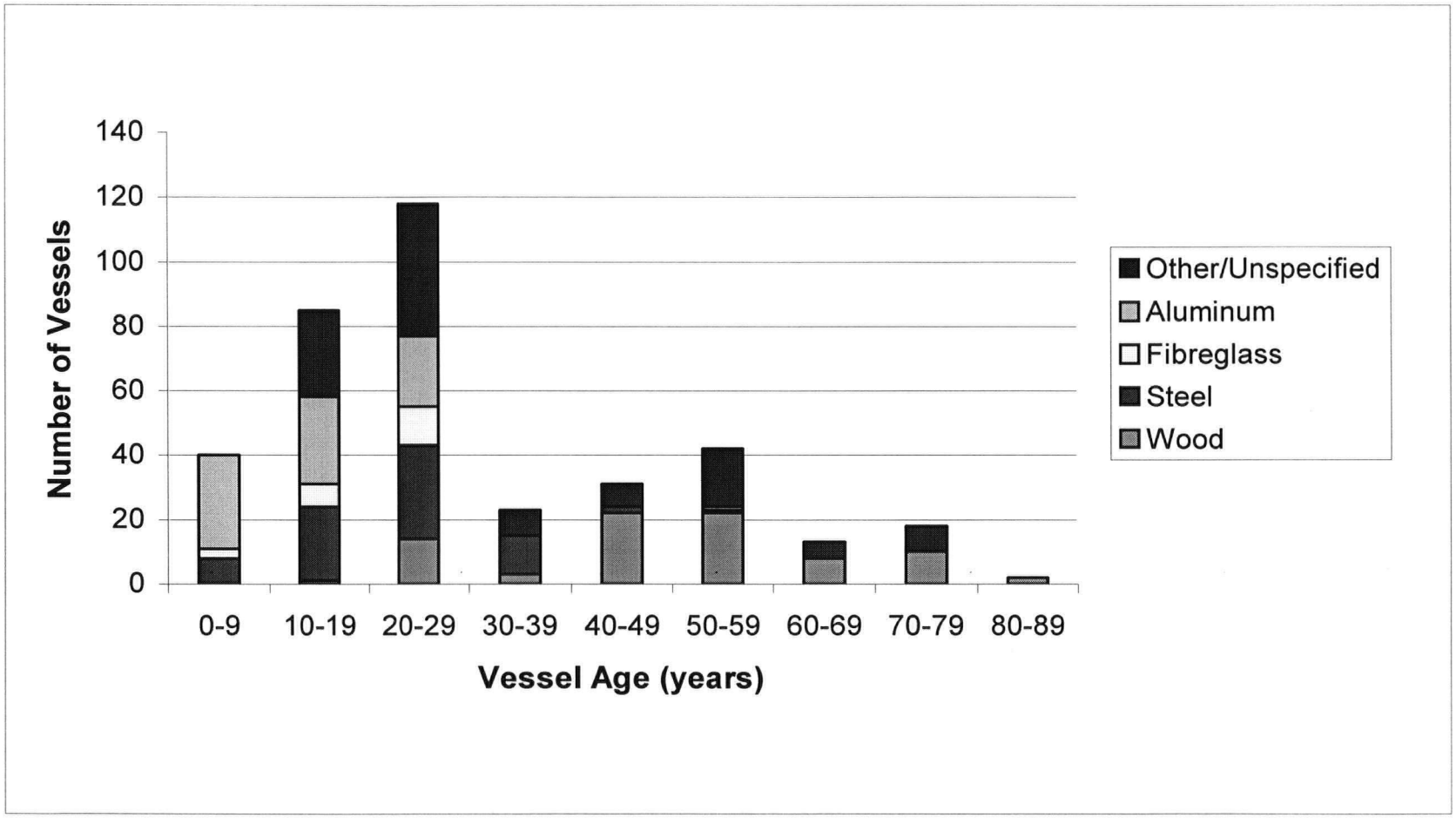


*Figure 12. Age Distribution and Primary Hull Materials Used in the Construction of Salmon Purse Seiners in British Columbia*

Source: Data from Mr. Brian Moore, Program Planning and Economics Branch, Fisheries and Oceans Canada, May, 1998.
Data represents 372 vessels.

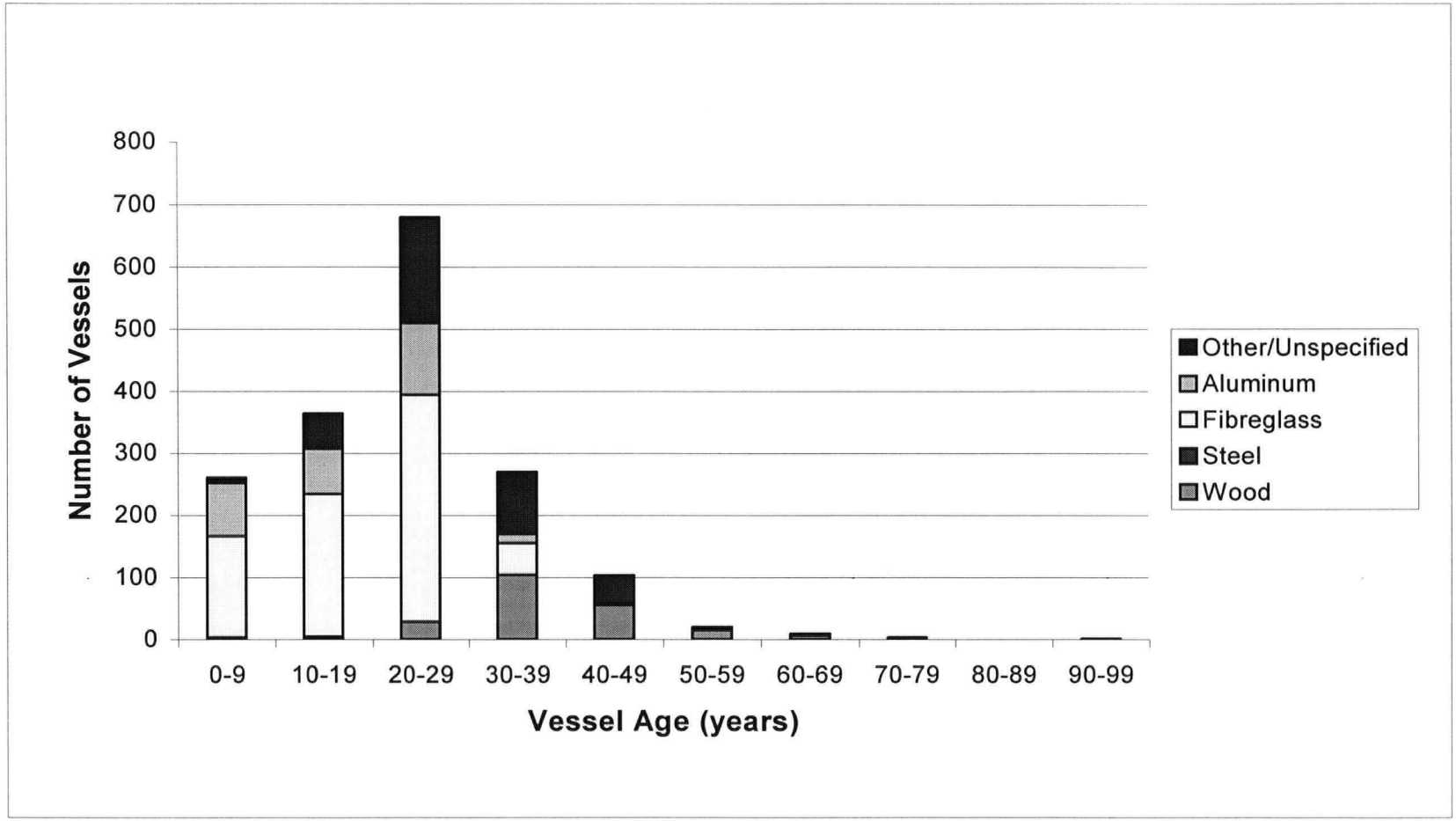


*Figure 13. Age Distribution and Primary Hull Materials Used in the Construction of Salmon Gillnetters in British Columbia*

Source: Data from Mr. Brian Moore, Program Planning and Economics Branch, Fisheries and Oceans Canada, May, 1998.
Data represents 1,734 vessels.

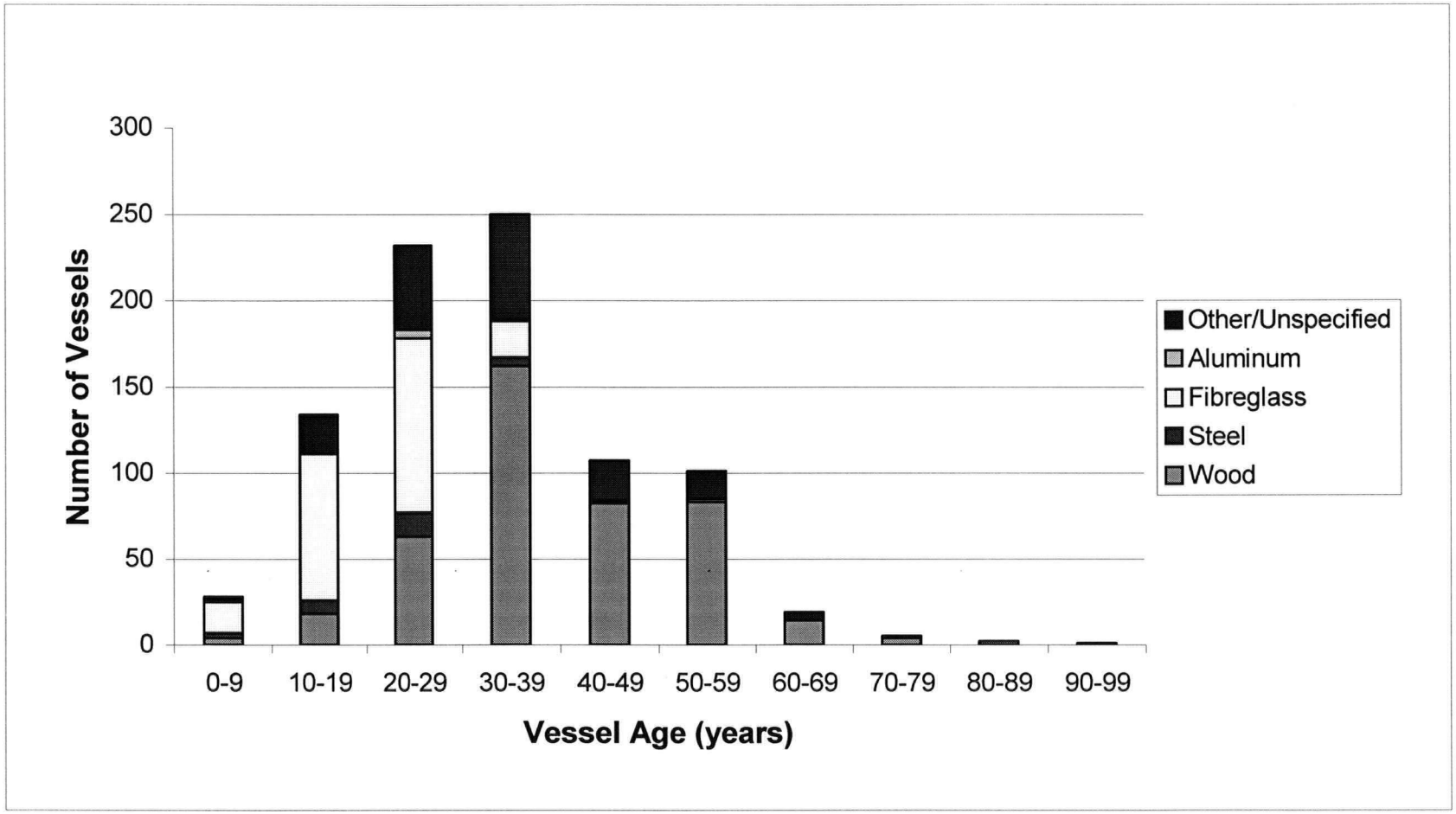


*Figure 14. Age Distribution and Primary Hull Material Used in the Construction of Salmon Trollers*

Source: Data from Mr. Brian Moore, Program Planning and Economics Branch, Fisheries and Oceans Canada, May, 1998. Data represents 886 vessels.

Given the complexity and diversity exhibited by the vessels that comprise the salmon fleet, it was necessary to simplify the analysis of the inputs associated with building and maintaining the fishing vessels themselves. The approach that I adopted was to model the major inputs required to build and maintain vessels typical of those that have been built over the last 20 years, for each of the three sub-sets of the fleet. Unfortunately, I was only able to obtain information regarding the inputs associated with building a typical:

- an 18 m long aluminium hulled seiner[192],
- a 10 m long fibreglass hulled gillnetter[193], and
- a 10 m long aluminium hulled gillnetter[194].

No data were available regarding the inputs associated with building a troll fishing vessel[195].

## *Quantifying the Direct Inputs to Build and Maintain Salmon Gillnet and Seine Vessels per Tonne of Salmon Landed*

Five analytical steps were involved in estimating the material, labour and energy inputs, per tonne of salmon landed, associated with building and maintaining the vessels listed above. Briefly, these steps were:

1. estimate the major material, labour and energy inputs required to build a complete vessel,
2. calculate the vessel fabrication inputs required on an annual basis, using estimates of the expected functional life of the various components or inputs,
3. multiply the vessel fabrication inputs required on an annual basis by an appropriate repair and maintenance factor to account for the material inputs associated with supplying

[192] Approximately half of the licensed British Columbia salmon seine vessels built in the last 20 years have aluminum hulls. The average length of these boats is approximately 18.1 m (from the data file provided by Mr. Brian Moore, Program Planning and Economics Branch, Fisheries and Oceans Canada).

[193] Approximately 70% of the licensed British Columbia salmon gillnet vessels built in the last 20 years have fibreglass hulls. The average length of these boats is approximately 10 m (from the data file provided by Mr. Brian Moore, Program Planning and Economics Branch, Fisheries and Oceans Canada).

[194] Approximately 28% of the licensed British Columbia salmon gillnet vessels built in the last 20 years have aluminium hulls. The average length of these boats is approximately 10 m (from the data file provided by Mr. Brian Moore, Program Planning and Economics Branch, Fisheries and Oceans Canada).

[195] I believe that part of the problem that I faced in trying to find data on the inputs required to build a troll fishing vessel is that relatively few have been built in British Columbia over the last decade or so. For example, of the 886 licensed salmon troll vessels in 1998, only 28 were under ten years old.

replacement parts and the labour and energy inputs required to repair and maintain the vessel's components,

4. determine the proportion of the total annual material, labour and energy inputs that are attributable specifically to salmon fishing, using the ratio of salmon fishing income to total vessel income for each vessel type[196], and

5. determine the inputs per tonne of salmon landed using the average annual tonnage of salmon landed by the specific types of vessels.

### The Direct Inputs to Build an 18 m Aluminium-Hulled Seiner, a 10 m Fibreglass-Hulled Gillnetter and a 10 m Aluminium-Hulled Gillnetter

Information on the material composition and fabrication labour and energy inputs required to build a typical 18 m long aluminium hulled purse seiner was drawn from two sources. Mr. Jim Walker[197], who was employed for 18 years as the manager and estimator for Shore Boats Limited[198] (shortened hereafter to Shore Boats), provided me with estimates of:

- the amount of aluminium required to fabricate a bare[199] 18 m purse seiner,
- the electricity required to weld a bare 18 m purse seiner, and
- the total amount of labour required to build a complete 18 m purse seiner[200].

This information was combined with data provided by the Canadian Fishing Company Limited (shortened hereafter to their trade name Canfisco)[201]. Using their fleet of working aluminium hulled purse seiners as a model, Canfisco provided estimates of the total mass of aluminium, steel and other components combined that are represented in a typical complete 18 m seiner including all mechanical

[196] This step was necessary because a typical salmon fishing boat is used for other activities besides salmon fishing.
[197] Mr. Walker is currently the manager of Alberni Engineering.
[198] Shore Boats was one of British Columbia's largest aluminum boat yards. While they built a wide range of vessels, aluminum seine and gillnet boats for both the British Columbia and Alaskan markets, were a large portion of their business.
[199] I am using the term "bare" to describe the basic shell of a boat that consists of a hull, decks, holds and cabin structure.
[200] This includes the labour required to not only build the bare boat but to also install the mechanical, electrical and hydraulic systems and to paint the finished boat.
[201] Up until 1996, Canfisco owned and operated approximately 30 salmon seiners. As a result of the fleet rationalization initiatives of the Department of Fisheries and Oceans, in 1996 their seine fleet was reduced to approximately 15 vessels (Mr. Chris Cue, seine fleet manager, Canadian Fishing Company, pers. comm. 1988).

equipment[202] and fixed fishing equipment[203]. The information provided by Mr. Walker and by Canfisco appears in Appendix O.

Detailed information on the inputs required to build a typical 10 m long fibreglass hulled gillnetter, complete with all mechanical systems, fixed fishing equipment, etc. was provided by Mr. Bob Pearson of Pearson Marine and Industrial Limited[204] (shortened hereafter to Pearson Marine). The information provided by Mr. Pearson appears in Appendix O.

Information on the material, labour and energy inputs required to build a typical 10 m long aluminium-hulled gillnetter, complete with all mechanical systems, fixed fishing gear etc., was drawn from two sources. Mr. Jim Walker, ex-manager of Shore Boats, provided an estimate of:

- the amount of aluminium required to fabricate the bare boat[205],
- the electricity required to weld the boat, and
- the total amount of labour required to build the complete boat[206].

This information was combined with data from Mr. Bob Pearson of Pearson Marine on the inputs required to fully rig out a "bare" gillnetter including all mechanical system inputs and fixed fishing equipment. The information provided by Messrs. Walker and Pearson appear in Appendix O.

## The Functional Life of Fishing Vessels and Their Components

Few prior biophysical analyses of fisheries report the specific functional life of fishing vessels and their component parts. As part of her process analysis of the energy inputs to build a tuna purse seiner, Rawitscher (1978) essentially adopts a financial accounting convention and "depreciates" the energy inputs to build the vessel over a 20-year period (Rawitscher 1978, Table A.1, p. 70). As part of their energy analysis of a hypothetical Swedish salmon ranching operation, Folke and Aneer (1988) assume that the energy inputs required to build the "small boat" necessary to harvest returning salmon would be "written off" over a ten-year period while its motor would be written off in five

[202] In addition to the main engine and transmission, the mechanical systems on a typical seiner include an auxiliary engine that is used to power the fishing equipment related hydraulic systems (personal communication, Mr. Jim Walker, Sept. 1998).

[203] Fixed fishing equipment on a typical purse seiner includes its mast and boom, and the net drum.

[204] Over the last decade, Mr. Pearson has built 56 fibreglass gillnetters.

[205] Once again, I am using the term "bare" to describe the basic shell of a boat that consists of a hull, decks, holds and cabin structure.

years (Folke and Aneer 1988, Table 6, p. 44). Rochereau (1976), however, drawing on data from the New England trawl fleet, arrived at very specific estimates of the life expectancies of the components that comprise a typical steel-hulled trawler (Table 55).

*Table 55. Life Expectancies of Trawl Fishing Vessel Components*

| Component | Life Expectancy (years) |
|---|---|
| Hull and structures | 19.1 |
| Main propulsion machinery | 9 |
| Auxiliary machinery | 6.5 |
| Fishing deck equipment | 9 |
| Outfitting and hull engineering | 11 |

Source: From Rochereau 1976, Table 2.4, p. 94.

In this analysis, I had information from which I could only estimate the average functional working life of the basic bare boat components of the vessels that make up the British Columbia salmon fleet. This was possible by assuming that the average age of the vessels currently in the fleet provides a minimum functional working life of the vessel's bare boat components. As the current average age of all the vessels in the British Columbia salmon fleet is approximately 27 years[207], I have assumed that a reasonable minimum average working life for the bare boat components is 30 years. As a result, all of the material, labour and energy inputs associated with building the bare boats themselves, as outlined in Appendix O, is spread over 30 years.

Recognising that, in general, the bare boat components last much longer than do a vessel's mechanical systems and fishing equipment[208], I have assumed that the average working life for all the other components of a salmon fishing vessel is 10 years. This generally approximates the findings of Rochereau (1976) as outlined in Table 55.

## Inputs to Repair and Maintain the Vessel's Components

I was unable to identify any previous analyses that provided estimates of the amounts of material, labour and energy required to repair and maintain fishing vessels, or their sub-components, over their functional working life. However, energy analyses of agricultural systems typically add between 33%

[206] This includes the labour required to not only build the bare boat but to also install the mechanical, electrical and hydraulic systems and to paint the finished boat.

[207] From data provided by Mr. Brian Moore, Program Planning and Economics Branch, Fisheries and Oceans Canada

[208] For example, Mr. Chris Cue, the seine operations manager for the Canadian Fishing Company Limited, indicates that they need to typically rebuild or replace their vessel's engines every 7,000 to 12,000 running hours.

and 66% of the original inputs required to build a piece of mechanical equipment[209] to account for the repairs and maintenance inputs necessary over its functional life (Pimentel 1980, Börjesson 1996).

In this analysis, for the bare boat components of the fishing vessels, in effect the non-moving or "passive" parts of a boat, I have assumed that an additional 25% of the initial material, labour and energy inputs that were required to build the boat are required to provide spare parts and to effect repairs and maintenance[210]. However, for the more "active" components of a fishing vessel, such as the mechanical systems and the fishing equipment, systems that are in many ways similar to the mechanical equipment used in agriculture, I have applied a repair and maintenance factor of 50%.

Combining the data on the material, labour and energy inputs required to build salmon fishing vessels (Appendix O) with the estimates of the average functional life of the major components and the repair and maintenance factors outlined above, I estimated total inputs required, on an annual basis, to build and maintain salmon fishing vessels (Table 56).

*Table 56. Estimated Direct Annual Material, Labour and Energy Inputs to Build and Maintain Typical Salmon Seine and Gillnet Vessels*

| Inputs | 18 m Aluminium Hulled Seiner | 10 m Fibreglass Hulled Gillnetter | 10 m Aluminium Hulled Gillnetter |
|---|---|---|---|
| Aluminum (kg) | 1,725 | 77 | 166 |
| Steel and/or iron (kg) | 1,380 | 306 | 285 |
| Lead (kg) | | 10 | 10 |
| Mixed metals and other materials (kg) | 180 | 59 | 59 |
| Glass (kg) | | 68 | 4 |
| Fibreglass resin (kg) | | 50 | |
| Wood ($m^3$) | | 0.21 | |
| Electricity (MJ) | 54,000 | | 13,500 |
| Labour (person-days) | 52 | 16 | 16 |

See Appendix O and the text above for details.

## Estimating the Direct Inputs per Tonne of Salmon Landed

As salmon fishing boats engage in other activities besides salmon fishing it was necessary to determine what proportion of the total annual inputs (from Table 56) are attributable to salmon fishing specifically. I did this by calculating an overall average salmon fishing income to total income ratio for each of the sub-sets of the salmon fleet using the income statements prepared by

[209] For example, tractors, combines, trucks etc.

[210] Note, this is the same repair and maintenance factor as I used in the analysis above of the inputs to build and maintain the saltwater grow-out site infrastructure.

Gislason (1997) for the years 1985, '88, '91, and '94[211]. Using this approach, approximately 66% of the inputs to build and maintain a purse seine boat are attributable to salmon fishing while approximately 92% of the inputs to build and maintain a gillnet boat are attributable to salmon fishing.

Finally, in order to estimate the direct material, labour and energy inputs associated with building and maintaining the fishing vessels, *per tonne of salmon landed*, it was necessary to calculate the average tonnage of salmon landed annually by each licensed seiner and gillnetter over say a ten-year period (Table 57).

*Table 57. Average Salmon Catch per Vessel for Gillnetters and Seiners in British Columbia from 1985 to 1994*

| | Total rnd wgt tonnes of all salmon taken by[a] | | Number of Licensed Vessels[b] | | Average Landings per vessel (t) | |
|---|---|---|---|---|---|---|
| Year | Gillnet | Seine | Gillnet | Seine | Gillnet | Seine |
| 1985 | 25,219 | 58,676 | 1,876 | 536 | 13.4 | 109.5 |
| 1986 | 26,130 | 53,156 | 1,988 | 526 | 13.1 | 101.1 |
| 1987 | 16,026 | 29,465 | 2,052 | 514 | 7.8 | 57.3 |
| 1988 | 19,281 | 50,401 | 2,151 | 522 | 9.0 | 96.6 |
| 1989 | 20,616 | 42,936 | 2,298 | 535 | 9.0 | 80.3 |
| 1990 | 23,257 | 47,338 | 2,219 | 534 | 10.5 | 88.6 |
| 1991 | 19,410 | 42,543 | 2,068 | 527 | 9.4 | 80.7 |
| 1992 | 23,183 | 28,641 | 2,106 | 513 | 11.0 | 55.8 |
| 1993 | 28,549 | 38,566 | 2,265 | 520 | 12.6 | 74.2 |
| 1994 | 21,178 | 27,426 | 2,208 | 508 | 9.6 | 54.0 |
| | | | **Ten Year Average:** | | **10.54** | **79.80** |

Source Notes: a. See Appendix M for sources.
b. From Gislason 1997, Exhibit A-1.

On average, between 1985 and 1994, licensed gillnetters in British Columbia landed approximately 10.5 round tonnes of salmon annually while purse seiners landed approximately 79.8 round tonnes of salmon annually (Table 57).

By first multiplying the total annual material, labour and energy inputs per vessel (Table 56) by the average salmon fishing income to total income ratios described above, and then dividing the result by the average annual tonnage of salmon landed per vessel (Table 57), I estimated the total direct inputs per tonne of salmon landed by a typical aluminium-hulled seiner and by typical fibreglass- and aluminium-hulled gillnetters (Table 58).

[211] Once again, these are the four years in which Costs and Earnings surveys of the salmon fleet have been conducted by Fisheries and Oceans Canada.

*Table 58. Estimated Direct Material, Labour and Energy Inputs per Tonne of Salmon Landed Required to Build and Maintain Typical Salmon Seine and Gillnet Vessels*

| Inputs | 18 m Aluminium Hulled Seiner | 10 m Fibreglass Hulled Gillnetter | 10 m Aluminium Hulled Gillnetter |
|---|---|---|---|
| Aluminium (kg) | 14.3 | 6.7 | 14.5 |
| Steel and/or iron (kg) | 11.4 | 26.8 | 25.0 |
| Lead (kg) | | 0.88 | 0.88 |
| Mixed metals and other materials (kg) | 1.49 | 5.1 | 5.1 |
| Glass (kg) | | 6.0 | 0.37 |
| Fibreglass resin (kg) | | 4.4 | |
| Wood ($m^3$) | | 0.018 | |
| Electricity (MJ) | 447 | | 1,183 |
| Labour (person-days) | 0.43 | 1.4 | 1.4 |

## Converting the Material and Electricity Inputs to Fishing Vessels into Indirect Energy Inputs and Greenhouse Gas Emissions per tonne of Salmon Landed

In order to incorporate the inorganic material inputs associated with building and maintaining fishing vessels into the ecological footprint and energy analyses, inputs were converted into their embodied energy and greenhouse gas emission equivalents using the energy and greenhouse gas emission intensity values outlined in Table 9 (Table 59).

*Table 59. Embodied Energy Inputs and Greenhouse Gas Emissions Associated with the Material and Electricity Required to Build and Maintain Fishing Vessels per Tonne of Salmon Landed*

| Vessel Type and Input | Input per tonne of salmon landed (kg or MJ)[a] | Energy Intensity (MJ/kg)[b] | Embodied Energy per tonne of salmon landed (MJ) | GHG Emission Intensity (kg $CO_2$ eq/kg or MJ)[c] | GHG Emissions per tonne of salmon landed (kg $CO_2$ eq) |
|---|---|---|---|---|---|
| **Aluminium Seiner** | | | | | |
| - aluminium | 14.3 | 140 | 2,002 | 8 | 114 |
| - steel | 11.4 | 25 | 285 | 2.5 | 29 |
| - mixed materials[d] | 1.49 | 25 | 37 | 2.5 | 4 |
| - electricity | 447 | | 1,276[e] | 0.0267 | 12 |
| **Totals:** | | | **3,600** | | **159** |
| **Fibreglass Gillnetter** | | | | | |
| - aluminium | 6.7 | 140 | 938 | 8 | 54 |
| - steel | 26.8 | 25 | 670 | 2.5 | 67 |
| - lead | 0.88 | 25 | 22 | 2.5 | 2 |
| - mixed metals[d] | 5.1 | 25 | 128 | 2.5 | 13 |
| - glass | 6.0 | 10 | 60 | 1 | 6 |
| - plastics (fibreglass resin) | 4.4 | 75 | 330 | 3 | 13 |
| **Totals:** | | | **2,148** | | **155** |
| **Aluminum Gillnetter** | | | | | |
| - aluminum | 14.5 | 140 | 2,030 | 8 | 116 |
| - steel | 25.0 | 25 | 625 | 2.5 | 63 |
| - lead | 0.88 | 25 | 22 | 2.5 | 2 |
| - mixed metals[d] | 5.1 | 25 | 128 | 2.5 | 13 |
| - glass | 0.37 | 10 | 4 | 1 | 0 |
| - electricity | 1,183 | | 3,380[e] | 0.0267 | 32 |
| **Totals:** | | | **6,189** | | **226** |

Notes: a. Quantities of material and electricity inputs from Table 58.
b. Energy intensities from Table 9.
c. Greenhouse gas emission intensities from Table 9.
d. I have assumed that the mixed materials and mixed metals inputs have an energy intensity of 25 MJ/kg and a greenhouse gas emission intensity of 2.5 kg $CO_2$ equivalent/kg.
e. For both of the aluminium hulled vessels, in order to address the energy quality problem, I have divided the direct electricity inputs from the second column by 0.35 to yield an estimate of the equivalent quantity of fossil fuel energy required.

Approximately 0.43 days of labour and 3,600 MJ of fossil fuel equivalent energy are required, per tonne of salmon landed by purse seiners, to build and maintain the vessels themselves (Tables 58 and

59). The greenhouse gas emissions amount to 159 kg of $CO_2$ equivalent per tonne of salmon landed (Tables 58 and 59).

Averaging the inputs associated with building and maintaining the two types of gillnet vessels, I estimate that 1.4 days of labour and approximately 4,165 MJ of fossil fuel equivalent energy are required per tonne of salmon landed. Similarly, the average greenhouse gas emissions amount to about 190 kg of $CO_2$ equivalent per tonne of salmon landed.

As there were no data upon which I could directly estimate the inputs associated with building and maintaining a typical troll fishing vessel, I assumed that the energy and labour inputs and greenhouse gas emissions fall between those of gillnet and purse seine vessels. Therefore, I assume that 1 day of labour and 3,900 MJ of energy are required to build and maintain troll vessels and 175 kg of $CO_2$ equivalent are released per tonne of salmon landed.

The final step in this part of the analysis entailed estimating the total energy and labour inputs, and greenhouse gas emissions per tonne of each species of salmon landed and for all salmon combined. As before, I did this by averaging the inputs and emissions on a gear specific basis using the proportion that each gear sector contributes to an average tonne of each species of salmon landed as the weighting factor (Table 60)[212].

*Table 60. Estimated Total Energy, and Labour Inputs and Greenhouse Gas Emissions Associated with Building and Maintaining Fishing Vessels per Tonne of Chinook, Coho, Sockeye, Pink and Chum Salmon Landed in B.C.*

| Species of Salmon | Energy Inputs to Build and Maintain Fishing Vessels per Tonne of Salmon Landed (MJ) | Labour Inputs to Build and Maintain Fishing Vessels per Tonne of Salmon Landed (days) | GHG Emissions to Build and Maintain Fishing Vessels per Tonne of Salmon Landed (kg $CO_2$ equiv) |
|---|---|---|---|
| Chinook | 3,910 | 1.0 | 175 |
| Coho | 3,890 | 1.0 | 175 |
| Sockeye | 3,900 | 0.9 | 175 |
| Chum | 3,820 | 0.8 | 170 |
| Pink | 3,720 | 0.6 | 165 |
| Average all salmon | 3,815 | 0.8 | 170 |

[212] By way of example, the calculation of the total energy input to build and maintain the fishing vessels used to land an average tonne of coho salmon would appear as follows: (2,960 MJ x 0.079) + (2,770 MJ x 0.103) + (2,870 MJ x 0.818) = 2,867 MJ which I have rounded to 2,870 MJ.

# Chapter 6: Results

In this chapter I present the results of the ecological footprint and energy analysis described in Chapters 4 and 5. This includes:

- the ecological footprint and total industrial energy inputs associated with producing an average tonne of intensively cultured Atlantic and chinook salmon, which includes estimates of:
  - the total edible and protein energy return on industrial energy investment ratios for intensively cultured Atlantic and chinook salmon,
  - the total feed energy conversion efficiency of intensively cultured Atlantic and chinook salmon,
- the ecological footprint and total industrial energy inputs associated with producing and harvesting an average tonne of commercially caught chinook, coho, sockeye, chum and pink salmon that includes estimates of:
  - the total edible and protein energy return on industrial energy investment ratios for commercially caught chinook, coho, sockeye, chum and pink salmon, and
- the ecological footprint and total industrial energy inputs associated with landing an average tonne of salmon using gillnet, troll and purse seine fishing gear.

Following the presentation of these results, I also explore how sensitive the major results are to changes in some of the input parameters and methodological assumptions.

## Ecological Footprint and Energy Analyses of Intensive Salmon Culture in British Columbia

Tables 61 and 62 present the results of the ecological footprint and energy analyses of intensive Atlantic and chinook salmon culture in British Columbia.

*Table 61. Summary of All Feed, Labour and Industrial Energy Inputs, Greenhouse Gas Emissions and Associated Ecosystem Support Required to Produce an Average Tonne (Round Weight) of Intensively Cultured Atlantic Salmon*

| Activity | "Dry" Feed (kg) | Labour (days) | Industrial Energy Inputs (MJ) and GHG Emissions (kg $CO_2$ equiv.) | | | | | | Ecosystem Support (ha) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Gasoline | Diesel | Nat. Gas | Propane | Elect. | Total[a] | Marine | Terrestrial |
| Direct Operating Inputs to Smolt Production[b] | 34 | 0.67 | 69 | 176 | 0 | 251 | 679 | 2,436 | | |
| Direct Operating Inputs to Marine Grow-out Operations[b] | 1,736 | 3.3 | 1,171 | 1,037 | 0 | 239 | 0 | 2,447 | | |
| Direct Operating Inputs to Adult Salmon Transport[b] | 0 | 0.51 | 0 | 3,119 | 0 | 0 | 0 | 3,119 | | |
| Operating Inputs Sub-Totals: | **1,770** | 4.5 | 1,240 | 4,332 | 0 | 490 | 679 | 8,002 | | |
| Inputs & Ecosystem Support to Provide 1,770 kg Feed | | 0.09[c] | 0 | 51,999[d] | 20,702[d] | 0 | 4,335[d] | 85,087 | 9.9[e] | 1.04[f] |
| Total Operating Labour and Industrial Energy Inputs | | **4.6** | 1,240 | 56,331 | 20,702 | 490 | 5,014 | 93,089 | | |
| Embodied Energy to Provide Grow-Out Site Infrastructure | | | | | | | | 869[g] | | |
| Total Industrial Energy Inputs | | | | | | | | **93,958** | | |
| GHG Emissions from Direct and Indirect Energy Inputs[h] | | | 115 | 4,951 | 1,199 | 28 | 134 | 6,427[i] | | |
| GHG Emissions to Provide Grow-Out Site Infrastructure | | | | | | | | 43[k] | | |
| Total GHG Emissions | | | | | | | | **6,470** | | |
| Ecosystem Support to Sequester the equiv. of 6.470 t $CO_2$ | | | | | | | | | 0 | 1.77[l] |
| Ecosystem Support to Sustain 4.6 days of Labour | | | | | | | | | 0.012[m] | 0.030[n] |
| Total Ecosystem Support | | | | | | | | | **9.91** | **2.84** |

Notes: a. All industrial energy values in this column are expressed as fossil fuel equivalents. Electricity inputs are converted to fossil fuel equivalents by assuming a 35% conversion efficiency.
b. From Table 14
c. Calculated by multiplying 1.77 t of feed by 0.05 person-days, the direct labour inputs required to manufacture a tonne of salmon feed (see Table 17).
d. Calculated by multiplying 1.77 t of feed by the energy inputs of diesel fuel, natural gas and electricity, from Table 34, required to produce a tonne of salmon feed.

e. Calculated by multiplying 1.77 t of feed by 5.6 ha, the area of marine ecosystem that is required to produce the marine organisms used to supply the fish meal components of a tonne of salmon feed.
f. Calculated by multiplying 1.77 t of feed by 0.59 ha, the total area of agricultural ecosystem that is required to sustain the provision of direct crop inputs and indirect fodder inputs per tonne of salmon feed.
g. From Table 36.
h. Calculated using the following greenhouse gas emission intensity values: 0.0926 kg $CO_2$ eq./MJ of gasoline, 0.0879 kg $CO_2$ eq./MJ diesel fuel, 0.0579 kg $CO_2$ eq./MJ natural gas or propane, and 0.0267 kg $CO_2$ eq./MJ of electricity.
i. A straight sum of all energy related greenhouse gas emissions.
k. From Table 36.
l. Calculated by dividing 6.470 t of $CO_2$ by 3.6644 t $CO_2$/ha, the estimated average British Columbia forest ecosystem $CO_2$ assimilation rate.
m. Calculated by dividing 4.6 days of labour by 365 days per year and multiplying by 0.96 ha of marine ecosystem support required to sustain the average Canadian's annual food consumption.
n. Calculated by dividing 4.6 days of labour by 365 days per year and multiplying by 2.40 ha of terrestrial ecosystem support required to sustain the average Canadian's annual food consumption.

*Table 62. Summary of All Feed, Labour and Industrial Energy Inputs, Greenhouse Gas Emissions and Associated Ecosystem Support Required to Produce an Average Tonne (Round Weight) of Intensively Cultured Chinook Salmon*

| Activity | "Dry" Feed (kg) | Labour (days) | Industrial Energy Inputs (MJ) and GHG Emissions (kg $CO_2$ equiv.) | | | | | | Ecosystem Support (ha) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Gasoline | Diesel | Nat. Gas | Propane | Elect. | Total[a] | Marine | Terrestrial |
| Direct Operating Inputs to Smolt Production[b] | 23 | 0.45 | 45 | 117 | 0 | 166 | 450 | 1,614 | | |
| Direct Operating Inputs to Marine Grow-out Operations[b] | 2,183 | 10.9 | 1,842 | 1,290 | 0 | 0 | 463 | 4,455 | | |
| Direct Operating Inputs to Adult Salmon Transport[b] | 0 | 0.51 | 0 | 3,119 | 0 | 0 | 0 | 3,119 | | |
| Operating Inputs Sub-Totals: | **2,206** | 11.9 | 1,887 | 4,526 | 0 | 166 | 913 | 9,188 | | |
| Inputs & Ecosystem Support to Provide 2,206 kg Feed | | 0.11[c] | 0 | 64,808[d] | 25,801[d] | 0 | 5,402[d] | 106,043 | 12.4[e] | 1.30[f] |
| Total Operating Labour and Industrial Energy Inputs | | **12.0** | 1,887 | 69,334 | 25,801 | 166 | 6,315 | 115,231 | | |
| Embodied Energy to Provide Grow-Out Site Infrastructure | | | | | | | | 1,505[g] | | |
| Total Industrial Energy Inputs | | | | | | | | **116,736** | | |
| GHG Emissions from Direct and Indirect Energy Inputs[h] | | | 174 | 6,094 | 1,494 | 10 | 169 | 7,941[i] | | |
| GHG Emissions to Provide Grow-Out Site Infrastructure | | | | | | | | 75[k] | | |
| Total GHG Emissions | | | | | | | | **8,016** | | |
| Ecosystem Support to Sequester the equiv. of 8.016 t $CO_2$ | | | | | | | | | 0 | 2.19[l] |
| Ecosystem Support to Sustain 12.0 days of Labour | | | | | | | | | 0.031[m] | 0.078[n] |
| Total Ecosystem Support | | | | | | | | | **12.4** | **3.57** |

Notes: a. All industrial energy values in this column are expressed as fossil fuel equivalents. Electricity inputs are converted to fossil fuel equivalents by assuming a 35% conversion efficiency.
b. From Table 15.
c. Calculated by multiplying 2.206 t of feed by 0.05 person-days, the direct labour inputs required to manufacture a tonne of salmon feed (see Table 17).
d. Calculated by multiplying 2.206 t of feed by the energy inputs of diesel fuel, natural gas and electricity, from Table 34, required to produce a tonne of salmon feed.

e. Calculated by multiplying 2.206 t of feed by 5.6 ha, the area of marine ecosystem that is required to produce the marine organisms used to supply the fish meal components of a tonne of salmon feed.
f. Calculated by multiplying 2.206 t of feed by 0.59 ha, the total area of agricultural ecosystem that is required to sustain the provision of direct crop inputs and indirect fodder inputs per tonne of salmon feed.
g. From Table 36.
h. Calculated using the following greenhouse gas emission intensity values: 0.0926 kg $CO_2$ eq./MJ of gasoline, 0.0879 kg $CO_2$ eq./MJ diesel fuel, 0.0579 kg $CO_2$ eq./MJ natural gas or propane, and 0.0267 kg $CO_2$ eq./MJ of electricity.
i. A straight sum of all energy related greenhouse gas emissions.
k. From Table 36.
l. Calculated by dividing 8.016 t of $CO_2$ by 3.6644 t $CO_2$/ha, the estimated average British Columbia forest ecosystem $CO_2$ assimilation rate.
m. Calculated by dividing 12.0 days of labour by 365 days per year and multiplying by 0.96 ha of marine ecosystem support required to sustain the average Canadian's annual food consumption.
n. Calculated by dividing 12.0 days of labour by 365 days per year and multiplying by 2.40 ha of terrestrial ecosystem support required to sustain the average Canadian's annual food consumption.

## *The Ecological Footprint of Intensively Cultured Salmon in B.C.*

I estimate that approximately 9.9 ha of marine ecosystem support and 2.8 ha of terrestrial ecosystem support is required to produce one tonne of intensively cultured Atlantic salmon in British Columbia (Table 61). Based these results, the approximately 32,900 round tonnes of Atlantic salmon harvested by the B.C. industry in 1998 had a marine ecological footprint of about 3,200 $km^2$, and a terrestrial ecological footprint of about 900 $km^2$.

Similarly, one tonne of intensively cultured chinook salmon requires the support of 12.4 ha of marine ecosystem and 3.6 ha terrestrial ecosystem (Table 62). These results suggest that the approximately 8,200 round tonnes of chinook salmon harvested by the industry in 1998 had a marine ecological footprint of about 1,000 $km^2$, and a terrestrial ecological footprint of almost 300 $km^2$.

Of the marine ecosystem support that sustains both intensively cultured Atlantic and chinook salmon, over 99% is required to produce the aquatic organisms used in the manufacture of salmon feed[213]. The remainder is required to sustain human labour inputs.

Of the terrestrial component of the ecological footprint, in the case of both Atlantic and chinook salmon culture, almost two-thirds is required to assimilate carbon dioxide equivalent to the total greenhouse gases that are emitted. These emissions amount to the equivalent of about 6.5 tonne of $CO_2$ per tonne of Atlantic salmon produced and approximately 8.0 tonnes of $CO_2$ per tonne of chinook salmon produced (Tables 61 and 62). Of this, over 99% results from direct and indirect industrial energy inputs to the two systems. The remaining less than one percent results from the provision of the inorganic and synthetic organic material inputs required to build and maintain the grow-out site infrastructure.

Most of the remaining terrestrial ecological footprint of both cultured Atlantic and chinook salmon is accounted for by the direct and indirect agricultural crop inputs to salmon feed. In the case of Atlantic salmon, this amounts to slightly over one hectare per tonne of salmon produced while a tonne of cultured chinook requires the support of approximately 1.3 hectares of agricultural ecosystem. Only about two percent of the terrestrial ecosystem support to intensive salmon culture is required to sustain labour inputs.

[213] More specifically, this is the ecosystem support required to produce the fish meal components of contemporary salmon feed.

## *Energy Analysis of Intensive Salmon Culture*

The average tonne of intensively cultured Atlantic salmon in British Columbia requires a total industrial energy investment, expressed in terms of fossil fuel equivalents, of approximately 94,000 MJ (Table 61). An average tonne of intensively cultured chinook salmon requires a total industrial energy investment of approximately 117,000 MJ (Table 62). As Figures 15 and 16 illustrate, in both cases feed alone accounts for approximately 90% of the total energy inputs. In the case of Atlantic salmon, this amounts to slightly over 85,000 MJ per tonne of salmon produced while in the case of chinook salmon, approximately 106,000 MJ of industrial energy are required to provide feed inputs (Tables 61 and 62).

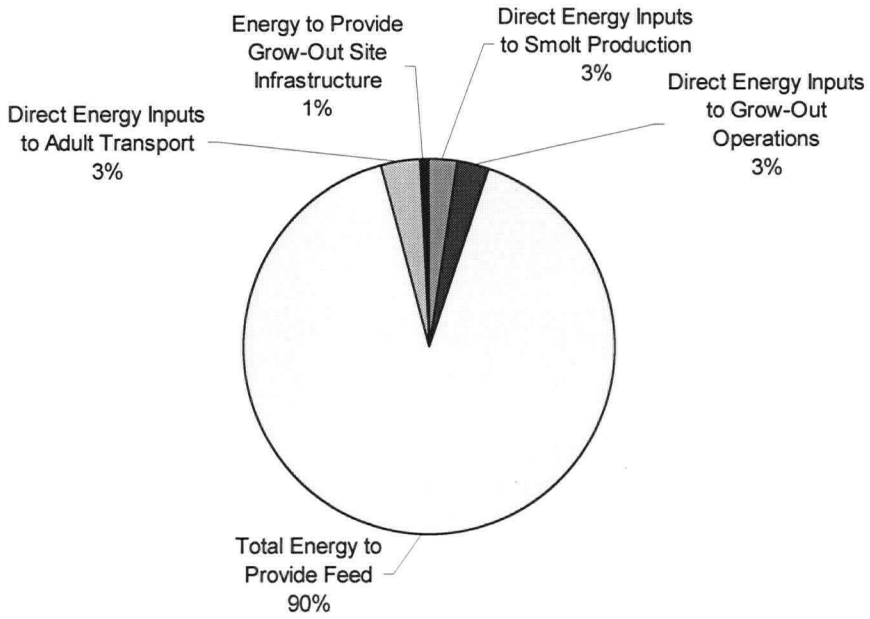


*Figure 15. Sources of Industrial Energy Inputs to Produce a Tonne of Intensively Cultured Atlantic Salmon (total input: 94,100 MJ fossil fuel equivalent)*

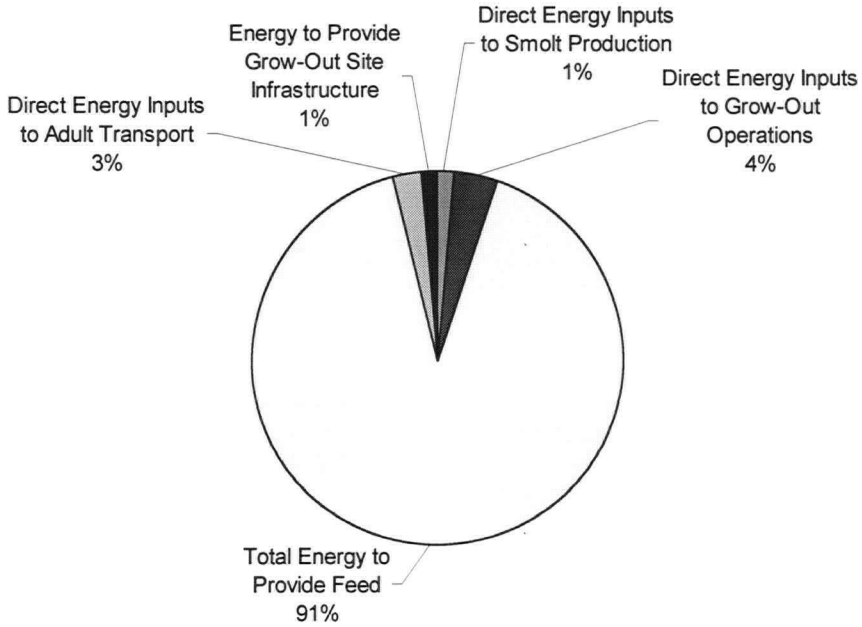


*Figure 16. Sources of Industrial Energy Inputs to Produce a Tonne of Intensively Cultured Chinook Salmon (total input: 116,900 MJ fossil fuel equivalent)*

In the case of both cultured species, the energy required to transport adult salmon at the time of harvest amounts to only 3% of the total energy inputs. Similarly, the energy embodied in grow-out

site infrastructure represents about 1% of the total inputs to both cultured species. Small differences in energy requirements occur, however, with respect to smolt production and grow-out site operations. In the case of Atlantic salmon, both smolt production and grow-out site related energy inputs account for 3% of the total required. In contrast, in chinook culture about 1% of the energy inputs are accounted for by smolt production and 4% go towards grow-out site operations (Figures 15 and 16).

## Energy Return On Investment Ratios for Intensively Cultured Salmon

From the industrial energy inputs just described, I estimated the gross edible energy return on the industrial energy investment ratio, and the edible protein energy return on the industrial energy investment ratio for both intensively cultured Atlantic and chinook salmon (Table 63).

*Table 63. Energy Return on Investment Ratios for Intensively Cultured Atlantic and Chinook Salmon*

| Efficiency Measure | Cultured Atlantic Salmon | Cultured Chinook Salmon |
|---|---|---|
| Gross Edible Energy Return on Total Industrial Energy Investment[a] | 5.2% | 4.2% |
| Edible Protein Energy Return on Total Industrial Energy Investment[b] | 3.3% | 2.6% |

Notes: a. Calculated by dividing 4,940 MJ of gross edible energy per live weight tonne of salmon (assumes that 65% of a carcass is edible and the gross wet weight energy content of salmon flesh is 7.6MJ/kg) by 94,050 MJ of total industrial energy input for Atlantic salmon (Table 61) and 116,851 MJ of total industrial energy input for chinook salmon (Table 62).
b. Calculated by dividing 3,068 MJ of edible protein energy per live weight tonne of salmon (assumes that 20% of the edible portion of a carcass is protein that has a gross energy content of 23.6 MJ/kg) by 94,050 MJ of total industrial energy input for Atlantic salmon (Table 61) and 116,851 MJ of total industrial energy input for chinook salmon (Table 62).

Contemporary Atlantic salmon culture in British Columbia provides a 5.2% total edible food energy return and a 3.3% edible protein energy return on the total industrial energy investment that is required. Similarly, intensive chinook culture in British Columbia provides a 4.2% total food energy return and a 2.6% edible protein energy return on the total industrial energy invested (Table 63).

## Industrial Energy Inputs Associated with Producing Salmon Feed

As salmon feed accounts for such a large proportion of the total energy inputs to intensive salmon culture, Figure 17 presents an activity-based breakdown of the energy inputs to salmon feed using data presented in Table 34.

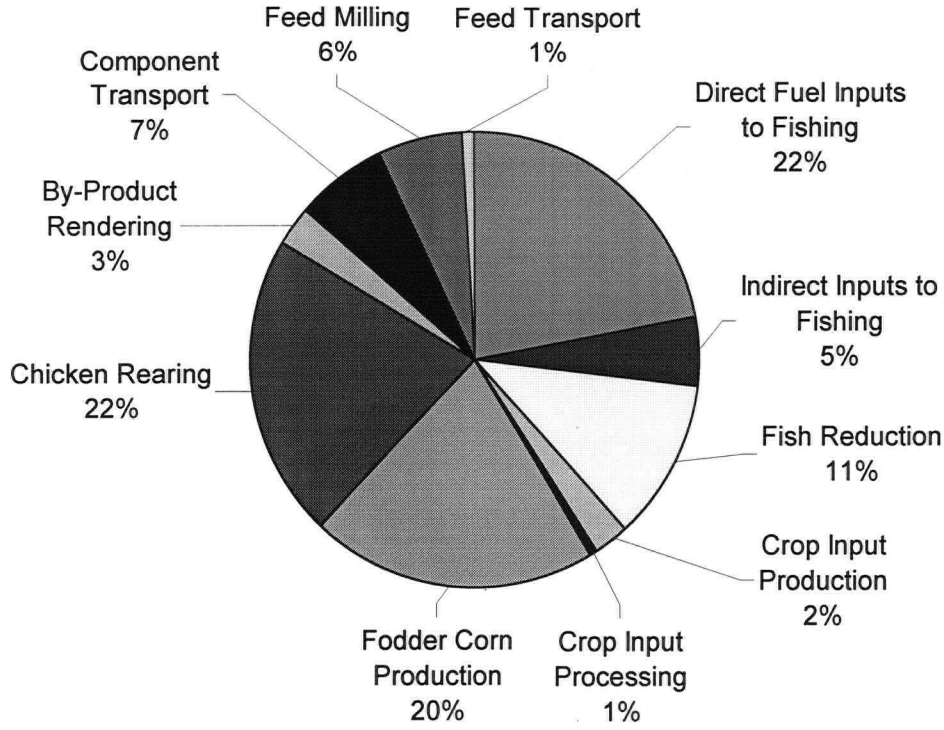


*Figure 17. Breakdown of Industrial Energy Inputs to Produce a Tonne of Contemporary Salmon Feed (total input approximately 48,000 MJ fossil fuel equivalent)*

The two largest industrial energy inputs, each accounting for 22% of the total, are: the fuel consumed to capture fish for reduction[214], and 2) the energy required to rear the mass of chicken equivalent to the by-products needed for the blood, meat and feather meal inputs. When the latter is combined with the energy needed raise the corn for chicken fodder, representing 20% of the total, and the energy required to process by-products, at 3% of the total, the three by-product meals accounts for fully 45% of the total energy input to salmon feed. In contrast, providing the fish-derived feed components accounts for approximately 38%, and the crop-derived components account for only 3% of the total energy inputs (Figure 17).

Transporting the various components, along with their precursors, from their ecosystems of origin ultimately to the feed mill accounts for approximately 7% of the total energy inputs (Figure 17). Energy inputs associated with feed milling account for a slightly smaller proportion, at 6% of the total, while transporting the finished feed to the consumer accounts for about 1% of the total (Figure 17).

[214] Recall that in this analysis, the fish oil inputs to salmon feed represented a greater quantity of whole fish than was represented by the fish meal components. As such, only the industrial energy inputs associated with the capture and reduction of the raw fish needed to provide oil is included to avoid double counting.

### *Nutritional Energy Inputs to Intensive Salmon Culture*

As part of my analysis of the inputs to salmon feed in Chapter 4, I estimated that the gross nutritional energy content of an average tonne of feed was approximately 22,400 MJ (Table 18). Given that the production of an average round tonne of Atlantic salmon requires 1.77 tonnes of feed (Table 61), then a total of about 39,600 MJ of gross nutritional energy is required to yield one tonne of Atlantic salmon. Assuming that a round tonne of salmon contains 7,600 MJ of gross energy, this suggests that contemporary intensive Atlantic salmon culture in British Columbia displays a gross or total feed conversion efficiency of approximately 19.2%, or about 3.5% lower than the conversion efficiency of a population of wild salmon as estimated by Brett (1986).

Similarly, given that a tonne of cultured chinook salmon consumes an average of 2.206 tonnes of feed (Table 62), a total of approximately 49,400 MJ of gross nutritional energy is required to yield the 7,600 MJ of energy embodied in the salmon itself. This implies a total feed conversion efficiency of approximately 15.4%, almost 7.5% lower than the population conversion efficiency of wild salmon (Brett 1986).

## Ecological Footprint and Energy Inputs Associated with the Commercial Salmon Fishery in British Columbia

The results of the analysis of the ecological footprint and total industrial energy inputs associated with growing and capturing a round weight tonne of chinook, coho, sockeye, chum and pink salmon are presented in Tables 64, 65, 66, 67, and 68, respectively.

*Table 64. Summary of All Feed, Labour and Energy Inputs, Greenhouse Gas Emissions and Ecosystem Support Required to Produce and Harvest an Average Tonne (Round Weight) of Chinook Salmon Caught by the Commercial Fishery*

| Activity | "Dry" Feed (kg) | Labour (days) | Industrial Energy Inputs (MJ) and GHG Emissions (kg $CO_2$ equiv.) | | | | | | Ecosystem Support (ha) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Gasoline | Diesel | Nat. Gas | Propane | Elect. | Total[a] | Marine | Terrestrial |
| Ecosystem Support to Sustain Wild Forage | | | | | | | | | 10.0[b] | 0 |
| Direct Operating Inputs to Artificial Smolt Production[c] | **11.9** | 1.0 | 81 | 147 | 0 | 30 | 514 | 1,727 | | |
| Inputs & Ecosystem Support to Provide 11.9 kg Feed | | 0 | 0 | 350[d] | 139[d] | 0 | 29[d] | 572 | 0.07[e] | 0.007[f] |
| Labour and Energy Inputs to Fishing | | 10.1[g] | | 28,500[h] | | | | 28,500 | | |
| Total Operating Labour and Industrial Energy Inputs | | 11.1 | 81 | 28,997 | 139 | 30 | 543 | 30,799 | | |
| Labour and Embodied Energy to Build and Maintain Vessels | | 1.0[i] | | | | | | 3,910[l] | | |
| Embodied Energy to Provide Fishing Gear | | | | | | | | 510[k] | | |
| Total Labour and Energy Inputs | | **12.1** | | | | | | **35,219** | | |
| GHG Emissions from Direct and Indirect Energy Inputs[l] | | | 7.5 | 2,610 | 8.0 | 1.7 | 14.5 | 2,642[m] | | |
| GHG Emissions to Build and Maintain Vessels | | | | | | | | 175[l] | | |
| GHG Emissions to Provide Fishing Gear | | | | | | | | 33[k] | | |
| Total GHG Emissions | | | | | | | | **2,850** | | |
| Ecosystem Support to Sequester the equiv. of 2.85 t $CO_2$ | | | | | | | | | 0 | 0.78[n] |
| Ecosystem Support to Sustain 12.1 days of Labour | | | | | | | | | 0.032[o] | 0.079[p] |
| Total Ecosystem Support | | | | | | | | | **10.1** | **0.87** |

Notes: a. All industrial energy values in this column are expressed as fossil fuel equivalents. Electricity inputs are converted to fossil fuel equivalents by assuming a 35% conversion efficiency.
b. From Table 38.

c. From Table 40.
d. Calculated by multiplying 0.0119 t of feed by the energy inputs of diesel fuel, natural gas and electricity, from Table 34, required to produce a tonne of salmon feed.
e. Calculated by multiplying 0.0119 t of feed by 5.6 ha/tonne, the area of marine ecosystem that is required to sustain the provision of marine organisms used to supply the fish oil components of a tonne of salmon feed.
f. Calculated by multiplying 0.0119 t of feed by 0.59 ha/tonne, the total area of agricultural ecosystem that is required to sustain the provision of direct crop inputs and indirect fodder inputs per tonne of salmon feed.
g. From Table 47.
h. From Table 44. Also note that this energy input represents a blend of diesel fuel and gasoline, of which the largest portion is diesel fuel.
i. From Table 60.
k. From Table 53.
l. Calculated using the following greenhouse gas emission intensity values: 0.0926 kg $CO_2$ eq./MJ of gasoline, 0.09 kg $CO_2$ eq./MJ for the diesel fuel/gasoline combination, 0.0579 kg $CO_2$ eq./MJ natural gas or propane, and 0.0267 kg $CO_2$ eq./MJ of electricity.
m. A straight sum of all energy related greenhouse gas emissions.
n. Calculated by dividing 2.85 t of $CO_2$ by 3.6644 t $CO_2$/ha, the estimated average British Columbia forest ecosystem $CO_2$ assimilation rate.
o. Calculated by dividing 12.1 days of labour by 365 days per year and multiplying by 0.96 ha of marine ecosystem support required to sustain the average Canadian's annual food consumption.
p. Calculated by dividing 12.1 days of labour by 365 days per year and multiplying by 2.40 ha of terrestrial ecosystem support required to sustain the average Canadian's annual food consumption.

*Table 65. Summary of All Feed, Labour and Energy Inputs, Greenhouse Gas Emissions and Ecosystem Support Required to Produce and Harvest an Average Tonne (Round Weight) of Coho Salmon Caught by the Commercial Fishery*

| Activity | "Dry" Feed (kg) | Labour (days) | Industrial Energy Inputs (MJ) and GHG Emissions (kg $CO_2$ equiv.) | | | | | | Ecosystem Support (ha) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Gasoline | Diesel | Nat. Gas | Propane | Elect. | Total[a] | Marine | Terrestrial |
| Ecosystem Support to Sustain Wild Forage | | | | | | | | | 9.2[b] | 0 |
| Direct Operating Inputs to Artificial Smolt Production[c] | **18.8** | 0.53 | 103 | 48 | 0 | 0 | 2,670 | 7,780 | | |
| Inputs & Ecosystem Support to Provide 18.8 kg Feed | | 0 | 0 | 553[d] | 220[d] | 0 | 46[d] | 904 | 0.11[e] | 0.011[f] |
| Labour and Energy Inputs to Fishing | | 9.3[g] | | 28,100[h] | | | | 28,100 | | |
| Total Operating Labour and Industrial Energy Inputs | | 9.8 | 103 | 28,701 | 220 | 0 | 2,716 | 36,784 | | |
| Labour and Embodied Energy to Build and Maintain Vessels | | 1.0 | | | | | | 3,890[I] | | |
| Embodied Energy to Provide Fishing Gear | | | | | | | | 510[k] | | |
| Total Labour and Energy Inputs | | **10.8** | | | | | | **41,184** | | |
| GHG Emissions from Direct and Indirect Energy Inputs[l] | | | 9.5 | 2,583 | 12.7 | 0 | 72.5 | 2,678[m] | | |
| GHG Emissions to Build and Maintain Vessels | | | | | | | | 175[I] | | |
| GHG Emissions to Provide Fishing Gear | | | | | | | | 33[k] | | |
| Total GHG Emissions | | | | | | | | **2,886** | | |
| Ecosystem Support to Sequester the equiv. of 2.886 t $CO_2$ | | | | | | | | | 0 | 0.79[n] |
| Ecosystem Support to Sustain 10.8 days of Labour | | | | | | | | | 0.028[o] | 0.070[p] |
| Total Ecosystem Support | | | | | | | | | **9.3** | **0.87** |

Notes: a. All industrial energy values in this column are expressed as fossil fuel equivalents. Electricity inputs are converted to fossil fuel equivalents by assuming a 35% conversion efficiency.
b. From Table 38.

c. From Table 40.
d. Calculated by multiplying 0.0188 t of feed by the energy inputs of diesel fuel, natural gas and electricity, from Table 34, required to produce a tonne of salmon feed.
e. Calculated by multiplying 0.0188 t of feed by 5.6 ha/tonne, the area of marine ecosystem that is required to sustain the provision of marine organisms used to supply the fish oil components of a tonne of salmon feed.
f. Calculated by multiplying 0.0188 t of feed by 0.59 ha/tonne, the total area of agricultural ecosystem that is required to sustain the provision of direct crop inputs and indirect fodder inputs per tonne of salmon feed.
g. From Table 47.
h. From Table 44. Also note that this energy input represents a blend of diesel fuel and gasoline, of which the largest portion is diesel fuel.
i. From Table 60.
k. From Table 53.
l. Calculated using the following greenhouse gas emission intensity values: 0.0926 kg $CO_2$ eq./MJ of gasoline, 0.09 kg $CO_2$ eq./MJ for the diesel fuel/gasoline combination, 0.0579 kg $CO_2$ eq./MJ natural gas or propane, and 0.0267 kg $CO_2$ eq./MJ of electricity.
m. A straight sum of all energy related greenhouse gas emissions.
n. Calculated by dividing 2.886 t of $CO_2$ by 3.6644 t $CO_2$/ha, the estimated average British Columbia forest ecosystem $CO_2$ assimilation rate.
o. Calculated by dividing 10.8 days of labour by 365 days per year and multiplying by 0.96 ha of marine ecosystem support required to sustain the average Canadian's annual food consumption.
p. Calculated by dividing 10.8 days of labour by 365 days per year and multiplying by 2.40 ha of terrestrial ecosystem support required to sustain the average Canadian's annual food consumption.

*Table 66. Summary of All Labour and Energy Inputs, Greenhouse Gas Emissions and Ecosystem Support Required to Produce and Harvest an Average Tonne (Round Weight) of Sockeye Salmon Caught by the Commercial Fishery*

| Activity | Labour (days) | Industrial Energy Inputs (MJ) | GHG Emissions (kg $CO_2$ equiv.) | Ecosystem Support (ha) | |
|---|---|---|---|---|---|
| | | | | Marine | Terrestrial |
| Ecosystem Support to Sustain Wild Forage | | | | 5.0[a] | 0 |
| Direct Labour and Fuel Inputs to Fishing and Resulting GHG Emissions | 8.1[b] | 22,800[c] | 2,052[d] | | |
| Labour and Embodied Energy to Build and Maintain Vessels and Resulting GHG Emissions | 0.9[e] | 3,900[e] | 175[e] | | |
| Embodied Energy and Associated GHG Emissions to Provide Fishing Gear | | 520[f] | 28[f] | | |
| Total Inputs and GHG Emissions | **9.0** | **27,220** | **2,255** | | |
| Ecosystem Support to Sequester the equiv. of 2.255 t $CO_2$ | | | | 0 | 0.62[g] |
| Ecosystem Support to Sustain 9.0 days of Labour | | | | 0.024[h] | 0.058[i] |
| Total Ecosystem Support | | | | **5.0** | **0.68** |

Notes:
a. From Table 38.
b. From Table 47.
c. From Table 44. Also note that this energy input represents a blend of diesel fuel and gasoline, of which the largest portion is diesel fuel.
d. Calculated by multiplying the estimated direct fuel energy input (22,800 MJ) by 0.09 kg CO2 eq./MJ, the greenhouse gas emission intensity value that I have assumed applies to the diesel fuel/gasoline combination.
e. From Table 60.
f. From Table 53.
g. Calculated by dividing 2.255 t of $CO_2$ by 3.6644 t $CO_2$/ha, the estimated average British Columbia forest ecosystem $CO_2$ assimilation rate.
h. Calculated by dividing 9.0 days of labour by 365 days per year and multiplying by 0.96 ha of marine ecosystem support required to sustain the average Canadian's annual food consumption.
i. Calculated by dividing 9.0 days of labour by 365 days per year and multiplying by 2.40 ha of terrestrial ecosystem support required to sustain the average Canadian's annual food consumption.

*Table 67. Summary of All Labour and Energy Inputs, Greenhouse Gas Emissions and Ecosystem Support Required to Produce and Harvest an Average Tonne (Round Weight) of Chum Salmon Caught by the Commercial Fishery*

| Activity | Labour (days) | Industrial Energy Inputs (MJ) | GHG Emissions (kg $CO_2$ equiv.) | Ecosystem Support (ha) | |
|---|---|---|---|---|---|
| | | | | Marine | Terrestrial |
| Ecosystem Support to Sustain Wild Forage | | | | 4.6[a] | 0 |
| Direct Labour and Fuel Inputs to Fishing and Resulting GHG Emissions | 6.8[b] | 19,600[c] | 1,764[d] | | |
| Labour and Embodied Energy to Build and Maintain Vessels and Resulting GHG Emissions | 0.8[e] | 3,820[e] | 170[e] | | |
| Embodied Energy and Associated GHG Emissions to Provide Fishing Gear | | 530[f] | 27[f] | | |
| Total Inputs and GHG Emissions | **7.6** | **23,950** | **1,961** | | |
| Ecosystem Support to Sequester the equiv. of 1.961 t $CO_2$ | | | | 0 | 0.54[g] |
| Ecosystem Support to Sustain 7.6 days of Labour | | | | 0.020[h] | 0.049[i] |
| Total Ecosystem Support | | | | **4.6** | **0.59** |

Notes:
a. From Table 38.
b. From Table 47.
c. From Table 44. Also note that this energy input represents a blend of diesel fuel and gasoline, of which the largest portion is diesel fuel.
d. Calculated by multiplying the estimated direct fuel energy input (19,600 MJ) by 0.09 kg CO2 eq./MJ, the greenhouse gas emission intensity value that I have assumed applies to the diesel fuel/gasoline combination.
e. From Table 60.
f. From Table 53.
g. Calculated by dividing 1.961 t of $CO_2$ by 3.6644 t $CO_2$/ha, the estimated average British Columbia forest ecosystem $CO_2$ assimilation rate.
h. Calculated by dividing 7.6 days of labour by 365 days per year and multiplying by 0.96 ha of marine ecosystem support required to sustain the average Canadian's annual food consumption.
i. Calculated by dividing 7.6 days of labour by 365 days per year and multiplying by 2.40 ha of terrestrial ecosystem support required to sustain the average Canadian's annual food consumption.

*Table 68. Summary of All Labour and Energy Inputs, Greenhouse Gas Emissions and Ecosystem Support Required to Produce and Harvest an Average Tonne (Round Weight) of Pink Salmon Caught by the Commercial Fishery*

| Activity | Labour (days) | Industrial Energy Inputs (MJ) | GHG Emissions (kg $CO_2$ equiv.) | Ecosystem Support (ha) | |
|---|---|---|---|---|---|
| | | | | Marine | Terrestrial |
| Ecosystem Support to Sustain Wild Forage | | | | 4.5[a] | 0 |
| Direct Labour and Fuel Inputs to Fishing and Resulting GHG Emissions | 5.9[b] | 18,000[c] | 1,620[d] | | |
| Labour and Embodied Energy to Build and Maintain Vessels and Resulting GHG Emissions | 0.6[e] | 3,720[e] | 165[e] | | |
| Embodied Energy and Associated GHG Emissions to Provide Fishing Gear | | 530[f] | 28[f] | | |
| Total Inputs and GHG Emissions | **6.5** | **22,250** | **1,813** | | |
| Ecosystem Support to Sequester the equiv. of 1.813 t $CO_2$ | | | | 0 | 0.49[g] |
| Ecosystem Support to Sustain 6.5 days of Labour | | | | 0.017[h] | 0.042[i] |
| Total Ecosystem Support | | | | **4.5** | **0.53** |

Notes: a. From Table 38.
b. From Table 47.
c. From Table 44. Also note that this energy input represents a blend of diesel fuel and gasoline, of which the largest portion is diesel fuel.
d. Calculated by multiplying the estimated direct fuel energy input (18,000 MJ) by 0.09 kg CO2 eq./MJ, the greenhouse gas emission intensity value that I have assumed applies to the diesel fuel/gasoline combination.
e. From Table 60.
f. From Table 53.
g. Calculated by dividing 1.813 t of $CO_2$ by 3.6644 t $CO_2$/ha, the estimated average British Columbia forest ecosystem $CO_2$ assimilation rate.
h. Calculated by dividing 6.5 days of labour by 365 days per year and multiplying by 0.96 ha of marine ecosystem support required to sustain the average Canadian's annual food consumption.
i. Calculated by dividing 6.5 days of labour by 365 days per year and multiplying by 2.40 ha of terrestrial ecosystem support required to sustain the average Canadian's annual food consumption.

## *The Ecological Footprint of Commercially Caught Salmon in B.C.*

Summarising the results presented in Tables 64 through 68, Table 69 presents the ecological footprint associated with producing an average tonne of each species of commercially caught salmon in British Columbia.

*Table 69. Ecological Footprint Required to Produce and Harvest a Tonne of Commercially Caught Chinook, Coho, Sockeye, Chum and Pink Salmon in B.C.*

| Species | Marine Ecosystem Support Required (ha) | Terrestrial Ecosystem Support Required (ha) | Ecological Footprint (ha) |
|---|---|---|---|
| Chinook | 10.1 | 0.87 | 10.97 |
| Coho | 9.3 | 0.87 | 10.17 |
| Sockeye | 5.0 | 0.68 | 5.68 |
| Chum | 4.6 | 0.59 | 5.19 |
| Pink | 4.5 | 0.53 | 5.03 |

The ecological footprint associated with growing and harvesting salmon from the wild, varies depending upon the species being harvested (Table 69). Of the five commercially caught species, chinook have the largest ecological footprint amounting to a total of almost 11 ha, 10.1 ha of which represents marine ecosystem support with the remaining almost 0.9 ha representing terrestrial ecosystem support. At the other extreme, an average tonne of commercially caught pink salmon has a total ecological footprint of a little over 5 ha. Of this, 4.5 ha is marine ecosystem support with the remaining 0.53 ha representing terrestrial ecosystem support. In the case of all five species, the marine ecosystem support component represents at least 88% of the total ecological footprint required.

To facilitate comparison, Figure 18 displays the marine and terrestrial ecological footprint associated with the production of an average tonne of commercially caught chinook, coho, sockeye, chum, and pink salmon along with the ecological footprint associated with the production of an average tonne of intensively cultured Atlantic and chinook salmon.

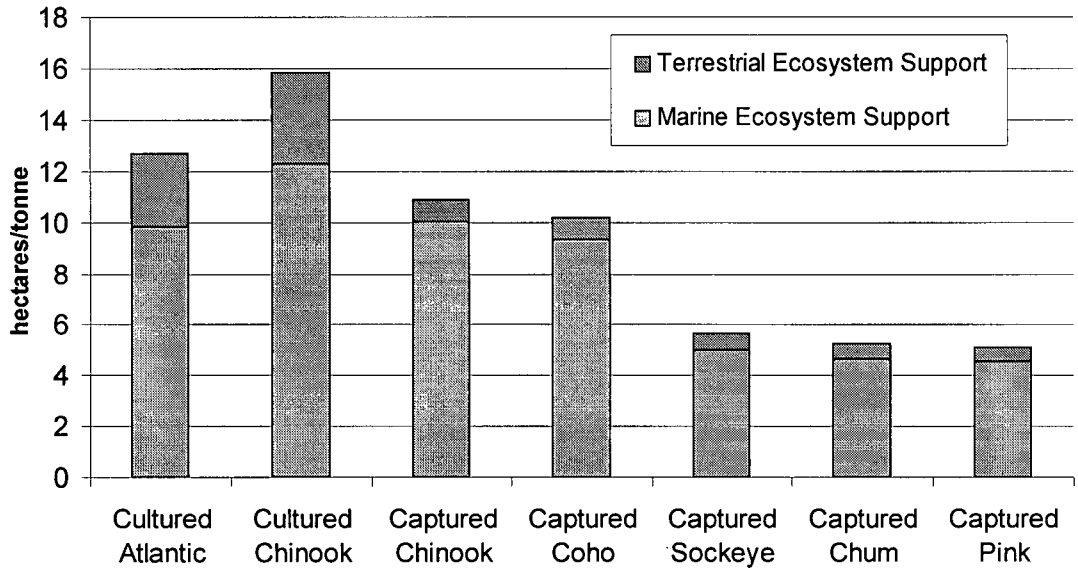


*Figure 18. Marine and Terrestrial Ecological Footprint Required to Produce a Tonne of Salmon in B.C.*

For each of the five commercially caught species, over 99% of the marine ecosystem support is required to provide wild forage (Tables 64 through 68). The remaining, relatively trivial, marine ecosystem support is required to: 1) provide the marine origin food consumed to sustain labour inputs, and 2) in the case of chinook and coho only, a small amount of marine ecosystem support is also required to provide the aquatic inputs to salmon feed used in the artificially rearing of smolts[215].

With respect to terrestrial ecosystem support, again for all five commercially caught species, between 90% and 92% of the ecological footprint is accounted for by forest ecosystem required to assimilate a quantity of $CO_2$ equal to the total greenhouse gases emitted through direct and indirect industrial energy inputs (Tables 64 through 68). These greenhouse gas emissions amount to the equivalent of about 2.85 tonnes of $CO_2$ per tonne of commercially caught chinook salmon, 2.89 tonnes $CO_2$ per tonne of coho salmon, 2.26 tonnes $CO_2$ per tonne of sockeye salmon, 1.96 tonnes $CO_2$ per tonne of chum, and 1.81 tonnes $CO_2$ per tonne of pink salmon.

In the case of sockeye, chum and pink salmon, all of the remaining terrestrial ecosystem support, amounting to between 8% and 9% of the total, is needed to provide the food inputs to labour. In the case of chinook and coho salmon, while most of the non-$CO_2$ assimilation forest ecosystem support is also needed to sustain labour inputs, a very small fraction, amounting about 1% of the total

terrestrial footprint, is required to produce the crop-origin inputs to salmon feed used to artificially rear smolts.

## *Energy Analysis of the Commercial Salmon Fishery*

The total industrial energy inputs, expressed in terms of fossil fuel equivalents, associated with the production and harvesting of an average tonne of salmon captured from the wild amounts to approximately: 35,200 MJ/t for chinook salmon; 41,200 MJ/t for coho salmon; 27,200 MJ/t for sockeye salmon; 24,000 MJ/t for chum salmon; and 22,300 MJ/t for pink salmon (Tables 64 through 68). Figures 19 through 23 illustrate the breakdown of industrial energy inputs to commercially caught chinook, coho, sockeye, chum and pink salmon, respectively.

[215] About 11.9 kg and 18.8 kg of "dry" salmon feed is required to artificially rear the chinook and coho smolts respectively that contribute to the average tonne of chinook and coho caught in the wild (see Tables 64 and 65).

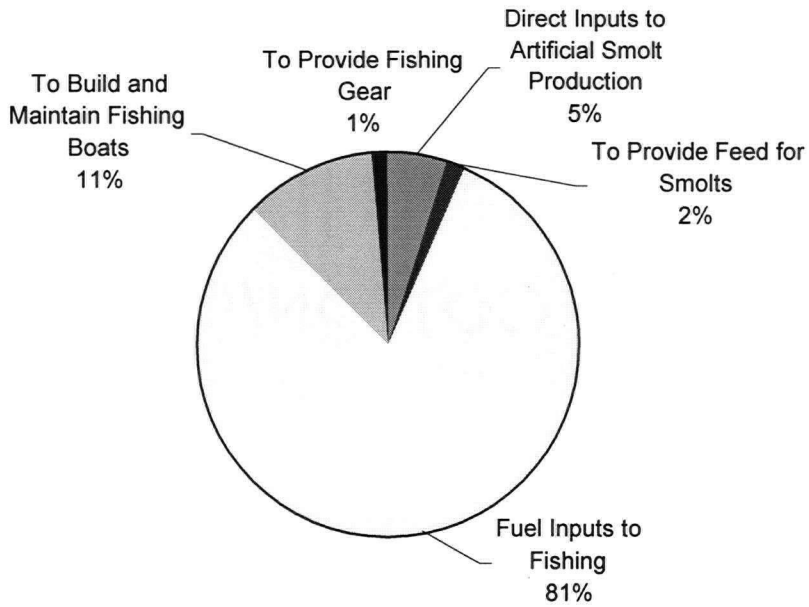


*Figure 19. Breakdown of Industrial Energy Inputs to Produce a Tonne of Commercially Caught Chinook Salmon (total input: 35,200 MJ fossil fuel equivalent)*

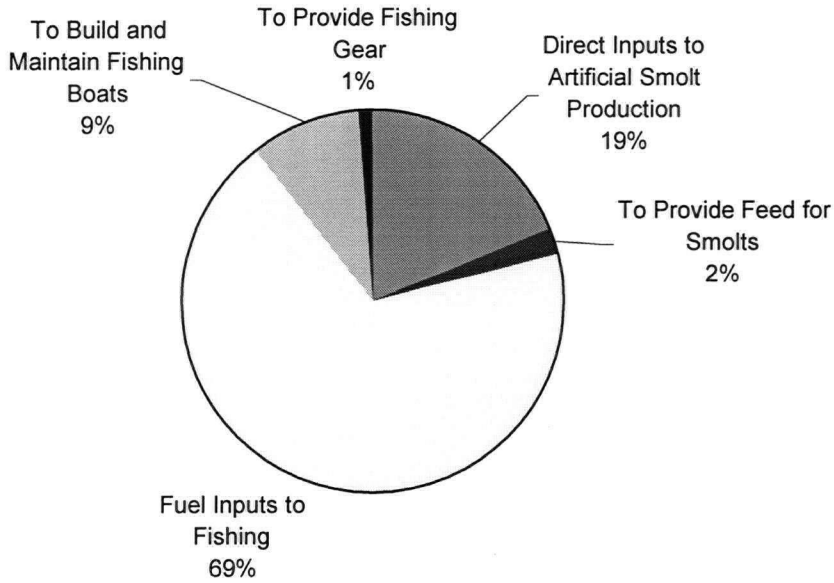


*Figure 20. Breakdown of Industrial Energy Inputs to Produce a Tonne of Commercially Caught Coho Salmon (total input: 41,200 MJ fossil fuel equivalent)*

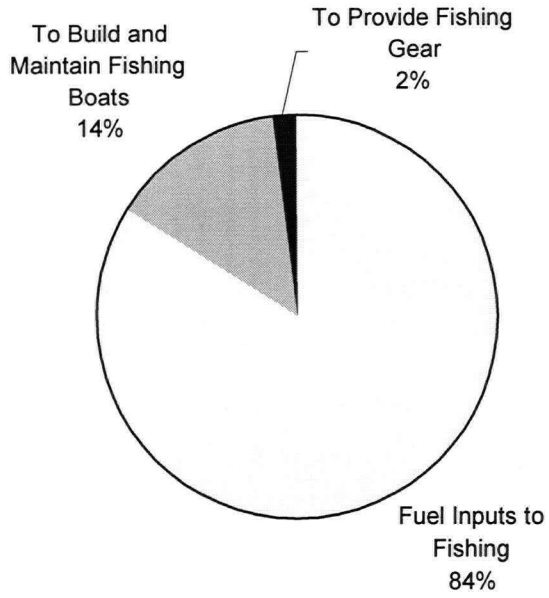


*Figure 21. Breakdown of Industrial Energy Inputs to Produce a Tonne of Commercially Caught Sockeye Salmon (total input: 27,200 MJ fossil fuel equivalent)*

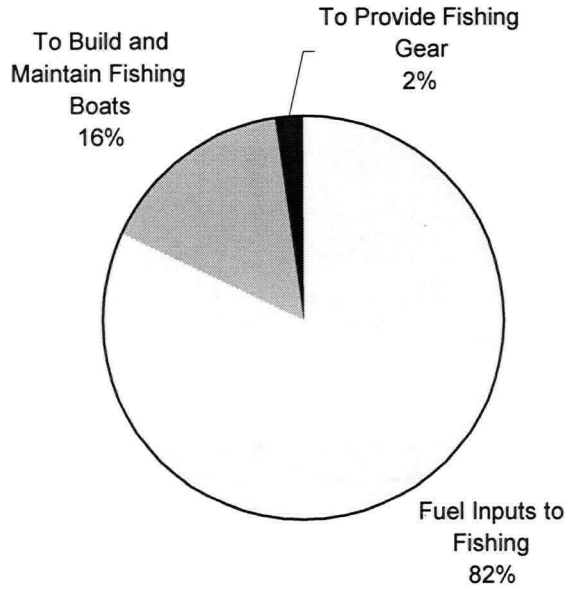


*Figure 22. Breakdown of Industrial Energy Inputs to Produce a Tonne of Commercially Caught Chum Salmon (total input: 24,000 MJ fossil fuel equivalent)*

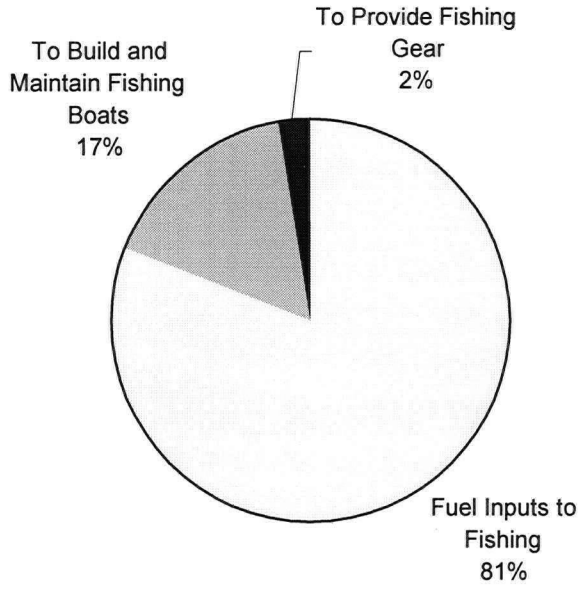


*Figure 23. Breakdown of Industrial Energy Inputs to Produce a Tonne of Commercially Caught Pink Salmon (total input: 22,300 MJ fossil fuel equivalent)*

For all five species, the fuel consumed while fishing represents the largest single industrial energy input (Figures 19 through 23). It ranges from a high of about 28,500 MJ per tonne of chinook landed, to 18,000 MJ per tonne of pink salmon landed. In four of the five species, fuel consumed while fishing accounts for between 81% and 84% of the total energy inputs. The only exception to this pattern is coho salmon for which fuel accounts for only about 69% of the total industrial energy consumed.

The reduced importance of fuel inputs to commercially caught coho is not a result of relatively low rates of fuel consumption. Indeed, only chinook salmon fishing has a higher fuel energy input (Tables 64 and 65). Instead, it reflects the relatively large energy inputs associated with the artificial rearing of coho smolts in SEP hatcheries. For example, when the hatchery-related direct energy inputs are combined with the embodied energy associated with providing salmon feed consumed by coho smolts, a fossil fuel equivalent of approximately 8,684 MJ is attained (Table 65). This amounts to 21% of the total industrial energy associated with landing an average tonne of coho (Table 65 and Figure 20). The scale of these energy inputs is highlighted further by noting that SEP-origin coho

accounted for only an average of 10.6%[216] of the British Columbia commercial coho catch over the period from 1985 to 1994 (Appendix L).[217]. As a result, a total of approximately 81,900 MJ of fossil fuel equivalent energy would be needed to rear enough coho smolts in hatcheries so that after being released into the wild, an entire tonne of adults would result[218].

Considering the energy costs of artificial chinook smolt production in a similar manner, the direct energy inputs at the hatchery together with the embodied energy in salmon feed amounts to the fossil fuel equivalent of approximately 2,300 MJ, representing about 7% of the total industrial energy inputs to commercially caught chinook (Table 64 and Figure 19). Given that, on average, approximately 16.2% of the chinook landed by the commercial fleet between 1985 and 1994 originated in SEP hatcheries (Appendix L), approximately 14,200 MJ of industrial energy would have to be expended to rear enough chinook smolts that once released into the wild, one tonne of hatchery produced adult salmon would result[219].

After direct fuel inputs, for four of the five commercially caught species, the next largest energy input is the direct and indirect energy required to build and maintain fishing vessels[220]. As a proportion of the total energy inputs required, the vessel related inputs range from 9%, in the case of coho salmon, to 17% in the case of pink salmon (Figures 19 through 23).

For all five commercially caught species, the energy embodied in the fishing gear "consumed" makes the smallest contribution to the total industrial energy input accounting for only between 1% and 2% (Figures 19 through 23).

In order to compare production systems and species produced, Figure 24 presents the total industrial energy inputs needed to produce a round tonne of each species of farmed and commercially caught salmon.

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[216] This proportion is calculated on a piece basis not on the basis of weight.
[217] This assumes that, on average, artificially reared and wild coho weigh the same when they are captured.
[218] Calculated as follows: (1000 kg ÷ 106 kg) x 8,684 MJ = 81,925 MJ.
[219] Calculated as follows: (1000 kg ÷ 162 kg) x 2,300 MJ = 14,198 MJ.
[220] Once again, the exception is commercially caught coho for which the energy to build and maintain fishing vessels is the third largest input after fuel and the inputs to artificial smolt production..

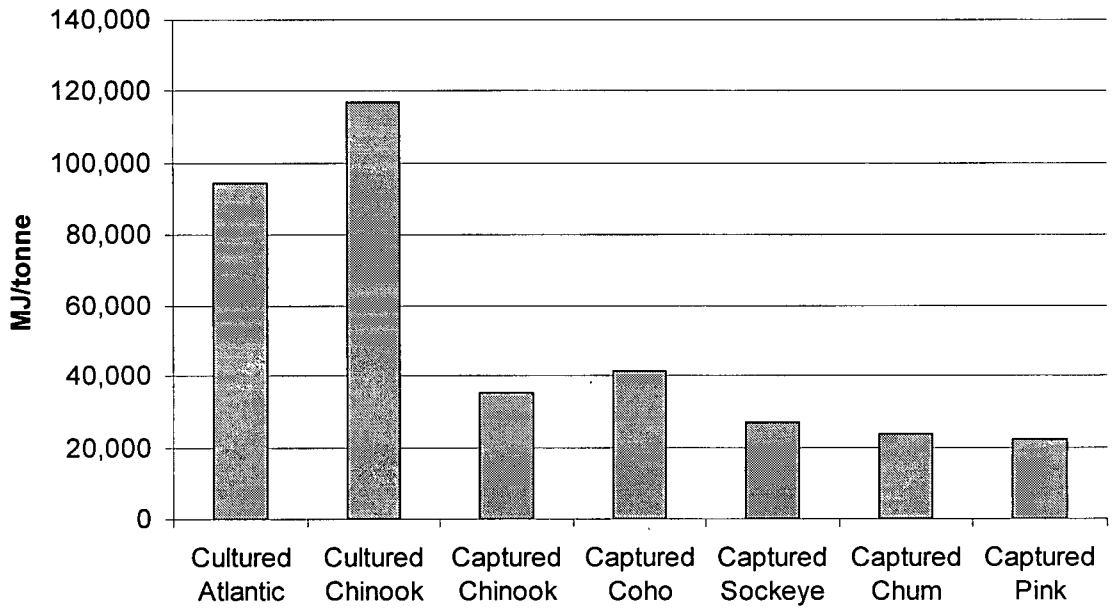


*Figure 24. Total Industrial Energy Inputs (Expressed as Fossil Fuel Equivalents) per Tonne of Salmon Produced by the Intensive Culture Industry and the Commercial Salmon Fishery in B.C.*

## Energy Return On Investment Ratios for the Commercial Salmon Fishery

From the estimates of total industrial energy inputs (Tables 64 through 68), I estimated the: 1) gross edible energy return on the industrial energy investment ratio, and 2) the edible protein energy return on the industrial energy investment ratio for all species of commercially caught salmon (Table 70).

*Table 70. Energy Return on Investment Ratios for Different Species of Commercially Caught Salmon*

| Efficiency Measure | Commercially Caught | | | | |
|---|---|---|---|---|---|
| | Chinook | Coho | Sockeye | Chum | Pink |
| Gross Edible Energy Return on Total Industrial Energy Investment[a] | 14% | 12% | 18% | 21% | 22% |
| Edible Protein Energy Return on Total Industrial Energy Investment[b] | 8.7% | 7.4% | 11% | 13% | 14% |

Notes: a. Calculated by dividing 4,940 MJ of gross edible energy per live weight tonne of salmon (assumes that 65% of a carcass is edible and the gross wet weight energy content of salmon flesh is 7.6MJ/kg) by the total industrial energy input for each species from Tables 64 through 68.
b. Calculated by dividing 3,068 MJ of edible protein energy per live weight tonne of salmon (assumes that 20% of the edible portion of a carcass is protein that has a gross energy content of 23.6 MJ/kg) by the total industrial energy input for each species from Tables 64 through 68.

Gross edible energy return on industrial energy investment ratios range from a low of 12% for coho salmon to a high of 22% in the case of pink salmon (Table 70). Similarly, the protein energy return

on industrial energy investment ratios range from a low of 7.4% for coho to a high of 14% for pink salmon (Table 70).

## *Ecological Footprint and Energy Analysis Associated with Harvesting Salmon Using Different Fishing Gears*

I assessed the differences in the biophysical costs associated with alternative salmon fishing gears by summing the labour, industrial energy inputs and greenhouse gas emissions per tonne of salmon landed using purse seine, troll and gillnet fishing technologies (Table 71).

*Table 71. Energy and Labour Inputs and Greenhouse Gas Emissions Associated with Landing An Average Tonne of Salmon in British Columbia*

| Type of Fishing Gear | To Fishing Operations | | | To Build and Main. Vessels | | | To Provide Gear | | Totals | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fuel (MJ)[a] | GHG Emissions (kg $CO_2$ eq.)[b] | Labour (days)[c] | Energy (MJ) | GHG Emissions (kg $CO_2$ eq.) | Labour (days) | Energy (MJ)[d] | GHG Emissions (kg $CO_2$ eq.)[d] | Energy (MJ) | GHG Emissions (kg $CO_2$ eq.) | Labour (days) |
| Purse Seine | 12,900 | 1,161 | 3.8 | 3,600[e] | 159[e] | 0.43[f] | 540 | 27 | 17,040 | 1,347 | 4.2 |
| Gillnet | 29,400 | 2,646 | 11.3 | 4,170[g] | 190[g] | 1.4[h] | 505 | 26 | 34,075 | 2,862 | 12.7 |
| Troll | 29,900 | 2,691 | 10.6 | 3,900[i] | 175[i] | 1.0[i] | 511 | 35 | 34,311 | 2,901 | 11.6 |

Notes: a. All values from Table 43. Also note that these energy inputs represents a blend of diesel fuel and gasoline, of which the largest portion is diesel fuel.

b. All values calculated by multiplying the estimated direct fuel energy input from the first column by 0.09 kg $CO_2$ eq./MJ, the greenhouse gas emission intensity value that I have assumed applies to the diesel fuel/gasoline combination.

c. All values from Table 46.

d. All values from Table 52.

e. From Table 59.

f. From Table 58.

g. These values represent the approximate average of the estimated energy input and greenhouse gas emissions per tonne of salmon landed by a typical aluminium-hulled gillnetter and a typical fibreglass hulled gillnetter (see Table 59).

h. This value represent the approximate average of the labour inputs per tonne of salmon landed to build and maintain a typical aluminium-hulled gillnetter and a typical fibreglass-hulled gillnetter (see Table 58).

i. No data were available upon which to base an estimate of the average labour and energy inputs and greenhouse gas emissions associated with building and maintaining a typical troller. As a result, I have simply assumed that the inputs and emissions per tonne of salmon landed by trollers falls approximately mid-way between the inputs, per tonne of salmon landed, for gillnetters and seiners.

## Ecological Footprint of Salmon Harvesting Technologies

Landing a generic tonne of salmon using purse seine technology required a labour input of approximately 4.2 person-days, a fossil fuel equivalent industrial energy input of about 17,000 MJ, and resulted in greenhouse gas emissions equal to approximately 1.35 tonnes of carbon dioxide (Table 71). The forest ecosystem support associated with assimilating this quantity of $CO_2$ amounts to approximately 0.37 ha[221] while the labour inputs require the additional support of approximately 0.01 ha[222] of marine ecosystem and 0.03[223] ha of terrestrial ecosystem. The total resulting ecological footprint associated with purse seining equals approximately 0.41 ha/tonne.

Similarly, a tonne of salmon landed using gillnet technology required a labour input of about 12.7 person-days, a total energy input of approximately 34,100 MJ, and resulted in total greenhouse gas emissions equivalent to approximately 2.86 tonnes of carbon dioxide (Table 71). The forest ecosystem support required to assimilate this quantity of $CO_2$ amounts to approximately 0.78 ha[224]. To sustain the labour inputs, an additional approximately 0.03 ha[225] of marine ecosystem support and 0.08 ha[226] of terrestrial ecosystem support is required. As a result, the total ecological footprint associated with harvesting salmon using gillnet technology amounts to approximately 0.89 ha per tonne.

Finally, a tonne of salmon landed by commercial trollers required a labour input of about 11.6 person-days, a total fossil fuel equivalent energy input of approximately 34,300 MJ, and resulted in greenhouse gas emissions equivalent to approximately 2.9 tonnes of carbon dioxide (Table 71). The forest ecosystem support required to assimilate this quantity of $CO_2$ amounts to about 0.79 ha[227] while the support required to sustain the labour inputs amounts to about 0.03 ha[228] of marine

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[221] Calculated by dividing 1.35 t $CO_2$ by 3.6644 t $CO_2$/ha, the average British Columbia forest ecosystem $CO_2$ assimilation rate used throughout this research.

[222] Calculated by dividing 4.2 days by 365 days per year and then multiplying the divisor by 0.96 ha, the area of marine ecosystem required to support the average Canadian's annual food consumption.

[223] Calculated by dividing 4.2 days by 365 days per year and then multiplying the divisor by 2.40 ha, the area of terrestrial ecosystem required to support the average Canadian's annual food consumption.

[224] Calculated by dividing 2.86 t $CO_2$ by 3.6644 t $CO_2$/ha, the average British Columbia forest ecosystem $CO_2$ assimilation rate used throughout this research.

[225] Calculated by dividing 12.7 days by 365 days per year and then multiplying the divisor by 0.96 ha, the area of marine ecosystem required to support the average Canadian's annual food consumption.

[226] Calculated by dividing 12.7 days by 365 days per year and then multiplying the divisor by 2.40 ha, the area of terrestrial ecosystem required to support the average Canadian's annual food consumption.

[227] Calculated by dividing 2.90 t $CO_2$ by 3.6644 t $CO_2$/ha, the average British Columbia forest ecosystem $CO_2$ assimilation rate used throughout this research.

[228] Calculated by dividing 11.7 days by 365 days per year and then multiplying the divisor by 0.96 ha, the area of marine ecosystem required to support the average Canadian's annual food consumption.

ecosystem and 0.08 ha[229] of terrestrial ecosystem. Therefore, the total ecological footprint associated with harvesting a tonne of salmon using troll fishing gear amounts to approximately 0.90 ha.

### Energy Return On Investment Ratios of Different Harvesting Technologies

Using the total industrial energy inputs associated with harvesting a tonne of salmon using the three different fishing gears (Table 71), I estimated the: 1) gross edible energy return on the industrial energy investment ratio, and 2) the edible protein energy return on the industrial energy investment ratio for each type of gear (Table 72).

*Table 72. Energy Return on Investment Ratios of Commercial Salmon Harvesting Technologies*

| Efficiency Measure | Harvesting Technology | | |
|---|---|---|---|
| | Purse Seine | Gillnet | Troll |
| Gross Edible Energy Return on Total Industrial Energy Investment[a] | 29% | 15% | 14% |
| Edible Protein Energy Return on Total Industrial Energy Investment[b] | 18% | 9.0% | 8.9% |

Notes: a. Calculated by dividing 4,940 MJ of gross edible energy per live weight tonne of salmon (assumes that 65% of a carcass is edible and the gross wet weight energy content of salmon flesh is 7.6MJ/kg) by the total industrial energy input for each gear type from Table 71.
b. Calculated by dividing 3,068 MJ of edible protein energy per live weight tonne of salmon (assumes that 20% of the edible portion of a carcass is protein that has a gross energy content of 23.6 MJ/kg) by the total industrial energy input for each gear type from Table 71.

Purse seining provides approximately double the edible energy return on the industrial energy invested when compared with either gillnet or troll fishing technologies (Table 72).

## Sensitivity Analysis

In this section I explore the degree to which the results of the analysis are sensitive to changes to some of the input parameters and assumptions. This is important because it provides an indication of the robustness of the results.

While dozens of input parameters and assumptions have gone into this analysis, I only explore the effect of altering four of them. These four were chosen because they affect the sub-models differently or in a non-linear manner. For example, as part of the sensitivity analysis, I have not analysed the effect of using alternative carbon dioxide assimilation values for forest ecosystems although a range

[229] Calculated by dividing 11.7 days by 365 days per year and then multiplying the divisor by 2.40 ha, the area of terrestrial ecosystem required to support the average Canadian's annual food consumption.

of values could have been used[230]. This is because while increasing or decreasing the carbon assimilation rate would clearly affect the absolute size of the carbon sink portion of each system's ecological footprint, their relative size would not change.

The four input parameters or assumptions whose effect on the model I explored are:

1. changing the accounting convention used to address the partitioning problem,
2. the effect of reducing the feed consumption rate within the intensive salmon culture sub-model,
3. using a uniform net primary productivity value for all marine ecosystem support calculations, and
4. the effect of changes in the average trophic level of marine organism inputs to both sub-models.

## *Alternative Accounting Conventions to Address the Partitioning Problem*

Throughout the base case analysis, inputs to co-products of other economic activities were allocated in direct proportion to their mass. In practice, adopting this accounting convention meant that the inputs and ecosystem support associated with salmon feed included the inputs to produce:

- a quantity of chicken equal to the wet weight of livestock by-products, whose meals ultimately constitute 12% by weight of the salmon feed modelled (Table 17), and
- fish meal and oil derived from herring carcasses from the roe herring fishery that together comprise 9.3% of the salmon feed modelled (Table 17).

### Treating Co-Products as Free Inputs

As discussed in Chapter 4, an alternative but less appropriate accounting convention is to treat these inputs as essentially biologically and energetically "free". Practically, the effect of this approach is that the feed, labour and industrial energy required to grow and/or harvest the biomass represented is

[230] For example, while I used a carbon dioxide assimilation rate of 3.66 tonnes $CO_2$/ha/yr (which is equivalent to 1 t C/ha/yr) throughout my model, other recent ecological footprint analyses have used assimilation rates of approximately 1.5 tonnes $CO_2$/ha/yr (Folke *et al.* 1997), 6.6 tonnes $CO_2$/ha/yr (Wackernagel and Rees 1996), and 18.3 tonnes $CO_2$/ha/yr (Larsson, *et al.* 1994).

zero. However, the inputs associated with transporting and processing livestock by-products and herring carcasses into their respective meals remain "chargeable" to the production of salmon feed and farmed salmon.

In order to test the impact of this alternative accounting convention, I recalculated the ecological footprint and energy costs of both salmon feed and farmed salmon by treating livestock by-products and herring carcasses are free inputs but holding all other factors constant (Table 73).

*Table 73. Effect of Treating Livestock By-Products and Herring Carcasses as "Free"*

| Result | Accounting Convention Applied to Co-Products from Other Activities | |
|---|---|---|
| | Inputs Follow Mass[a] | Inputs are Free[b] |
| Per Tonne of Salmon Feed Produced: | | |
| - Marine ecosystem support required | 5.6 ha | 4.8 ha |
| - Agricultural ecosystem support required | 0.58 ha | 0.13 ha |
| - Total industrial energy input required[c] | 48,100 MJ | 15,347 MJ |
| Per Tonne of Intensively Cultured Atlantic Salmon Produced: | | |
| - Marine ecosystem support required | 9.9 ha | 8.5 ha |
| - Agricultural ecosystem support required | 1.0 ha | 0.2 ha |
| - Other terrestrial ecosystem support required | 1.8 ha | 0.6 ha |
| - Total industrial energy input required[c] | 93,960 MJ | 36,100 MJ |
| - Gross edible energy return on industrial energy invested | 5.2% | 13.7% |
| - Edible protein energy return on industrial energy invested | 3.3% | 8.5% |
| Per Tonne of Intensively Cultured Chinook Salmon Produced: | | |
| - Marine ecosystem support required | 12.4 ha | 10.6 ha |
| - Agricultural ecosystem support required | 1.3 ha | 0.3 ha |
| - Other terrestrial ecosystem support required | 2.2 ha | 0.8 ha |
| - Total industrial energy input required[c] | 116,740 MJ | 44,600 MJ |
| - Gross edible energy return on industrial energy invested | 4.2% | 11.1% |
| - Edible protein energy return on industrial energy invested | 2.6% | 6.9% |

Notes: a. Values in this column simply reiterate the findings of the base case analysis that were derived using the accounting convention that inputs associated with providing livestock by-products and herring carcasses are proportionate to their mass.
b. Values in this column reflect the effects of assuming that livestock by-products and herring carcasses from the roe herring fishery are biologically and energetically free inputs. The industrial energy inputs associated with the further processing and transportation of these inputs remains fully "chargeable" to the ultimate user and is therefore incorporated into the model.
c. Expressed as fossil fuel equivalents

It is clear that the choice of whether co-products of other economic activities are treated as biologically and energetically free, can have a dramatic effect on the outcome of the analysis (Table 73). Specifically, in treating the approximately 21% by weight of salmon feed that is derived from by-products and herring carcasses as free, the industrial energy inputs chargeable to the feed decreases by approximately 68%, while the energy inputs chargeable to salmon drop by

approximately 62%. More dramatic, however, is the effect on the terrestrial ecological footprint. Under the free input convention, the agricultural ecosystem support to salmon feed and farmed salmon drops by over 75% while the remaining terrestrial ecosystem support for farmed salmon decreases by approximately 55%.

To put this into perspective, Figure 25 presents the total ecological footprint associated with intensively cultured Atlantic and chinook salmon under both the base case accounting convention (that inputs to co-products follow mass), and the alternative convention (that these inputs are free). For comparison, Figure 25 also includes the ecosystem support area associated with commercially caught chinook, coho, sockeye, chum and pink salmon.

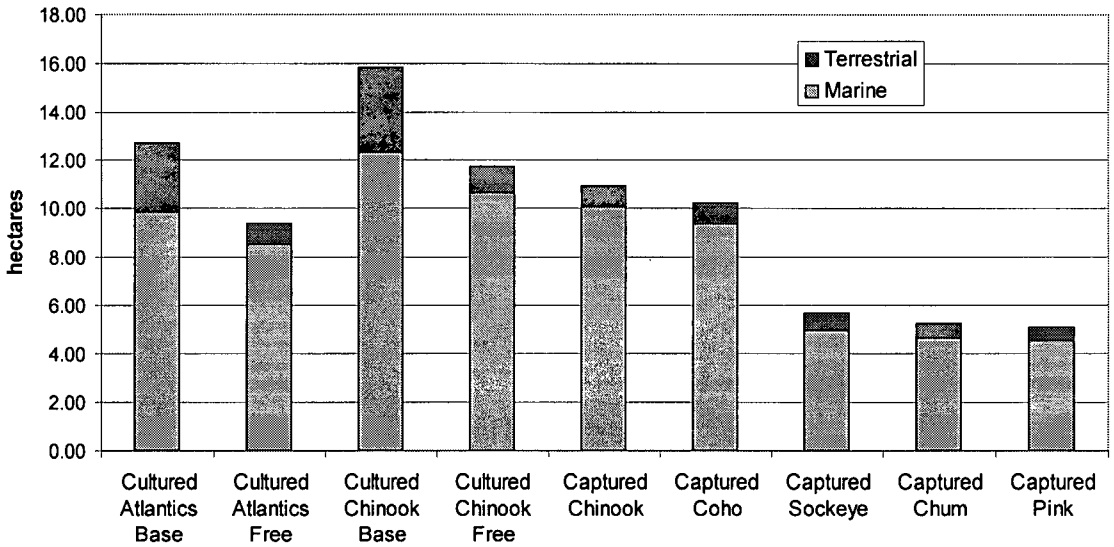


*Figure 25. Effect of Treating Co-Product Derived Inputs to Salmon Feed as Free Inputs on the Ecological Footprint of Farmed Salmon*

Notes to Figure 25: The "Cultured Atlantics Base" and "Cultured Chinook Base" bars reflect the ecosystem support required to produce a tonne of salmon under the base case assumption that inputs to co-product derived salmon feed components follow their mass. The "Cultured Atlantics Free" and "Cultured Chinook Free" bars reflect the ecosystem support required to produce a tonne of salmon under the alternative assumption that inputs to co-product derived feed components are provided biologically and energetically "free of charge".

While the ecological footprint associated with both intensively cultured Atlantic and chinook salmon is reduced when adopting the convention that feed components derived from co-products are free, for the most part the ecological footprint of commercially caught salmon remains smaller (Figure 25). Only farmed Atlantic salmon modelled under the free co-product convention has a smaller ecological footprint than that associated with commercially caught chinook and coho salmon. Commercially

caught sockeye, chum and pink salmon still have the smallest ecological footprints regardless of which accounting convention is used.

### Using Relative Economic Value as a Partitioning Criterion

A third accounting convention that could be used to address the partitioning problem would be to assign inputs required to provide a given co-product in proportion to its economic value to the industry that is producing it. For example, the biophysical inputs associated with producing blood or feathers from the poultry processing industry could be assigned to subsequent consumers of these co-products (for example farmed salmon) on the basis of their relative economic value to chicken processors. Such an approach is conceptually tenable given that currently in North America, few live-stock by-products are true wastes in the sense that they have zero economic value.

However, because of the complexity that it would add to the current model, it is beyond the scope of this research to exhaustively explore the effect of employing relative value as the basis of an accounting convention. This is primarily because to fully explore the implications of this convention, a range of relative economic values would have to be run through the model for each of the co-product derived components of salmon feed. Yet without generating a detailed model, it is possible to make the following observations. Using relative economic value will never result in lower biophysical costs chargeable to subsequent users of co-products than by employing the convention that all co-product derived inputs are free. It is possible though that by using relative economic value, the biophysical costs of some co-product could exceed that which results when using mass as the partitioning criterion. This can be illustrated using blood from poultry processing as an example. Typically, the recovery of whole blood from poultry processing runs between 3.1% and 4.2% of the live weight of the bird (Polin,1992). Therefore, in any situation in which the economic value of the recovered blood exceeds 4.2% of the total economic value of the slaughtered bird, the biophysical costs chargeable to any secondary consumers of that blood, including farmed salmon, would be greater when using relative economic value instead of mass as the partitioning criteria.

Before continuing with other aspects of the sensitivity analysis, it is important to make the following observation. The effect of adopting one partitioning problem convention over another is exaggerated when a higher proportion of the inputs to salmon feed are derived from co-products of other activities. Conversely, the effect is reduced if the proportion of co-product derived inputs used is decreased, to the point that when no co-products are used, the choice of which accounting convention to employ becomes moot.

## *Reducing the Rate of Total Feed Use by the Intensive Salmon Culture Industry*

As feed accounts for approximately 90% of the total biophysical costs associated with intensive salmon culture, it was important to evaluate what effect changing the total feed use rate has on the ecological and energy efficiency of the salmon culture system as a whole. In particular, exploring the impact of reducing the feed use rate is most meaningful as the industry is constantly working to decrease their feed consumption per tonne of salmon produced[231]. For example, there are undocumented reports that some companies in British Columbia currently achieve total feed use rates of approximately 1.3 tonnes of feed per tonne of Atlantic salmon produced (Mr. Jason Mann, EWOS Canada Ltd. pers. comm. 1998). Similarly, in other jurisdictions the industry-wide average feed use rate is reported to be below 1.4 tonnes of feed per tonne of salmon produced (Dr. John Forster, salmon farming industry consultant, pers. comm. 1999).

To test how feed use rate reductions affect the biophysical costs of intensive salmon culture, I ran a series of alternative rates through the model of both Atlantic and chinook salmon while maintaining all other input parameters and assumptions constant. The alternative feed use rates used for Atlantic salmon were 1.3, 1.4, 1.5, 1.6, and 1.7 tonnes of feed per tonne of salmon produced (Table 74 and Figure 26) while the alternative rates used for chinook were 1.7, 1.8, 1.9, 2.0, and 2.1 tonnes of feed per tonne of salmon produced (Table 75 and Figure 27).

[231] This is because feed represents the largest single cost sector in salmon farming (Forster 1995, Higgs 1997)

*Table 74. Ecosystem Support and Energy Efficiency that Results from Reducing the Total Feed Used in Atlantic Salmon Culture*

| Result | Major effects of reducing total feed use rate (tonnes of feed: tonne of salmon produced) | | | | | |
|---|---|---|---|---|---|---|
| | 1.77:1[a] | 1.7:1 | 1.6:1 | 1.5:1 | 1.4:1 | 1.3:1 |
| Marine ecosystem support (ha) | 9.9 | 9.5 | 8.9 | 8.4 | 7.8 | 7.3 |
| Terrestrial ecosystem support (ha) | 2.8 | 2.7 | 2.6 | 2.4 | 2.3 | 2.1 |
| Total industrial energy input (MJ)[b] | 94,000 | 90,700 | 85,900 | 81,100 | 76,300 | 71,500 |
| Gross edible energy return on industrial energy invested | 5.2% | 5.4% | 5.7% | 6.1% | 6.5% | 6.9% |
| Edible protein energy return on industrial energy invested | 3.3% | 3.4% | 3.6% | 3.8% | 4.0% | 4.3% |

Notes: a. The results in this column reiterate the base case analysis results under a total feed use rate of 1.77 tonnes of feed per tonne of salmon produced.
b. All energy input values are expressed in fossil fuel equivalents.

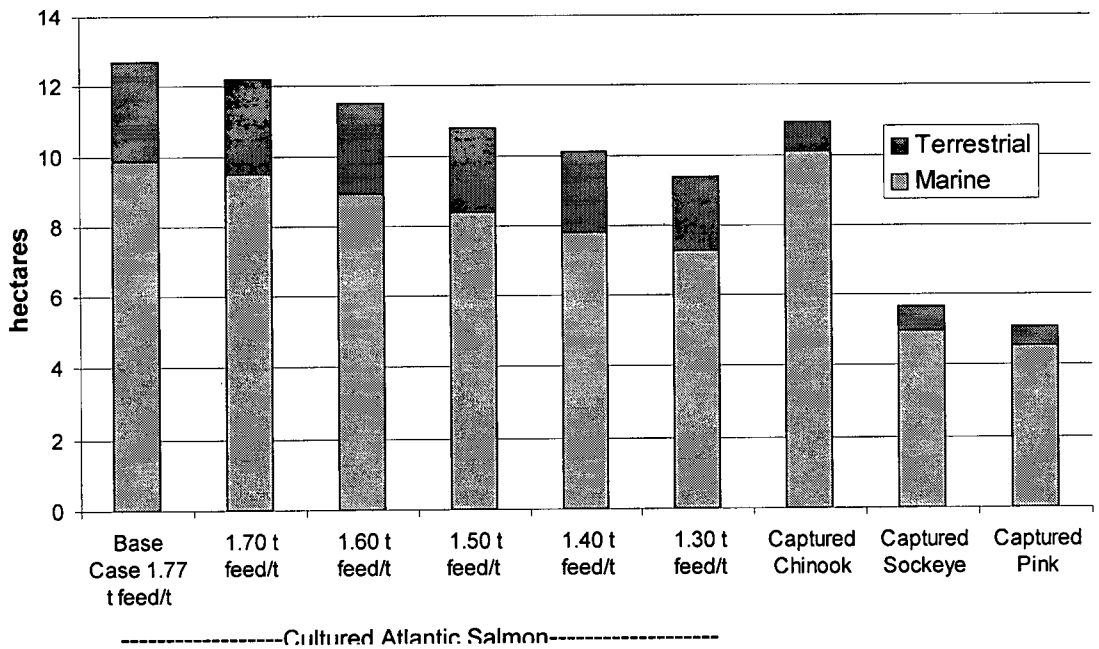


*Figure 26. Ecological Footprint Required to Produce One Tonne of Intensively Cultured Atlantic Salmon Under a Range of Total Feed Use Rates*

(Note to Figure26: The ecological footprint of commercially caught chinook, sockeye and pink salmon are included for comparison.)

*Table 75. Ecosystem Support and Energy Efficiency that Results from Reducing the Total Feed Used in Chinook Salmon Culture*

| Result | Major effects of reducing total feed use rate (tonnes of feed: tonne of salmon produced) | | | | | |
|---|---|---|---|---|---|---|
| | 2.2:1[a] | 2.1:1 | 2.0:1 | 1.9:1 | 1.8:1 | 1.7:1 |
| Marine ecosystem support (ha) | 12.4 | 11.7 | 11.2 | 10.6 | 10.1 | 9.5 |
| Terrestrial ecosystem support (ha) | 3.6 | 3.4 | 3.2 | 3.1 | 2.9 | 2.8 |
| Total industrial energy input (MJ)[b] | 116,700 | 111,800 | 107,000 | 102,200 | 97,400 | 92,600 |
| Gross edible energy return on industrial energy invested | 4.2% | 4.4% | 4.6% | 4.8% | 5.1% | 5.3% |
| Edible protein energy return on industrial energy invested | 2.6% | 2.7% | 2.9% | 3.0% | 3.2% | 3.3% |

Notes: a. The results in this column reiterate the base case analysis results under a total feed use rate of approximately 2.2 tonnes of feed per tonne of salmon produced.
b. All energy input values are expressed in fossil fuel equivalents.

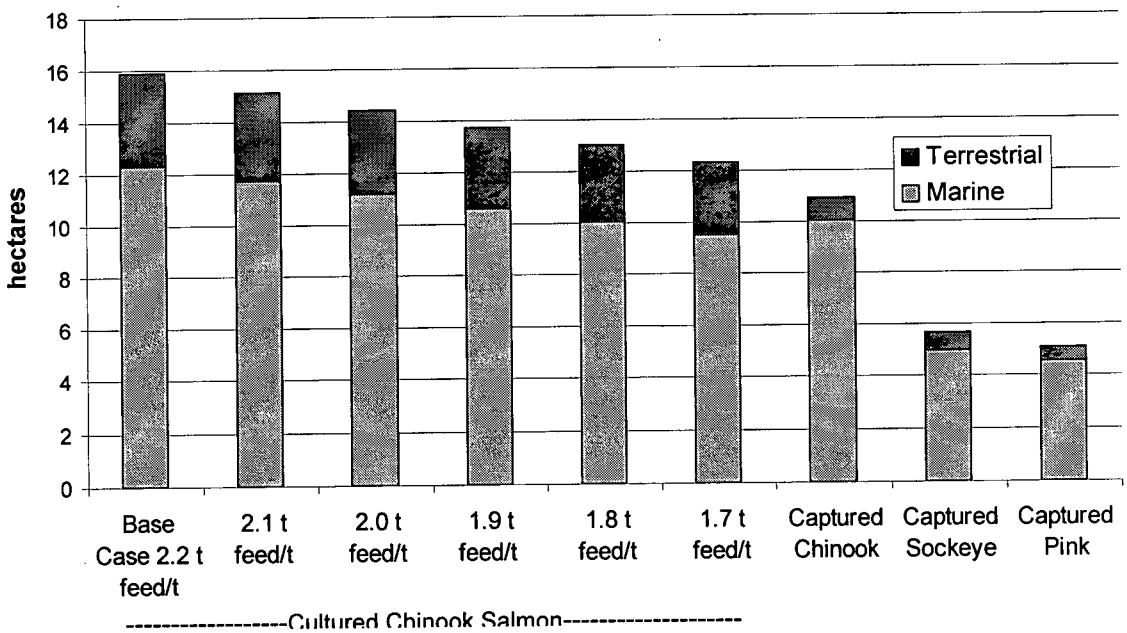


*Figure 27. Ecological Footprint Required to Produce One Tonne of Intensively Cultured Chinook Salmon Using a Range of Total Feed Use Rates*

(Note to Figure 27: The ecological footprint of commercially caught chinook, sockeye and pink salmon are included for comparison.)

From the data in Tables 74 and 75 and from Figures 26 and 27, relatively small changes in the total feed use rate can have a marked effect on both the ecological footprint and energy efficiency of intensive salmon culture. In addition, at total feed use rates of approximately 1.5 tonnes of feed per tonne of salmon produced and below, the total ecological footprint associated with intensive salmon culture drops within the range of ecosystem support associated with some commercially caught

species (Figure 26). However, it is worth noting that even at the lowest total feed input rate modelled, 1.3 tonnes feed/tonne of Atlantic salmon produced, the ecological footprint associated with salmon culture remains larger than that associated with commercially caught sockeye, chum or pink salmon, the three most abundant salmon species harvested in British Columbia. Similarly, the energy efficiency of intensive salmon culture, as measured using either of the energy return on investment ratios calculated, remains much poorer than the energy efficiency associated with commercially caught salmon over the entire range of alternative feed input rates used (see Tables 70, 74 and 75).

## *Net Primary Productivity*

Throughout the research, I employed estimates of net primary productivity that I believe best represented the source ecosystems that sustain either the prey of wild salmon or the marine organism based inputs to salmon feed. Furthermore, in order to minimise uncertainty that could result from using primary productivity estimates from a variety of sources, I opted to use a single source reference for all of the marine net primary productivity values used in this research (Longhurst *et al.* 1995).

An alternative approach would be to use a constant net primary productivity value throughout the various sub-models while holding all other input parameters and assumptions constant. Effectively this allows a direct comparison to be made of the primary productivity required to sustain the production of a tonne of salmon under the two systems.

While a number of different global marine net primary productivity values could be used, I have chosen to use 282 g $C/m^2/yr$, the global average marine net primary productivity estimate of Longhurst *et al.* (1995). Figure 28 displays the marine ecological footprint for each of the cultured and captured salmon species produced in British Columbia using: 1) the same source ecosystem specific estimates of net primary productivity that were used in the base case model, and 2) a uniform net primary productivity estimate of 282 g $C/m^2/yr$ throughout the model.

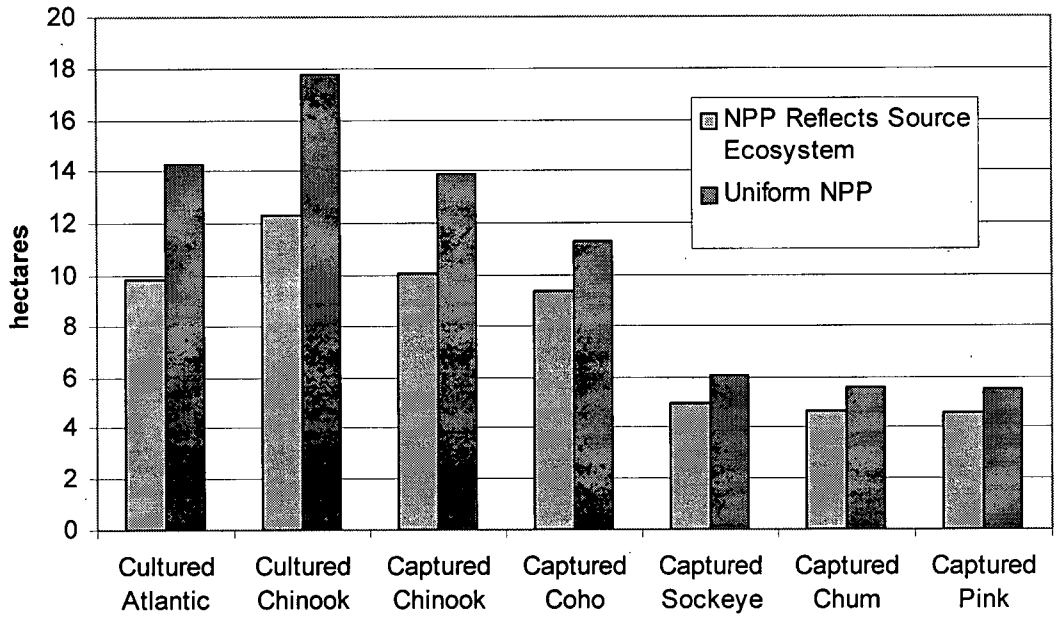


*Figure 28. Marine Ecosystem Support to Produce One Tonne of Salmon Using Both Source Ecosystem Specific and Uniform Estimates of Net Primary Productivity*

By assigning a uniform net primary productivity value throughout the model, the relative results found in the base case analysis remain the same (Figure 28). Intensively cultured chinook salmon require the largest area of marine ecosystem support while the ecosystem support associated with Atlantic salmon culture is comparable to that of commercially caught chinook salmon with the remaining commercially caught species, coho, sockeye, chum and pink salmon, requiring progressively smaller areas of marine ecosystem support. This relative result would remain the same for any uniform net primary productivity value used throughout the model even though the absolute areas of marine ecosystem support would change.

Finally, it should also be noted that the difference in the relative size of the ecosystem support area required to grow a tonne of sockeye, chum or pink salmon is greater than that required to grow a tonne of cultured chinook or Atlantic salmon when a uniform net primary productivity value is used throughout the model then when source ecosystem specific net primary productivity values are used[232]. In other words, the source ecosystem specific net primary productivity values used in the

[232] For example, when using source ecosystem specific net primary productivity values in the model, the marine ecosystem support area to grow a tonne of sockeye salmon is approximately 50% of that required to grow a tonne of cultured Atlantic salmon and only 40% of that to grow a tonne of cultured chinook salmon. However, when a uniform net primary productivity value is used throughout the model the marine ecosystem support required to grow a tonne of sockeye salmon is only 42% of that required for a tonne of cultured Atlantic salmon and 34% of that required to grow a tonne of cultured chinook.

base case model tend to down-play the difference in marine ecosystem support required to produce a tonne of cultured and captured salmon.

## Average Trophic Level of Aquatic Inputs

Another input parameter that has the potential to significantly affect the size of the marine ecosystem support to produce a tonne of salmon are the estimates of the average trophic level of 1) prey consumed by salmon foraging in the wild, and 2) the organisms used to provide fish meal and oil inputs to salmon feed. This is because in Equation 1 (used to calculate the primary productivity required to sustain a given biomass of marine organisms), the average trophic level of organisms is incorporated as an exponential to the base ten. As a result, relatively small changes in the estimated average trophic level can have a relatively large impact on the resulting primary productivity required and consequently the ecosystem support area needed.

This effect can be demonstrated by re-calculating the marine ecological footprint to produce a tonne of wild chinook, coho, sockeye, chum and pink salmon using the mean, and the lower and upper 95% confidence limits of the mean trophic level of their prey (Table 76).

*Table 76. Marine Ecological Footprint to Produce of a Tonne of Each Species of Commercially Caught Salmon Using the Mean, and the Lower and Upper 95% Confidence Limits of the Mean Trophic Level of Their Prey*

| Species | Lower 95% Confidence Limit of the Mean T.L. of Prey [a] | Mean Trophic Level of Prey[a] | Upper 95% Confidence Limit of the Mean T.L. of Prey [a] | Area, in Hectares, of Marine Ecosystem Support Required to Produce a Tonne of Salmon Using the | | |
|---|---|---|---|---|---|---|
| | | | | Lower 95% Conf. Limit | Mean Trophic Level | Upper 95% Conf. Limit |
| Chinook | 2.85 | 2.90 | 2.95 | 9.0 | 10.1 | 11.3 |
| Coho | 2.74 | 2.81 | 2.88 | 8.0 | 9.4 | 11.0 |
| Sockeye | 2.39 | 2.54 | 2.69 | 3.5 | 5.0 | 7.0 |
| Chum | 2.43 | 2.51 | 2.59 | 3.9 | 4.6 | 5.6 |
| Pink | 2.41 | 2.50 | 2.59 | 3.7 | 4.5 | 5.6 |

Notes: a. From Appendix I.

To illustrate the effect of using these alternative trophic level values, Figure 29 presents the marine ecological footprint of each species of commercially caught salmon using the mean and the lower and upper 95% confidence limit of the mean trophic level of their prey as well as that associated with farmed Atlantic and chinook salmon.

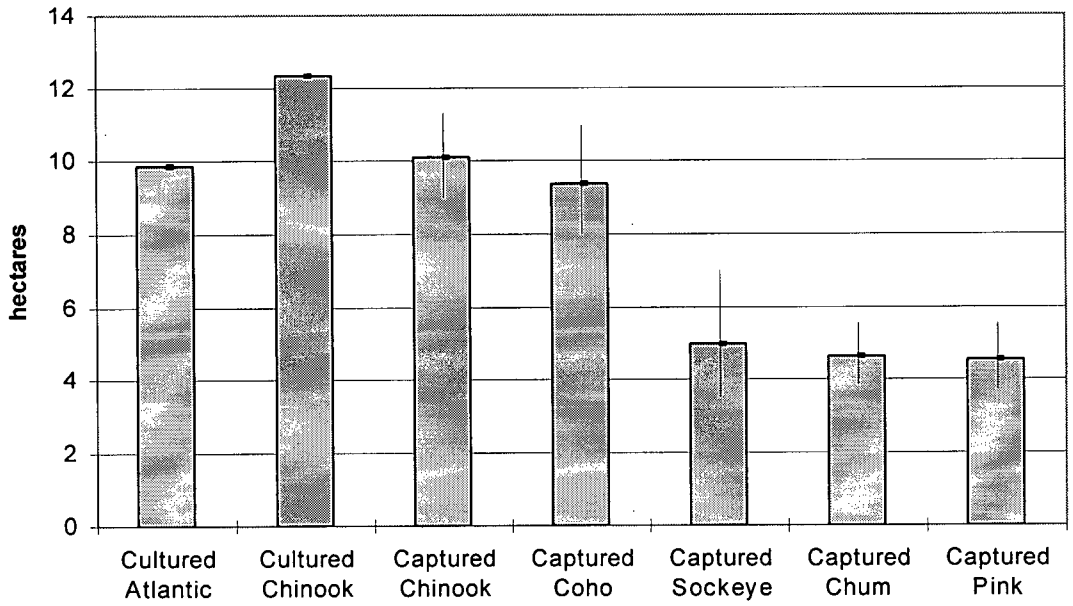


*Figure 29. Marine Ecological Footprint of Wild Caught Salmon Using the Mean and the Lower and Upper 95% Confidence Limits of the Mean Trophic Level of Their Prey*

It is clear from Table 76 and Figure 29 that relatively small changes in the trophic level values used to calculate the primary productivity required can result in relatively large changes in the total marine ecological footprint. It is interesting to note, however, that sockeye, chum and pink salmon still have the smallest marine ecological footprint of all salmon modelled even when using the upper 95% confidence limits of the mean prey trophic level to calculate ecosystem support required.

# Chapter 7: Conclusions and Discussion

In this chapter I draw on the results presented in Chapter 6 to answer the research questions originally posed. In doing so, I also compare my results with those of previous biophysical analyses of fishing, aquaculture, and terrestrial food production systems. This is followed by a discussion of some additional insights gained through the process of conducting this research along with its broad sustainability implications.

## Answering the Research Questions Posed

### *Are there differences between the biophysical costs associated with the commercial fishery and the intensive salmon culture industry?*

Under the assumptions and input parameters used, there are clear differences in the biophysical costs associated with producing salmon in B.C. Differences are evident between both the production systems employed and the species produced within a given production system.

As currently practised in British Columbia, intensive salmon culture is the most biophysically "costly" and hence least sustainable method of producing salmon. This general conclusion holds, to a greater or lesser extent, regardless of the metric used to measure biophysical efficiency. Moreover, this broad outcome endured under most of the alternative input parameters and assumptions explored as part of the sensitivity analysis. The only partial exceptions occurred when co-products of other economic activities were treated as biophysically free inputs to farmed salmon feed and when total feed use rates by farmed salmon fall below 1.6 tonnes per tonne of salmon produced.

#### Using Ecological Footprint Analysis to Compare the Systems

This research is the first time that ecological footprint analysis has been used to compare the relative biophysical sustainability of a commercial fishery exploiting largely wild fish stocks and a competing intensive culture system.

The results indicate that both farmed Atlantic and chinook salmon have a larger total ecological footprint than any of the five commercially harvested species. At over 12.5 ha per tonne of farmed Atlantic salmon, and 16 ha per tonne of farmed chinook, this difference is most pronounced in

comparison with wild caught sockeye, chum and pink salmon whose footprints are all under 6 ha per tonne. In between these two groups are commercially caught coho and chinook salmon whose ecological footprint's fall between 10 and 11 ha per tonne (Table 77 and Figure 18).

*Table 77. Ecological Footprint of Farmed and Commercially Caught Salmon as of 1996*

| | Ecosystem Support per Tonne of Salmon Produced[a] | | | Total 1996 Production in B.C. (tonnes)[b] | Ecosystem Support to All Salmon Produced in 1996 | | |
|---|---|---|---|---|---|---|---|
| | Terrestrial (ha) | Marine (ha) | Total (ha) | | Terrestrial ($km^2$) | Marine ($km^2$) | Total ($km^2$) |
| Farmed: | | | | | | | |
| - Atlantic | 2.8 | 9.9 | 12.7 | 18,139 | 508 | 1,796 | 2,304 |
| - chinook | 3.6 | 12.4 | 16.0 | 8,023 | 289 | 995 | 1,284 |
| Commercially harvested: | | | | | | | |
| - chinook | 0.87 | 10.1 | 11.0 | 426 | 4 | 43 | 47 |
| - coho | 0.87 | 9.3 | 10.2 | 3,320 | 29 | 309 | 338 |
| - sockeye | 0.68 | 5.0 | 5.7 | 15,007 | 102 | 750 | 852 |
| - chum | 0.59 | 4.6 | 5.2 | 6,271 | 37 | 289 | 326 |
| - pink | 0.53 | 4.5 | 5.0 | 8,140 | 43 | 366 | 409 |
| | | | **Totals:** | **59,326** | **1,012** | **4,548** | **5,560** |

Notes: a. From Tables 61, 62 and 69.
b. All values in round weights. Farmed salmon production data from B.C. Salmon Farmers Association, pers. comm. 1998. Commercial salmon landings data from Fisheries and Oceans annual B.C. Catch Statistics.

When these ecosystem support areas are applied to the entire production of farmed and commercially caught salmon in B.C. in 1996, the total ecological footprint amounts to over 5,500 square kilometres. Of this, approximately 1,000 $km^2$ of terrestrial ecosystem support is needed along with about 4,500 $km^2$ of marine ecosystem support (Table 77).

Considering the marine portion of the ecological footprint specifically, cultured salmon appropriate ecosystem support at a rate that is, at best, comparable to some species of wild salmon (chinook and coho) and, at worst, much greater than that appropriated by other wild species (sockeye, chum and pink) (Table 77). Remarkably, this occurs in spite of the fact that only 56% of the farmed salmon diet, as modelled, was derived from marine ecosystems (Table 17) while the feed required to grow commercially caught salmon is drawn almost exclusively from marine ecosystems[233]. This result holds even when using a uniform net primary productivity value for all source ecosystems (Figure 28).

[233] The only exception to this is the tiny amount of terrestrial origin feed consumed by hatchery-origin chinook and coho salmon smolts.

This relatively inefficient use of marine primary productivity on the part of farmed salmon in part reflects their relatively poor conversion of feed energy into fish biomass energy when all system-wide losses of feed are accounted for. For example, while the feed energy conversion efficiency of contemporary Atlantic and chinook salmon culture was estimated to be 19.2% and 15.4% respectively, this is below the 22.8% feed conversion efficiency, as estimated by Brett (1986), that was used to model the ecological footprint of wild salmon.

Another factor that contributes to the relatively large size of the marine ecological footprint of farmed salmon is the average trophic level at which they functionally "feed" within marine ecosystems. Specifically, the fish represented by the fish meal components of the salmon feed modelled occupy an average trophic level of slightly over 2.9 (Table 20). Meanwhile, the average trophic level at which wild salmon feed ranges from as low as 2.5 in the case of pink salmon to 2.9 in the case of chinook salmon (Appendix I and Table 37).

The only situations tested as part of the sensitivity analysis in which the marine ecosystem support to farmed Atlantic salmon dropped markedly below that of wild caught chinook or coho occurred when:

1. the fish processing waste derived meal and oil inputs to salmon feed were treated as biophysically free (Figure 25), or

2. the total feed consumption rate of farmed Atlantics was reduced (Figure 26).

However, in no situation tested as part of the sensitivity analysis did the marine ecosystem support to farmed salmon drop to near that of wild sockeye, chum or pink salmon.

Considering the terrestrial component of the ecological footprint, the differences between production systems are even more pronounced. Farmed Atlantic and chinook salmon appropriate an area of terrestrial ecosystem support that is three and four times larger, respectively, than that associated with commercially caught chinook or coho and over five and six times larger than that associated with commercially caught pink salmon per tonne of salmon produced (Table 77 and Figure 18).

These large differences reflect two main factors. Much larger areas of hypothetical $CO_2$ sink forest are required to support farmed salmon production as it results in much greater quantities of energy-related greenhouse gases being emitted per tonne of salmon produced than is the case with commercially harvested salmon (Tables 61, 62, and 64 through 68). Secondly, over 40% of the diet of farmed salmon is derived either directly or indirectly from agricultural ecosystems.

The only situation tested as part of the sensitivity analysis in which the terrestrial ecosystem support to farmed salmon was reduced to a level comparable to wild caught salmon occurred when all co-product derived inputs to salmon feed were treated as biophysically free (Table 73 and Figure 25).

### *Comparing My Results with Previous Ecological Footprint Analyses*

Prior to this research, only three ecological footprint analyses have been conducted of fish or shellfish production systems. Without explicitly referring to it as ecological footprint analysis, Folke (1988) evaluated the ecosystem support required to grow Atlantic salmon within the context of four ocean ranching options and an intensive net-pen culture operation in Sweden. Amongst other things, he found that both ocean ranching and intensive culture relied on large, yet similarly-sized areas of marine ecosystem support to grow the same quantity of salmon. However, the terrestrial ecosystem support to grow crop-based feed inputs to farmed salmon was approximately two orders of magnitude larger than that associated with ranched salmon production (Table 78).

More recently, Larsson *et al.* (1994) used ecological footprint analysis to account for a range of biological and industrial inputs to semi-intensive pond culture of shrimp in Colombia. Their analysis found that together, the aquatic and terrestrial ecosystem support to shrimp culture can exceed the area occupied by the culture facility itself by between 37 and 189 times[234].

Finally, Berg *et al.* (1996) conducted an analysis of hypothetical intensive cage and semi-intensive pond culture systems for tilapia in Zimbabwe. While a direct comparison of the ecosystem support appropriated by these two culture systems is not appropriate as the analysis of the pond culture system explicitly excluded ecosystem support associated with exogenously sourced feed inputs, the results indicate that the total ecosystem support to the intensive culture system would exceed the area occupied by the facility itself by about five orders of magnitude.

The results of these three analyses, all normalised per tonne of output produced, are summarised in Table 78 along with the results of the current research.

[234] This large variation in ecosystem support results primarily from uncertainty with respect to the area of mangrove forest needed as a nursery for juvenile shrimp before they are brought into the culture pond (Larsson *et al.* 1994).

*Table 78. Ecological Footprints of Aquatic Food Production Systems*

| Production System | Ecological Footprint | | Analysis Includes Ecosystem Support to | Source |
|---|---|---|---|---|
| | Aquatic (ha/tonne) | Terrestrial (ha/tonne) | | |
| Farmed Atlantic salmon in Sweden | 100 | 7.5 | feed | Folke 1988 |
| Atlantic salmon ranching in Sweden - all interception fishing is stopped so that ranched fish are harvested exclusively in the vicinity of the hatchery | 125 | < 0.08 | feed | Folke 1988 |
| Atlantic salmon ranching in Sweden - interception fisheries continue so that returns to the hatchery are reduced | 525 | <0.08 | feed | Folke 1988 |
| Semi-intensive shrimp culture in Colombia | 5.4 | 3.8 to 42 | feed, energy, water and supply of wild juveniles | Larsson *et al.* 1994[a] |
| Intensive net-pen culture of Tilapia in Zimbabwe | 17 | 0.3 | feed, $O_2$ production, P assimilation | Berg *et al.* 1996[b] |
| Semi-intensive pond culture of Tilapia in Zimbabwe | 0.28 | 0 | $O_2$ production, P assimilation | Berg *et al.* 1996[c] |
| **Farmed Atlantic salmon in B.C.** | **9.9** | **2.8** | **feed, energy, materials, labour** | **This analysis** |
| **Farmed chinook salmon in B.C.** | **12.4** | **3.6** | **feed, energy, materials, labour** | **This analysis** |
| **Commercially caught chinook salmon in B.C.** | **10.1** | **0.87** | **feed, energy, materials, labour** | **This analysis** |
| **Commercially caught coho salmon in B.C.** | **9.3** | **0.87** | **feed, energy, materials, labour** | **This analysis** |
| **Commercially caught sockeye salmon in B.C.** | **5.0** | **0.68** | **feed, energy, materials, labour** | **This analysis** |
| **Commercially caught chum salmon in B.C.** | **4.6** | **0.59** | **feed, energy, materials, labour** | **This analysis** |
| **Commercially caught pink salmon in B.C.** | **4.5** | **0.53** | **feed, energy, materials, labour** | **This analysis** |

Notes: a. Ecosystem support areas re-calculated based on an average shrimp production rate of 4 tonne/ha/year (Larsson *et al.* 1994).
b. Ecosystem support areas re-calculated based on an average Tilapia production rate of 125 kg/m2 of net-pen/year (Berg *et al.* 1996).
c. Ecosystem support areas re-calculated based on an average Tilapia production rate of 0.5 kg/m2 of pond/year (Berg *et al.* 1996).

Comparing my results to those of previous analyses (Table 78), what is most striking is that Folke's (1988) estimate of marine ecosystem support to intensive Atlantic salmon culture is an order of magnitude larger than what I have estimated for a comparable system in British Columbia. Upon reviewing his analysis together with the report that contains the underlying detailed calculations (Folke and Aneer 1988), the factors that appear to contribute most to this difference are:

1. In estimating the primary productivity required to sustain pelagic fish incorporated into salmon feed, Folke and Aneer used estimates of the net yield of pelagic fish from their source ecosystems (see Folke and Aneer 1988, p. 35). In doing so, they implicitly recognise that other eco-trophic pathways exist within the source ecosystems that do not involve small pelagic fish. Consequently, this approach will almost invariably result in comparatively large estimates of ecosystem support as any species of interest will only ever account for a fraction of the net primary productivity generated within a given area of ecosystem. In contrast, the technique that I used throughout this research assumes that all of the net primary productivity generated within a given area of ecosystem is dedicated to producing the organisms of interest. While this approach may appear to be ecologically naïve, it results in a much more conservative estimate of ecosystem support. Moreover the technique that I have used is not affected by natural or human - influenced changes in relative abundance of the species of interest.

2. The source ecosystem net primary productivity values used by Folke and Aneer (90 to 160 g $C/m^2 \cdot year$) are much lower than the net primary productivity values used in this research.

The differences between my results and Folke's highlight one of the challenges associated with drawing hard conclusions from the absolute results of any one specific ecological footprint analysis or in comparing the results of two analyses conducted independently. Because the final footprint values generated can be significantly influenced by any one of many input parameters or assumptions, the most meaningful results are those generated when conducting a "head-to-head" comparative analysis.

## Using Energy Analysis to Compare the Systems

The results of the energy analyses also indicate major differences between the biophysical costs of farmed and commercially caught salmon (Table 79). Atlantic salmon, the lêast energy-intensive farmed species, require over twice the fossil fuel equivalent energy input as do coho salmon, the

most energy intensive commercially caught species. When compared to the least energy-intensive commercial species, pink salmon, farmed Atlantics require over four times the energy input.

*Table 79. Energy Return on Investments and Total Industrial Energy Inputs to Farmed and Commercially Caught Salmon in 1996*

| | Gross Edible EROI[a] | Edible Protein EROI[a] | Industrial Energy Intensity (GJ/tonne)[b] | Total 1996 Production in British Columbia (tonnes)[c] | Total 1996 Fossil Fuel Equiv. Energy Input (TJ) |
|---|---|---|---|---|---|
| Farmed: | | | | | |
| - Atlantic | 5.2% | 3.3% | 94 | 18,139 | 1,705 |
| - chinook | 4.2% | 2.6% | 117 | 8,023 | 939 |
| Commercially harvested: | | | | | |
| - chinook | 14% | 8.7% | 35 | 426 | 15 |
| - coho | 12% | 7.4% | 41 | 3,320 | 136 |
| - sockeye | 18% | 11% | 27 | 15,007 | 405 |
| - chum | 21% | 13% | 24 | 6,271 | 150 |
| - pink | 22% | 14% | 22 | 8,140 | 179 |
| | | | **Totals:** | **59,326** | **3,529** |

Notes: a. From Tables 63 and 70.
b. From Tables 61, 62, 64, 65, 66, 67, and 68.
c. All values in round weights. Farmed salmon production data from B.C. Salmon Farmers Association, pers. comm. 1998. Commercial salmon landings data from Department of Fisheries and Oceans British Columbia Commercial Catch Statistics.

Multiplying the species-specific energy intensities by the tonnage of each species produced in British Columbia in 1996, a little over 3,500 TJ of fossil fuel equivalent energy was dissipated in the production of a combined 59,326 tonnes of salmon (Table 79). To put this into context, this is the energetic equivalent of almost 100 million litres of diesel fuel[235].

### *Comparing My Results with Previous Energy Analyses*

Over the last thirty years, energy analyses have been conducted on a wide range of food production systems. Using protein energy return on investment ratios, I have compared my results with the energy efficiency of other food production systems (Table 80). While the energy efficiency of salmon farming in British Columbia is comparable to that of other intensive aquaculture systems and a variety of livestock production systems, collectively they are some of the least energy efficient food production systems for which data are available. In contrast, commercially caught salmon in B.C. provide much better protein energy returns relative to the industrial energy invested.

[235] Where the energy content of 1 litre of diesel fuel equals 36.036 MJ (Rose and Cooper 1977).

*Table 80. Edible Protein Energy Return on Investment Ratios for a Variety of Food Production Systems*

| Food Production System | Edible Protein EROI | Source |
|---|---|---|
| Seaweed culture (West Indies) | 100% | Folke and Kautsky 1992[a] |
| Cultured carp (Indonesia) | 94% | Ackefors *et al.* 1993[b] |
| Wheat (USA) | 41% | Ackefors *et al.* 1993[b] |
| Kapenta fishery (Zimbabwe) | 25% | Michélsen 1995[a] |
| **Purse seine fishery for salmon (B.C.)** | **18%** | **This study** |
| Groundfish trawl fishery (Washington State) | 17% | Wiviott and Mathews 1975 |
| All commercial fishing (New Bedford, Mass. 1968-'88) | 17-3% | Mitchell and Cleveland 1993 |
| Rice (USA) | 14% | Ackefors *et al.* 1993[b] |
| Cultured Tilapia (Africa) | 14% | Ackefors *et al.* 1993[b] |
| **Commercially caught pink salmon (B.C.)** | **14%** | **This study** |
| **Commercially caught chum salmon (B.C.)** | **13%** | **This study** |
| **Commercially caught sockeye salmon (B.C.)** | **11%** | **This study** |
| Cultured carp (Israel) | 11% | Ackefors *et al.* 1993[b] |
| All commercial fishing (New England, 1975) | 10% | Rochereau and Pimentel 1978[c] |
| Mussel farming (Scandinavia) | 10% | Folke and Kautsky 1992[a] |
| **Gillnet fishery for salmon (B.C.)** | **9%** | **This study** |
| **Troll fishery for salmon (B.C.)** | **8.9%** | **This study** |
| **Commercially caught chinook salmon (B.C.)** | **8.7%** | **This study** |
| Cultured Tilapia (Israel) | 8.7% | Ackefors *et al.* 1993[b] |
| Sea ranching of Atlantic salmon (Sweden) | 8.3% | Folke and Kautsky 1992[a] |
| Turkey (USA) | 7.7% | Pimentel 1997[d] |
| **Commercially caught coho salmon (B.C.)** | **7.4%** | **This study** |
| Milk (USA) | 7.1% | Pimentel 1997[d] |
| Semi-intensive pond culture of Tilapia (Zimbabwe) | 6% | Berg *et al.* 1996 |
| Swine (USA) | 5.6% | Pimentel 1997[d] |
| Commercial cod fishery (USA) | 5% | Folke and Kautsky 1992[a] |
| Land-based trout farming (N. Ireland - 1972) | 4.2% | Pitcher 1977[a] |
| Chicken (USA) | 3.8% | Ackefors *et al.* 1993[b] |
| Eggs (USA) | 3.8% | Pimentel 1997[d] |
| Intensively cultured catfish (USA) | 3.4% | Ackefors *et al.* 1993[b] |
| **Intensively cultured Atlantic salmon (B.C.)** | **3.3%** | **This study** |
| Intensively cultured catfish (USA) | 3.0% | Pimentel *et al.*,1996 |
| **Intensively cultured chinook salmon (B.C.)** | **2.6%** | **This study** |
| Intensively cultured Tilapia (Zimbabwe) | 2.5% | Berg *et al.* 1996 |
| Semi-intensive shrimp culture (Colombia) | 2% | Larsson *et al.* 1994 |
| Lamb (USA) | 2% | Pimentel 1997[d] |
| Intensively cultured Atlantic salmon (Sweden) | 2% | Folke and Kautsky 1992[a] |
| Beef (USA) | 1.9% | Pimentel 1997[d] |
| Intensively cultured seabass (Thailand) | 1.5% | Pimentel *et al.*,1996 |
| Intensively cultured shrimp (Thailand) | 1.4% | Pimentel *et al.*,1996 |
| Beef (USA) | 0.8% | Ackefors *et al.* 1993[b] |

Notes: a. As cited in Berg *et al.* (1996)

b. Ackefors *et al.* (1993) do not cite the original sources of these estimates. In addition, as they only provide energy inputs per gram of protein produced, I converted these to protein EROI ratios using a protein energy content value of 23.6 kJ/gram.

c. As cited in Mitchell and Cleveland 1996.

d. Energy inputs to contemporary US livestock production systems as reported by Pimentel (1997) include only the energy needed to provide feed inputs (Dr. David Pimentel, pers. comm. 1999).

What is remarkable about the data in Table 80 is that virtually all of the food production systems outlined, require more industrial energy input than they return as edible protein energy. Given the finite nature of fossil energy resources (Duncan and Youngquist 1999 & 2001), steadily declining global per capita availability of industrial energy generally (Duncan 1993), and the impacts that industrial energy consumption has on the ecosphere (Intergovernmental Panel on Climate Change 1990 & 1996, Ehrlich 1994b, Vitousek *et al.* 1997, Meyerson 1998) a strong argument can be made that both salmon farming and fishing along with all of the other food production systems outlined in Table 80 are absolutely unsustainable.

Alarmingly, the results outlined above regarding the relative and absolute sustainability of salmon farming run counter to widely-held public perceptions and industry assertions. For example, a 1999 public opinion survey commissioned by the B.C. Salmon Farmers Association (BCSFA) found that "71% of respondents agree that salmon farming is an environmentally sound and sustainable industry" (BCSFA 1999) while Wessells *et al.* (1999) found that U.S. consumers favoured eco-labelled farmed salmon over comparably certified wild-caught salmon. Reinforcing this perception, in a press release dated January 24, 2000, Anne McMullin, the executive director of the BCSFA is quoted as follows: "Study after study has shown that aquaculture in Canada is an environmentally and economically sustainable industry. But we must continue to improve to keep pace with the competition." (Canadian Aquaculture Industry Alliance 2000). And in a similar vein, Herb Dhaliwal the Canadian federal Minister of Fisheries and Oceans is quoted as follows in a press release dated August 23, 2000: "The aquaculture industry in British Columbia is an important part of the economy of that province" and further "Increasing safeguards that will benefit the industry is a positive step that will help ensure that the farming of fish and shellfish remain environmentally sustainable." (Fisheries and Oceans Canada 2000).

## *Are there differences between the biophysical costs associated with catching salmon using purse seine, gillnet or troll fishing technologies under recent historical conditions?*

Whether evaluated using ecological footprint or energy analysis, purse seining is approximately twice as biophysically efficient as gillnetting or trolling at catching salmon under recent historical conditions. Specifically, a tonne of purse seine caught salmon required a total fossil fuel equivalent energy input of about 17 GJ, while both trolling and gillnetting required a total fossil fuel equivalent energy input of approximately 34 GJ/tonne. Similarly, the industrial material, energy and labour

input related ecological footprint associated with purse seining amounted to approximately 0.4 ha/tonne of salmon landed. In contrast, the ecosystem support to sustain similar inputs to gillnetting and trolling amounted to about 0.8 and 0.9 ha/tonne of salmon landed, respectively (Tables 71 and 72 and associated text).

### Comparing My Results with Previous Analyses

To my knowledge, this is the first time that a commercial fishery has been evaluated using ecological footprint analysis. As such, there are no previous results with which I can compare mine. However, following the oil price shocks of the 1970's, energy analyses were conducted on a variety of commercial fisheries. In Tables 80 and 81, the relative energy efficiency of the three gear types used to harvest salmon in B.C. can be compared with other commercial fisheries using either edible protein energy return on industrial energy investment ratios (Table 80) or energy intensities (Table 81).

*Table 81. Energy Intensity of Commercial Fisheries*

| Fishery (based in) | Energy Intensity (GJ/t) | Analysis Includes Energy Inputs to | Source |
|---|---|---|---|
| Purse seining for capelin (Iceland) | 0.7 | Fuel | Ágústsson 1978 |
| **Purse seining for menhaden (U.S.)** | **1.5** | **Fuel, vessels** | **This study** |
| Purse seining for herring (Maine U.S.) | 2.2 to 2.4 | Fuel, gear, vessels | Rawitscher 1978 |
| Set nets for various species (Japan) | 2.9 | Fuel | Nomura 1980 |
| **Purse seining for herring (B.C.)** | **5.8** | **Fuel, vessels** | **This study** |
| Trawling for pollock (Japan) | 7.5 | Fuel | Nomura 1980 |
| Trawling for perch (Maine U.S.) | 6 to 8 | Fuel, gear, vessels | Rawitscher 1978 |
| Jigging for squid (Japan) | 7.2 to 72 | Fuel | Sato *et al.* 1989 |
| Trapping crabs (Maryland U.S.) | 8 to 10 | Fuel, gear, vessels | Rawitscher 1978 |
| Purse seining for pelagics (Japan) | 10 | Fuel | Nomura 1980 |
| Trawling for groundfish (Wash. U.S.) | 10 | Fuel, vessels and other | Wiviott and Mathews 1975 |
| **Purse seining for salmon (B.C.)** | **17** | **Fuel, gear, vessels** | **This study** |
| Gillnetting pink salmon (Wash. U.S.) | 13 to 19 | Fuel, gear, vessels | Rawitscher 1978 |
| Trawling for cod (Mass. U.S.) | 18 to 20 | Fuel, gear, vessels | Rawitscher 1978 |
| Trawling for flounder (R.I. U.S.) | 20 to 22 | Fuel, gear, vessels | Rawitscher 1978 |
| Jigging for squid (Japan) | 20 to 44 | Fuel | Nomura 1980 |
| Trawling for pollock (Japan) | 21 to 84 | Fuel and other | Watanabe and Uchida 1984 |
| Purse seining for tuna (Cal. U.S.) | 31 to 62 | Fuel, gear, vessels | Rawitscher 1978 |
| Trawling for croaker (Japan) | 33 to 75 | Fuel and other | Watanabe and Uchida 1984 |
| **Gillnetting for salmon (B.C.)** | **34** | **Fuel, gear, vessels** | **This study** |
| **Trolling for salmon (B.C.)** | **34** | **Fuel, gear, vessels** | **This study** |
| Trawling for shrimp (Australia) | 38 | Fuel, vessels | Leach 1976 |
| Trawling for groundfish (Japan) | 38 | Fuel | Nomura 1980 |
| Trawling for haddock (Mass. U.S.) | 34 to 42 | Fuel, gear, vessels | Rawitscher 1978 |
| Pole & line for skipjack (Japan) | 42 | Fuel | Nomura 1980 |
| Driftnetting for salmon (Japan) | 44 to 68 | Fuel | Nomura 1980 |
| Longlining for halibut (U.S.) | 48 to 51 | Fuel, gear, vessels | Rawitscher 1978 |
| Trawling for groundfish (Japan) | 52 | Fuel, vessels and other | Wiviott and Mathews 1975 |
| Trolling for chinook salmon (U.S.) | 82 to 87 | Fuel, gear, vessels | Rawitscher 1978 |
| Longlining for tuna (Japan) | 84 to 134 | Fuel | Nomura 1980 |
| Trapping lobster (Maine U.S.) | 141 to 145 | Fuel, gear, vessels | Rawitscher 1978 |
| Trawling for shrimp (Texas U.S.) | 270 to 312 | Fuel, gear, vessels | Rawitscher 1978 |
| Trawling for shrimp (U.S.) | 358 | Fuel | Leach 1976 |

Both in terms of edible protein energy return on industrial energy investment (Table 80) and energy intensity (Table 81), all three methods of fishing for salmon in B.C. fall within the range of values displayed by other fisheries and food producing sectors generally. However, purse seining for salmon appears to be one of the most energy efficient producer of *animal* protein for human consumption for which data are available (Table 80).

## *What opportunities exist to reduce the biophysical costs associated with producing salmon via the intensive farming process and the salmon fishery?*

### Salmon Farming

As feed accounts for such a large proportion of the total biophysical costs of farmed salmon production (Tables 61 and 62 and Figures 15 and 16), efforts to improve its sustainability should, at least initially, focus on feed. As illustrated in the sensitivity analysis of Chapter 6, reducing the total amount of feed used per tonne of salmon produced can have a marked impact on both the ecological footprint and energy efficiency of farmed salmon (Tables 74 and 75 and Figures 26 and 27). However, there are practical limits to how low the feed use rate can go. And even at a rate of 1.3 tonnes feed per tonne of salmon produced, the ecological footprint of farmed salmon is still much larger than that of wild caught sockeye, pink or chum salmon (Figure 26).

A second way in which the biophysical sustainability of farmed salmon could be improved is by substituting biophysically "costly" feed components with lower impact alternatives where this is possible. And while it is beyond the scope of this analysis to design a salmon feed that optimises biophysical sustainability, nutritional performance, and economic cost, two observations can be made. First, while livestock-derived components only account for 12% of the mass of the salmon feed modelled, they contribute almost 50% of the total industrial energy input and account for just over 50% of the terrestrial ecological footprint of farmed salmon. Conversely, crop derived inputs account for 31% of the mass of the feed modelled, but only 4% of the total industrial energy (Figure 30).

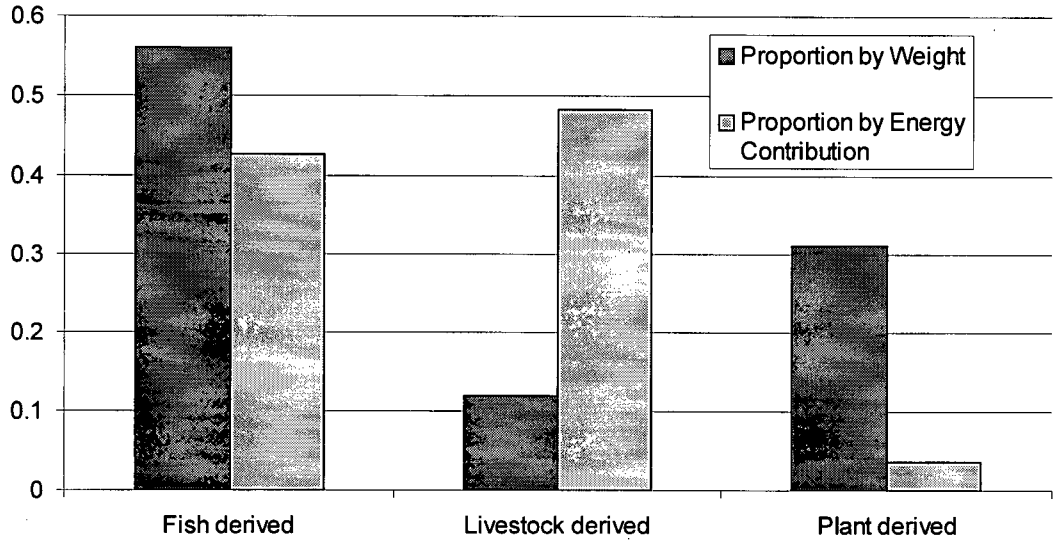


*Figure 30. Relative Contribution by Weight and Energy of Major Components of Salmon Feed*

Similarly, by simply replacing the B.C.-origin mixed fish oil, a component that accounts for only 3.6% of the weight of the feed modelled, with Gulf of Mexico menhaden oil, the total industrial energy inputs to salmon feed, and to farmed salmon generally, decrease by just over 20%[236]. This in turn translates into a 12% reduction in the terrestrial portion of the ecological footprint of farmed salmon[237].

An interesting conundrum in this regard is that, in many cases, the most biophysically expensive inputs to salmon feed are wastes or co-products of other industries. Should feed manufacturers eliminate these inputs in favour of lower biophysical cost alternatives as a means to improve their industry's sustainability, this could result in a net increase in the biophysical impact of the human enterprise at a global level. Specifically, this would occur when the lower biophysical cost alternatives are primary resources. Restating this problem more generally, by making rational decisions at a micro-level to improve an activity's sustainability can, under certain circumstances, result in a decrease in the biophysical sustainability of the human enterprise as a whole. And while

[236] This is largely because: 1) Gulf menhaden have a much higher average oil yield rate than do the fish processing wastes used to make B.C. mixed fish oil (Table 19). As a result, a much smaller quantity of wet fish must be landed, and reduced. and 2) The Gulf menhaden purse seine fishery has a much lower average fuel energy input, at 1,370MJ per tonne of fish landed (Table 27), than does the B.C. purse seine herring fishery with an estimated average fuel energy input of almost 5,000 MJ/tonne (Table 24).

[237] Note, however, that the marine portion of the ecological footprint remains unchanged as it's size was determined by the fish meal inputs to salmon feed.

this problem raises some difficult questions regarding how biophysical sustainability objectives are practically pursued, it has to my knowledge not been previously recognised in the literature.

### The Commercial Fishery

The scope for reducing the biophysical costs associated with the commercial salmon fishery are rather more limited especially with respect to its ecological footprint. This is because the prey consumed by salmon foraging in the wild is biologically/ecologically determined. Consequently, the marine ecological footprint of wild salmon is essentially "fixed". However, within the context of the industrial aspects of the fishery, there is a great deal of room to improve its biophysical sustainability.

As direct fuel consumption by fishing vessels accounts for the largest industrial energy input (Figures 19 through 23) anything that reduces fuel consumption per tonne of salmon landed by the fishery would improve its sustainability. Given that purse seiners burn less than 50% of the fuel consumed by either gillnetters of trollers, per tonne of salmon landed (Table 71), reducing or eliminating the gillnet and troll sectors in favour of purse seiners would potentially dramatically reduce fuel consumption. It is important to note, however, that such a course of action might have wholly undesirable social impacts that are almost completely unaccounted for within a biophysical sustainability analysis such as this[238].

In a similar vein, given that the B.C. salmon fishery is widely recognised to be overcapitalised, it is possible that reducing the absolute number of salmon fishing vessels while holding salmon abundance and all other technological aspects constant could result in lower average rates of fuel consumption. Moreover, as salmon were historically harvested very successfully using a variety of terminal fishing technologies, including traps, weirs, and fishwheels (Copes 1995 & 2000, Higgs 1982), all of which appear to require relatively small energy and material inputs (Hallock *et al.* 1957, Dunn and Rich 1978, Nomura 1980, Henderson and Healey 1993, Mikkelsen 1995, Jaeger 1997), any shift from the vessel-based fishery back to these technologies has the potential to dramatically improve the biophysical sustainability of the fishery. However, no data are currently available upon which a quantitative analysis of these final two options could be made.

Turning from harvesting to the artificial enhancement of salmon, reducing the degree to which the commercial fishery depends on hatchery produced fish would also improve its sustainability. The

[238] At best, social impacts are captured as changes in the labour inputs required.

benefits of this would be most pronounced in the case of coho salmon which, as a function of their basic life history, are reared in hatcheries for the longest period of time. For example, eliminating the approximately 11% of commercially caught coho that originate in SEP hatcheries in favour of wild spawned fish, would result in a 21% reduction in the industrial energy input to the coho fishery (Figure 20).

## Additional Observations

Although they do not speak directly to the research questions posed, in conducting this research I made a number of observations that are worthy of mention.

### *The Biophysical Cost of Substituting Wild Salmon Foraging Behaviour With an Industrial Process*

From an ecological perspective, a key difference between farmed and wild salmon is that by confining salmon to net-pens, we are substituting an industrial-technological feed-provision process for the foraging behaviour of wild salmon. Cast in the language of ecological economics, this is a clear example of the substitution of a service provided free by nature (natural income) by an artificial process mediated by manufactured capital.

Does this substitution result in a net biophysical cost or benefit? The challenge here was identifying which specific aspects of the two systems should be compared so as to best reflect the trade-offs associated with this substitution specifically. Ultimately, I decided that comparing the industrial energy inputs to provide the feed for farmed salmon with that associated with harvesting salmon from the wild would be a reasonable, though imperfect, basis of comparison. Furthermore, I used only the results associated with chinook salmon production, the one species common to both systems analysed, in order to eliminate inter-specific differences.

With this method, I estimate that there is currently a net biophysical cost associated with replacing the foraging behaviour of wild salmon with an industrial-technological process that amounts to approximately 70,000 MJ of fossil fuel equivalent energy per tonne of salmon[239]. Given the finite nature of fossil energy resources (Duncan and Youngquist 1999 & 2001), decreasing global per capita availability of industrial energy generally (Duncan 1993) and the impacts that industrial

[239] Calculated by subtracting 32,920 MJ - the sum of the direct fuel inputs, the energy to build and maintain fishing vessels and the energy embodied in fishing gear per tonne of chinook landed (Table 64) - from 106,043 MJ - the energy required to provide feed inputs to farmed chinook (Table 62).

energy consumption has on the ecosphere (Intergovernmental Panel on Climate Change 1990 & 1996, Ehrlich 1994b, Vitousek *et al.* 1997, Meyerson 1998), on this basis alone, salmon farming can not be regarded as a biophysically sustainable technological alternative to the commercial fishery as both systems currently exist. Moreover, to the degree to which farmed salmon have already replaced premium wild-caught salmon in many markets (Anderson and Fong 1997, Clayton and Gordon 1999, Sylvia *et al.* 2000), this represents a clear net *increase* in the economy's material and energy throughput at a time when there is a widely acknowledged need to dramatically reduce material and energy throughput in order to achieve sustainability (Business Council for Sustainable Development 1993, Ekins 1993, Schmidt-Bleek 1993a, 1993b, Pearce 1994, Rees 1995, Hinterberger and Schmidt-Bleek 1999).

It should be noted, however, that the biophysical cost profiles of both farmed and wild salmon can be changed as discussed above. Therefore, one can at least conceive of a situation in which salmon farming could become a more energetically sustainable technological option to the wild fishery. Using the basis of evaluation outlined above, this would occur whenever the energy inputs associated with farmed salmon feed production drop below that associated with executing a fishery for the same species. However, given the alternative harvesting options open to the commercial fishery, in my opinion it would be extremely difficult for the farmed salmon industry to reduce the energy inputs to their feed production to a level below that which could be attained by the commercial fishery using fixed terminal harvesting technologies.

## *Is Salmon Farming a Net Source or Sink of Edible Seafood?*

Recent publications have argued that contemporary salmon farming, along with some other forms of intensive fish and shellfish culture, functionally result in a net loss of fish that is potentially available for human consumption at a global level (Naylor *et al.* 1998, Naylor *et al.* 2000)[240]. This results primarily because of the relatively large amounts of fish meal and oil that are included within many standard aqaufeeds. The most recent of these analyses estimate that globally, approximately 3.2 kg of wild-caught fish are required to yield 1 kg of farmed salmon on the basis of the fish meal fraction of their diet (Naylor *et al.* 2000, Table 2, p. 1019). In comparison, my analysis indicates that when using fish meal as the basis of evaluation, Atlantic salmon farming in B.C. also results in a 3.2 to 1 wet fish

[240] It is interesting to note that this is not a new concern. For example, Weatherley and Cogger (1977) raised moral and ecological concerns regarding the use of "trash fish" as a feed input to intensive aquaculture over 20 years ago.

to wet fish conversion[241] while chinook farming results in a 4 to 1 conversion[242]. However, when using fish oil inputs to feed, the conversion rates increase to 5.3 to 1 for Atlantic salmon[243] and to 6.6 to 1 for chinook salmon[244].

In response, proponents of salmon farming argue that whether it is because of their relatively small size, their generally bony and oily character, or simply a reflection of taste/cultural issues, the demand simply doesn't exist currently to consume the quantities of fish now destined for reduction directly as food for humans (Lindbergh 1999). Moreover, it is argued that it is more efficient to feed fish meal and oil to salmon and other cold-blooded animals than it is to feed them to terrestrial livestock, the traditional consumer of most of the world's fish meals (Åsgård and Austreng 1995, Åsgård *et al.* 1998). It can be observed, however, that a variety of handling and processing techniques exist for converting and preserving small, bony, oily fish directly into highly palatable foodstuffs that are mainstays of many diets around the world (Hale *et al.* 1991, Hansen 1996) while fish oils are being used increasingly for margarine and cooking oil in Europe and Latin America (Hale *et al.* 1991, IFOMA 1999).

## Greenhouse Gas Emissions

Although the ecological footprint analyses of the two systems incorporated greenhouse gas emissions, because they provide an indication of potential impact on global climate change, they are worth noting explicitly, in and of themselves. Arranged in decreasing order and expressed in terms of $CO_2$ equivalents, the greenhouse gas emission intensities of salmon produced in B.C. are approximately: 8 tonnes/tonne farmed chinook salmon, 6.5 tonnes/tonne farmed Atlantic salmon, 2.9 tonnes/tonne of commercially harvested chinook and coho salmon, 2.3 tonnes/tonne of commercially harvested sockeye salmon, 2 tonnes/tonne of commercially caught chum salmon, and 1.8 tonnes/tonne of commercially caught pink salmon (Tables 61, 62, and 64 through 68). In general, these emissions compare very favourably with that of feedlot raised beef those total emission intensity amounts to 14.8 tonnes $CO_2$ equiv./tonne (Subak, 1999).

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[241] Calculated by multiplying 1,824 kg - the total wet weight of fish represented by fish meal inputs to the feed modelled (Table 19) by 1.77 - the total feed required to yield an average tonne of Atlantic salmon (Table 61).

[242] Calculated by multiplying 1,824 kg - the total wet weight of fish represented by fish meal inputs to the feed modelled (Table 19) by 2.21 - the total feed required to yield an average tonne of chinook salmon (Table 62).

[243] Calculated by multiplying 3,000 kg - the total wet weight of fish represented by fish oil inputs to the feed modelled (Table 19) by 1.77 - the total feed required to yield an average tonne of Atlantic salmon (Table 61).

[244] Calculated by multiplying 3,000 kg - the total wet weight of fish represented by fish oil inputs to the feed modelled (Table 19) by 2.21 - the total feed required to yield an average tonne of chinook salmon (Table 62).

### *The Importance of Labour Inputs*

Labour inputs to the two systems had a remarkably small impact on the total ecological footprint associated with salmon production. Within the context of salmon farming, labour only accounted for 1 to 2% of the terrestrial ecosystem support and less than 0.25% of the marine ecosystem support required (Table 61 and 62). With respect to commercially caught salmon, labour only contributed 8 to 9% of the terrestrial ecological footprint, and less than 0.5% of the marine footprint.

The relative insignificance of labour, however, may in part reflect the specific method used to incorporate it into the analysis[245]. Had I accounted for labour by converting total income earned into an energy equivalent using the relationship between Gross National Product and total industrial energy use within the Canadian economy (see Cleveland *et al.* 1984, Folke 1988, Larsson *et al.* 1994, Berg *et al.* 1996), labour may have had a greater impact on the overall results. For example, Folke (1988) found that labour inputs represented about 16% of the industrial energy inputs to intensive salmon culture and between 2 and 26% of the energy to salmon ranching. Similarly, Larsson *et al.* (1994) found that labour represented about 6% of the industrial energy inputs to shrimp culture while Berg *et al.* (1996) found that labour accounted for 20% and 40% of the total industrial energy input to cage and pond culture of tilapia, respectively.

## Epilogue

This analysis provides one of the first rigorous tests within the strong sustainability paradigm of the hypothesis that different technologies can have markedly different biophysical efficiencies. In doing so, this research demonstrates the utility of, and refines ecological footprint analysis as a tool by which to assess the sustainability of alternative production technologies.

Practically, given the biophysical unsustainability of contemporary intensive salmon aquaculture, both relative to the commercial fishery and in an absolute sense energetically, there is a clear need for the industry and regulators to take steps to dramatically reduce its biophysical costs. In the absence of such reductions, the continued promotion of salmon farming as a means of sustainable economic development for coastal communities in B.C. is, at best, disingenuous. Moreover, insofar as farmed salmon continue to supplant wild caught salmon in many markets, thus undermining the

[245] The ecological footprint of labour inputs were estimated using the marine and terrestrial ecosystem area required to sustain the average Canadian's annual food consumption as estimated by Wackernagel *et al.* (1997) (see Chapter 3 for greater detail).

economic viability of commercial fisheries, this represents a clear example of *un*sustainable economic development.

Although the contemporary commercial fishery may be more biophysically efficient than salmon farming, given that it too requires large inputs of industrial energy, opportunities to reduce these inputs should be actively pursued. And while it may be politically difficult, a transition to a highly materially and energetically efficient fishery is at least possible in the case of salmon given that they may be harvested using an array of seemingly low-input technologies such as traps, weirs and fishwheels.

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## *Appendix A: Summary and Analysis of Co-operative Assessment of Salmonid Health (C.A.S.H.) Program Data*

Established in 1990 by member companies of the British Columbia Salmon Farmers Association, the Co-operative Assessment of Salmonid Health (C.A.S.H.) program was an industry funded salmon health, growth and economic performance benchmarking project. Its primary objective was to enhance the British Columbia salmon farming industry's international competitiveness by increasing the efficiency and decreasing the cost of production of participating members.

Participating companies collected and submitted detailed records covering a range of environmental and performance measures for specific sub-populations or "groups" of their fish that are being reared under regular operating conditions. These records were then centrally processed and the results, along with industry-wide performance indicators, were reported back to the participating members in such a way as to protect the confidentiality of other participating companies.

Dr. Grace Karreman, the head of the C.A.S.H. program provided me with aggregated performance data for a total of 23 groups of Atlantic salmon spanning three year classes (1993, '94 and '95) and a total of 13 groups of chinook salmon encompassing two year classes (1993 and '94) (Table A-1). It is important to note here that the information provided by the C.A.S.H. program did not include any data from monitored fish groups that had experienced greater than 50% mortality during their saltwater production phase. In other words, the data summarised in Table A-1 is biased towards better performing fish groups.

*Table A-1. Summary of Data Provided by the C.A.S.H. Program*

| | | | Weighted Averages based on Final Harvest Weight | | | | |
|---|---|---|---|---|---|---|---|
| | Year Class | Number of | Average | Round feed | Average | | Final total rnd |
| | (year into | fish groups | entry wght | conversion | round weight | End survival | harvest wght |
| Species | salt water) | represented | (kg) | (kg feed/kg hrvt fish) | (kg) | (% of entry) | (kg) |
| Atlantic | 1993 | 9 | 0.088 | 1.53 | 4.6 | 72.4% | 1350 |
| Atlantic | 1994 | 5 | 0.073 | 1.42 | 4.7 | 80.1% | 1530 |
| Atlantic | 1995 | 9 | 0.057 | 1.4 | 5.2 | 76.0% | 780 |
| Atlantic salmon averages: | | | 0.075 | 1.46 | 4.77 | 76.4% | |
| Chinook | 1993 | 7 | 0.032 | 1.93 | 3.3 | 72.9% | 1350 |
| Chinook | 1994 | 6 | 0.04 | 2.2 | 3.4 | 82.7% | 700 |
| Chinook salmon averages: | | | 0.035 | 2.0 | 3.33 | 76.2% | |

Source: Dr. Grace Karreman, C.A.S.H. program, pers. comm., October, 1997.
Notes: For each year class, the performance data is reported as a weighted average of the all the fish groups included in that year class using the final harvest weight of the fish groups as the weighting factor.

For the 23 Atlantic salmon groups, the average smolt weighed 75 grams when entering saltwater, approximately 76.4% survive to be harvested[246], and upon harvesting the average fish weighed approximately 4.77 kg. Similarly, for the 13 chinook salmon groups represented, the average smolt weighed 35 grams upon entering saltwater, approximately 76.2% of the individuals survived to be harvested[247], and upon harvesting, the average chinook weighed approximately 3.33 kg (Table A-1).

From the above, I calculated that on average, approximately 20.6 kg of Atlantic salmon smolts had to enter saltwater to ultimately yield one tonne of harvested Atlantics while an average of approximately 13.7 kg of chinook smolts were required to ultimately yield one tonne of harvested chinook[248].

[246] Recall that the data presented in Table A-1 does not include those fish groups monitored by the C.A.S.H. program that experienced greater than 50% mortality.
[247] Ibid.
[248] Calculated using the following general equation:
(Ave. Smolt Weight in grams) ÷ (Ave. Final Harvest Weight in kg x Ave. Survival Rate).

# Appendix B: Analysis of the Direct Material, Labour and Energy Inputs to the Freshwater Phase of Farmed Salmon Production

Four companies provided data on their operating material, labour and energy inputs to, and smolt production from their freshwater operations. This data is summarised in Table B-1.

*Table B-1. Material, Labour and Energy Inputs to, and Smolt Production from Four Companies' Freshwater Operations*

| Data Covers | Company 1 | Company 2 | Company 3 | Company 4 | |
|---|---|---|---|---|---|
| Time interval[a] | f.y. 1995-'96 | f.y. 1996-'97 | f.y. 1996-'97 | 1996 | |
| No. of Hatcheries | 1 | 1 | 2 | 1 | |
| Lake-pen rearing | none | none | yes[b] | yes[c] | **Input and Production Totals[d]** |
| **Inputs** | | | | | |
| Labour (person-days) | 556 | 1,440 | 4,320 | 4,400 | **10,716** |
| Feed Use (kg) | 3,703 | 31,225 | 145,000 | 368,015 | **547,943** |
| $ spent on gasoline | | $4,200 | | $7,860 | |
| Ave. price per litre[e] | | $0.603 | | $0.603 | |
| Gasoline in litres | n/a | 6,965 | 14,000 | 13,035 | |
| Gasoline in MJ[f] | n/a | 224,627 | 451,500 | 420,373 | **1,096,500** |
| $ spent on diesel | | $1,200 | | $39,300 | |
| Ave. price per litre[g] | | $0.362 | | $0.540 | |
| Diesel in litres | n/a | 3,315 | 2,000 | 72,778 | |
| Diesel in MJ[h] | n/a | 119,470 | 72,080 | 2,622,911 | **2,814,461** |
| $ spent on propane | Not used | $25,589 | Not used | $23,580 | |
| Ave. price per litre[i] | | $0.263 | | $0.383 | |
| Propane in litres | | 97,345 | | 61,534 | |
| Propane in MJ[k] | | 2,458,927 | | 1,554,360 | **4,013,287** |
| Electricity in kWh | 90,213 | 756,288 | 2,170,000 | Not used | |
| Electricity in MJ[l] | 324,767 | 2,722,637 | 7,812,000 | | **10,859,404** |
| **Smolt Output** | | | | | |
| Species[m] | chinook | Atl., chin., coho & rbtrt | Atlantic | Atlantic | |
| Mass in kg | 685 | 21,204 | 104,000 | 203,644 | **329,533** |
| Number | 68,500 | n/a | 1,600,000 | 2,525,424 | |
| Ave. weight in grams | 10 | | 65 | 81 | |

Notes: a. f.y. is used to denote fiscal year.
b. This company's data includes all material, labour and energy inputs associated with lake-pen rearing as well as for hatchery operations.
c. Only the feed used during lake-pen rearing is included in this company's data set.
d. This column provides the sums of the inputs (with all energy inputs expressed in MJ) and production from all four companies.

e. Both companies which provided gasoline use data as a monetary expenditure used "unmarked" automobile gasoline. The British Columbia provincial average fuel prices used and their sources are summarised in Appendix C.
f. The energy content of gasoline is 32.25 MJ/l. Derived from Rose and Cooper (1977, p. 281).
g. Company 2 typically purchased "marked" commercial diesel fuel while Company 4 typically purchased "unmarked" automobile diesel fuel. The British Columbia provincial average fuel prices used and their sources are summarised in Appendix C.
h. The energy content of diesel fuel is 36.04 MJ/l. Derived from Rose and Cooper (1977, p. 281).
i. Both companies which provided propane use data as a monetary expenditure were able to provide either an average or a typical unit price paid for their propane.
k. The energy content of liquid propane is 25.26 MJ/l. Derived from Friedrich and Hayden (1974, p. 48).
l. One kWh of electricity equals 3.6MJ.
m. Where used, species names were abbreviated as follows: Atl.: Atlantic salmon, chin.: chinook salmon, and rbtrt: rainbow trout or steelhead.
n/a: not available

The companies are not identified by name as some requested that they remain anonymous as a condition of providing data for this research.

The raw data provided by the companies often differed in terms of the units in which inputs were reported. For example, labour inputs were either reported as the number of person-days worked or in terms of the number of full-time equivalent employees. All labour inputs were therefore standardised into the number of person-days worked based on the assumption that one full-time equivalent equals 240 person days of labour. In addition, it was often necessary to convert certain inputs, which were typically recorded, and reported to me, as monetary expenditures, into a standard physical unit equivalent. For example, fossil fuels were frequently reported in terms of their purchase cost. When this occurred with respect to gasoline or diesel, it was first necessary to determine whether the company purchased "marked" or "unmarked" fuel[249]. This was because the difference in the unit price between marked and unmarked fuels can be large, reflecting the disparity in the taxes that apply to these two forms of the same fuel. With the appropriate form of fuel identified, the relevant provincial average unit price for that form of fuel (Appendix C) was applied to "back out" an estimate of litres used. In the case of propane, the companies that used this fuel provided me with a typical or average unit price paid during the interval and I used this to estimate the physical volumes consumed.

[249] Unmarked fuels are those fuels which retail consumers are required to purchase. On the other hand, marked fuels can only be purchased by certain types of commercial consumers who by law are exempt from certain taxes which otherwise apply to the unmarked fuel consumers.

# Appendix C: Summary of Average British Columbia Liquid Fuel Prices for the Period 1985 to 1996

Average retail fuel prices were required on a number of occasions throughout this research when it was necessary to "back out" fuel volumes from expenditures made on fuel. Table C-1 presents average British Columbia retail prices for regular and commercial unleaded gasoline, and diesel fuel for the period 1985 to 1996.

*Table C-1. Average British Columbia Retail Prices of Petroleum Products, 1985-1996*

| | Average | Retail | Price | (cents/litre) |
|---|---|---|---|---|
| Year | Regular Unleaded Gasoline | Commercial Unleaded Gasoline | Automobile Diesel Fuel | Commercial Diesel Fuel |
| 1985 | 55.6 | 37.4 | 47.7 | 34.6 |
| 1986 | 47.2 | | 44.6 | 30.7 |
| 1987 | 50.4 | | 44.0 | 28.2 |
| 1988 | 48.2 | 29.9 | 44.4 | 27.3 |
| 1989 | 52.9 | | 44.4 | 28.0 |
| 1990 | 61.6 | | 48.6 | 31.1 |
| 1991 | 58.1 | 36.9 | 55.8 | 31.3 |
| 1992 | 54.1 | | 51.8 | 30.8 |
| 1993 | 55.0 | | 51.8 | 30.0 |
| 1994 | 56.0 | 33.3 | 51.8 | 30.7 |
| 1995 | 59.3 | | 52.1 | 32.6 |
| 1996 | 60.3 | | 54.0 | 36.2 |
| 1997 | 59.1 | | 54.8 | 34.7 |

Notes: All prices include all applicable provincial and federal taxes including the federal Goods and Services Tax after 1991.
1997 prices are based on a price forecast for the second half of the year.

Sources: Full retail price of regular unleaded gasoline, and automobile diesel as well as the commercial diesel fuel price excluding applicable provincial taxes and the GST, from Canadian Enerdata Limited (1997).
Commercial unleaded gasoline prices reconstructed using average annual Vancouver ex-tax retail prices for regular unleaded gasoline from Natural Resources Canada website to which were added the applicable provincial taxes on commercial fuels.
Applicable provincial taxes on commercial fuels provided by the Consumer Taxation Branch of the British Columbia Provincial Ministry of Finance and Corporate Relations.

## *Appendix D: Analysis of the Direct Material, Labour and Energy Inputs to the Saltwater Phase of Farmed Salmon Production*

A total of four companies that operate marine grow-out sites in British Columbia provided data on the material, labour and energy inputs to their grow-out operations along with the total corresponding salmon production. The data provided by each company covers a period of approximately one year and includes all activities associated with the rearing of salmon from the time that they enter saltwater until the time that they are harvested. During the time for which data were provided, two of the companies only produced chinook salmon and two of the companies only produced Atlantic salmon. The input and production data for the two chinook producers appears in Table D-1 while the input and production data for the two Atlantic salmon producers appears in Table D-2.

*Table D-1. Summary of the Material, Labour and Energy Inputs to and Chinook Salmon Production from Two Companies' Saltwater Grow-out Operations*

| Data Covers | Company A | Company B | | | |
|---|---|---|---|---|---|
| Time period[a] | f.y. 1995-'96 | f.y. 1996-'97 | | | |
| No. of grow-out sites | 1 | 3 | **Inputs and** | **Inputs per tonne** | |
| | | | **Production** | **chinook salmon** | |
| **Inputs** | | | **Totals[b]** | **produced[c]** | |
| Labour (person-days) | 857 | 5,760 | **6,617** | **10.9** | |
| Feed Use (kg) | 71,383 | 1,257,000 | **1,328,383** | **2,183** | |
| $ spent on gasoline | | $20,957 | | | |
| Ave. price per litre[d] | | $0.603 | | | |
| Gasoline in litres | n/a | 34,754 | | | |
| Gasoline in MJ[e] | n/a | 1,120,825 | **1,120,825** | **1,842** | |
| $ spent on diesel | | $7,883 | | | |
| Ave. price per litre[f] | | $0.362 | | | |
| Diesel in litres | n/a | 21,775 | | | |
| Diesel in MJ[g] | n/a | 784,780 | **784,780** | **1,290** | |
| $ spent on propane | Not used | Not used | | | |
| Ave. price per litre | | | | | |
| Propane in litres | | | | | |
| Propane in MJ | | | **0** | **0** | |
| Electricity in kWh | 41,136 | 37,061 | | | |
| Electricity in MJ[h] | 148,090 | 133,420 | **281,509** | **463** | |
| | | | | | |
| **Salmon Production** | | | | | |
| Species produced | chinook | chinook | | | |
| Round tonnes harvested | 12.0 | 544.0 | **556** | | |
| Year start to end change | | | | | |
| in biomass in water (t) | 52.6 | 0.0 | | | |
| Total production in tonnes | 64.6 | 544.0 | **609** | | |

Notes: a. f.y. is used to denote fiscal year.
b. This column reports the sums of the inputs (with all energy inputs expressed in MJ) and production from both chinook salmon producers combined.
c. This column reports the average quantities of inputs required to yield a tonne of chinook salmon based on the data provided by Companies A & B. Values were determined by dividing a given aggregate input by the total production (harvested production plus or minus the change in biomass in the water) for the two producers combined.
d. Both companies which provided gasoline use data as a monetary expenditure used "unmarked" automobile gasoline. The British Columbia provincial average fuel prices used and their sources are summarised in Appendix C.
e. The energy content of gasoline is 32.25 MJ/l. Derived from Rose and Cooper (1977, p. 281).
f. Company B typically purchased "marked" commercial diesel fuel. The British Columbia provincial average fuel prices used and their sources are summarised in Appendix C.
g. The energy content of diesel fuel is 36.04 MJ/l. Derived from Rose and Cooper (1977, p. 281).
h. One kWh of electricity equals 3.6MJ.

*Table D-2. Summary of the Material, Labour and Energy Inputs to and Atlantic Salmon Production from Two Companies' Saltwater Grow-out Operations*

| Data Covers | Company C | Company D | | | |
|---|---|---|---|---|---|
| Time period[a] | Jan.-Nov. '97 | c.y. 1996 | | | |
| No. of grow-out sites | 8 | 9 | **Input and Production Totals[b]** | **Inputs per tonne of Atlantic salmon Produced[c]** | |
| **Inputs** | | | | | |
| Labour (person-days) | 10,296 | 8,990 | **19,286** | **3.3** | |
| Feed Use (kg) | 6,727,000 | 3,332,243 | **10,059,243** | **1,736** | |
| $ spent on gasoline[d] | $41,091 | $85,000 | | | |
| Ave. price per litre[e] | $0.591 | $0.603 | | | |
| Gasoline in litres | 69,528 | 140,962 | | | |
| Gasoline in MJ[f] | 2,242,275 | 4,546,020 | **6,788,295** | **1,171** | |
| $ spent on diesel[d] | $41,091 | $49,560 | | | |
| Ave. price per litre[g] | $0.548 | $0.540 | | | |
| Diesel in litres | 74,984 | 91,778 | | | |
| Diesel in MJ[h] | 2,702,408 | 3,307,671 | **6,010,079** | **1,037** | |
| $ spent on propane | $13,919 | $7,100 | | | |
| Ave. price per litre[i] | $0.383 | $0.383 | | | |
| Propane in litres | 36,323 | 18,528 | | | |
| Propane in MJ[k] | 917,521 | 468,022 | **1,385,543** | **239** | |
| Electricity in kWh | Not used | Not used | | | |
| Electricity in MJ[l] | | | **0** | **0** | |
| **Salmon Production** | | | | | |
| Species produced | Atlantic | Atlantic | | | |
| Round tonnes harvested | 3,371.0 | 1,705.5 | **5,076** | | |
| Year start to end change in biomass in water (t)[m] | n/a | 718.7 | | | |
| Total production in tonnes | 3,371.0 | 2,424.1 | **5,795** | | |

Notes: a. Company C provided data covering the 11 month period from January to November, 1997.
b. This column reports the sums of the inputs (with all energy inputs expressed in MJ) and production from both Atlantic salmon producers combined.
c. This column reports the average quantities of inputs required to yield a tonne of Atlantic salmon based on the data provided by Companies C & D. Values were determined by dividing a given aggregate input by the total production (harvested production plus or minus the change in biomass in the water) for the two producers combined.
d. Company C was only able to quantify the total amount of money spent by them gasoline and diesel fuel combined. An assumption was therefore made that 50% of the expenditure was made on gasoline and 50% on diesel fuel.
c. Company D indicated that they regularly purchased "unmarked" gasoline. It was also assumed that Company C also only purchased "unmarked" gasoline. The British Columbia provincial average fuel prices used in the analysis along with their sources are summarised in Appendix C.
d. The energy content of gasoline is 32.25 MJ/l. Derived from Rose and Cooper (1977, p. 281).
e. Company D indicated that they regularly purchased "unmarked" diesel fuel. It was also assumed that Company C also only purchased "unmarked" diesel. The British Columbia provincial average fuel prices used in the analysis along with their sources are summarised in Appendix C.
f. The energy content of diesel fuel is 36.04 MJ/l. Derived from Rose and Cooper (1977, p. 281).
g. Company D indicated that they typically purchased propane for $0.383/litre. This unit price per litre was also applied to Company C's propane expenditure as they were unable to provide their own average unit price.

h. The energy content of liquid propane is 25.26 MJ/l. Derived from Friedrich and Hayden (1974, p. 48).
i. One kWh of electricity equals 3.6MJ.
k. Company C was unable to provide an estimate of the change in the salmon biomass in the water from the start to the end of the period for which they provided data. As a result, it was assumed to be zero.

The companies that provided the data in Tables D-1 and D-2 are not identified by name as some requested that they remain anonymous as a condition of providing data for this research.

As was the case with respect to the freshwater operations data (Appendix B), it was necessary to either standardise certain inputs, such as labour, into a common physical unit of measure, or to back out estimates of the actual physical quantities of inputs based on the average or typical unit costs of the inputs. This occurred most frequently with respect to fossil fuel use. In making these calculations, I used the same methods as described in Appendix B.

# *Appendix E: Analysis of the Direct Labour and Energy Inputs to Farmed Salmon Transport*

Mr. Don Millerd, a partner in Transmar Shipping Ltd. provided me with three years of detailed data regarding their operating expenses while transporting farmed Atlantic salmon from marine grow-out sites to shore-based processing facilities. During 1996, Transmar hauled approximately 7,692 round tonnes of salmon, 65% of which was transported live with the remaining 35% transported after being stunned and bled. To transport these fish, Transmar uses three converted seine vessels.

From the data provided, I calculated the average labour and fuel energy inputs required to transport a typical tonne of farmed salmon for each year and for all three years combined (Table E-1).

*Table E-1. Analysis of Operating Labour and Energy Inputs to Salmon Transport*

| **Year** | **1996** | **1995** | **1994** | |
|---|---|---|---|---|
| Total mass of salmon | | | | |
| hauled in kilograms | 7,692,569 | 7,151,217 | 5,693,559 | |
| | | | | |
| **Inputs** | | | | |
| Total wages in $ | $619,568 | $641,041 | $502,072 | |
| Assumed average wage | $40,000 | $40,000 | $40,000 | |
| Labour in full time equiv. | 15.5 | 16.0 | 12.6 | |
| Total labour in person days[a] | 3,717 | 3,846 | 3,012 | **Three Year** |
| Labour per tonne salmon | | | | **Average** |
| hauled in person-days | 0.48 | 0.54 | 0.53 | 0.51 |
| | | | | |
| Total expenditure on fuel[b] | $239,749 | $204,936 | $149,352 | |
| Average price per litre[c] | $0.362 | $0.326 | $0.307 | |
| Total fuel use in litres | 662,290 | 628,638 | 486,489 | **Three Year** |
| Fuel use per tonne salmon | | | | **Average** |
| hauled in MJ[d] | 3,103 | 3,168 | 3,079 | 3,119 |

Notes: a. It is assumed that one full-time equivalent position equals 240 person-days of labour.
b. All fuel burned by the three converted seine vessels is diesel. It is assumed that Transmar only purchased commercial or "marked" diesel fuel.
c. The British Columbia provincial average fuel prices used in the analysis along with their sources are summarised in Appendix C.
d. The energy content of diesel fuel is 36.04 MJ/l. Derived from Rose and Cooper (1977, p. 281).

# *Appendix F: Analysis of the Average Trophic Level of the Chilean Industrial Fishery 1990-1993*

Chile and Peru are the two largest producers and exporters of fish meal and oil in the world. In recent years, each country has typically accounted for between 30% and 40% of the world's total fish meal production. Prior to 1972 both countries' fish reduction industries were based almost exclusively on huge catches of a single species, the Peruvian anchovy (*Engraulis ringens*). However, more recently, the industrial fisheries of both countries have had to utilise a broader range of pelagic species to maintain their total output of fish meal and oil. For example, through the early 1990's, the Chilean industrial fishery was based largely upon the exploitation of three main species, Inca scad[250] (*Trachurus murphyi*), South Pacific sardine[251] (*Sardinops sagax sagax*) and Peruvian anchovy along with two less abundant species, Araucanian herring[252] (*Strangomera bentincki*) and chub mackerel (*Scomber japonicus*) (Polushin 1994).

Given that a number of species are harvested for reduction, in order to estimate an overall average trophic level for contemporary South American fish meal, two data sets were required. First, estimates were needed of the average trophic level for each of the five species commonly used for reduction. These species specific trophic level values could then be combined with landings data for each species to provide a weighted average trophic level estimate for the industrial fishery as a whole.

Estimates of average trophic level were made for each of the five species listed above using the results of three models of the trophic relationships between the major species and functional groups that inhabit the Peruvian upwelling ecosystem (Jarre *et al.* 1991) (Table F-1)

[250] Which is also known as the jack mackerel or the horse mackerel.
[251] Which is also known as the South American pilchard.
[252] Which is also known as the South Pacific herring.

*Table F-1. Estimated Average Trophic Levels of the Five Species Used for Reduction.*

| Species | Average Trophic Level for the Period[a] | | |
|---|---|---|---|
| | 1953 to 1959 | 1960 to 1969 | 1973 to 1979 |
| Inca scad (Trachurus murphyi)[b] | 3.3 | 3.2 | 3.4 |
| Chub mackerel (Scomber japonicus)[c] | 3.3 | 3.2 | 3.4 |
| South Pacific sardine (*Sardinops sagax sagax*)[d] | 2.8 | 2.7 | 2.8 |
| Araucanian herring (*Strangomera bentincki*)[e] | 2.8 | 2.8 | 2.9 |
| Peruvian anchovy (*Engraulis ringens*)[f] | 2.2 | 2.2 | 2.5 |

Notes: a. Average trophic level values are all expressed relative to autotrophs that are, by default, assigned a trophic level 1.
b. In the models of Jarre *et al.* (1991), *Trachurus murphyi* is referred to as Horse mackerel.
c. In the models of Jarre *et al.* (1991), *Scomber japonicus* is part of the functional group referred to as Mackerel.
d. In the models of Jarre *et al.* (1991), *Sardinops sagax sagax* is simply referred to as Sardine.
e. In the models of Jarre *et al.* (1991), *Strangomera bentincki* is part of the functional group referred to as "Other pelagics".
f. In the models of Jarre *et al.* (1991), *Engraulis ringens* is referred to as Anchoveta.

As average trophic level estimates vary between the three time periods for which models were available, I have used the lowest (most conservative) trophic level values that appear in Table F-1 for each species as the basis for the further calculations of the overall trophic level of the reduction fishery. Using Chilean landings data for the years 1990 to 1993 inclusive (Polushin 1994)[253] and the lowest trophic level values from Table F-1, I calculated an overall average trophic level of 2.9 for the Chilean industrial fishery through the early 1990's (Table F-2).

*Table F-2. Landings Data and Estimated Average Trophic Level of Chile's Industrial Fishery from 1990 to 1993.*

| | **Average** | **Annual Chilean Landings (tonnes)[b]** | | | |
|---|---|---|---|---|---|
| **Species** | **Trophic Level[a]** | **1990** | **1991** | **1992** | **1993** |
| Peruvian anchovy | 2.2 | 845,169 | 936,114 | 1,287,303 | 1,472,929 |
| (*Engraulis ringens*) | | | | | |
| South Pacific sardine | 2.7 | 900,275 | 734,448 | 808,838 | 481,161 |
| (*Sardinops sagax sagax*) | | | | | |
| Araucanian herring | 2.8 | 285,757 | 564,914 | 452,012 | 244,125 |
| (*Strangomera bentincki*) | | | | | |
| Inca scad | 3.2 | 2,471,875 | 3,020,512 | 3,212,060 | 3,236,244 |
| (*Trachurus murphyi*) | | | | | |
| Chub mackerel | 3.2 | 192,948 | 191,723 | 72,364 | 96,023 |
| (*Scomber japonicus*) | | | | | |
| Total landings (tonnes): | | 4,696,024 | 5,447,711 | 5,832,577 | 5,530,482 |
| Weighted average trophic level of landings: | | 2.9 | 2.9 | 2.9 | 2.9 |

Notes: a. Species specific trophic level values from Table F-1.
b. All landings data from Polushin 1994, p. 36.

# Appendix G: Average Productivities of Selected Canadian Grains and Oilseeds 1981 to 1996

Table G-1 presents the average annual productivities for Canadian wheat, canola, grain corn and soybeans for the years 1981 to 1996 along with averages of the last five and ten years.

*Table G-1. Average Productivities of Canadian Wheat, Canola, Corn and Soybeans from 1981 to 1996*

| | **Average Productivities of Canadian Grains and Oilseeds** | | | |
|---|---|---|---|---|
| | Wheat (kg/ha) | Canola (kg/ha) | Corn (kg/ha) | Soybean (kg/ha) |
| Year | (all Prairie Prov's) | (all Prairie Prov's) | (all Canada) | (all Canada) |
| 1981 | 1,970 | 1,330 | 5,860 | 2,170 |
| 1982 | 2,120 | 1,260 | 5,880 | 2,330 |
| 1983 | 1,900 | 1,130 | 5,520 | 2,020 |
| 1984 | 1,570 | 1,110 | 5,900 | 2,260 |
| 1985 | 1,720 | 1,260 | 6,200 | 2,500 |
| 1986 | 2,200 | 1,400 | 5,900 | 2,500 |
| 1987 | 1,900 | 1,400 | 7,000 | 2,800 |
| 1988 | 1,200 | 1,100 | 5,500 | 2,200 |
| 1989 | 1,800 | 1,100 | 6,400 | 2,300 |
| 1990 | 2,200 | 1,300 | 6,900 | 2,600 |
| 1991 | 2,200 | 1,300 | 6,700 | 2,400 |
| 1992 | 2,100 | 1,300 | 5,700 | 2,300 |
| 1993 | 2,200 | 1,300 | 6,600 | 2,600 |
| 1994 | 2,100 | 1,300 | 7,400 | 2,700 |
| 1995 | 2,200 | 1,200 | 7,300 | 2,800 |
| 1996 | 2,400 | 1,400 | 6,900 | 2,500 |
| **5 yr ave.** | **2,200** | **1,300** | **6,780** | **2,580** |
| **10 yr ave.** | **2,030** | **1,270** | **6,640** | **2,520** |

Source: Canadian Socio-Economic Information Management (CANSIM) database.

[253] While the proportional mix of species that go for reduction may vary between Chile and Peru, I believe that using landings data from only the Chilean industry is not unreasonable given that Chile would appear to produce more of the high quality prime and superprime fish meals favoured by the salmon farming industry (Polushin 1994).

# *Appendix H: Analysis of the Material Inputs and Associated Embodied Energy and Greenhouse Gas Emissions to Net-Cage System Infrastructure*

Mr. Doug Louvier, president of Wavemaster Canada Limited (hereafter referred to as Wavemaster) provided data on the material inputs which would be required to build a net-cage system consisting of ten galvanised steel cages with walkways, each measuring 30 metres on a side by 20 metres deep, along with all related netting including predator nets and bird nets, a floating combination feedshed/bunkhouse building, all required floatation for both the cage system and feedshed and a complete anchoring system. In addition, Mr. Louvier provided estimates of the typical functional working life of the various components of the system described. The information provided by Mr. Louvier appears in Table H-1.

As nets can be damaged and are easily fouled with debris, mussels, barnacles, algae and kelp, it is frequently necessary to clean and repair them. As a result, salmon farms must have additional netting on hand above and beyond that which is deployed at any one time. In order to account for this need for extra netting within the model, an additional 25% has been added to the base quantities of main fish netting and predator netting that were indicated by Mr. Louvier.

In addition, while all the components of the net-cage system being modelled have a specific finite functional working life, because net-cage systems can be damaged by storms, tides, collisions with vessels, when being towed, as well as through simple wear and tear, I included a repair and maintenance factor of 25% over the expected life of each component.

In order to quantify the material inputs, and consequently the embodied energy and greenhouse gas emissions, per tonne of salmon produced, it was also necessary to make assumptions regarding the length of the typical production cycle and the average stocking density for both chinook and Atlantic salmon. Stocking densities for chinook salmon typically range between 5 and 10 kg/m$^3$ and for Atlantic salmon between 8 and 18kg/m$^3$ (British Columbia Environmental Assessment Office 1997, vol. 3, p B-10). For the purposes of my model, the median values of 7.5 kg/m$^3$ for chinook and 13 kg/m$^3$ for Atlantic salmon were applied.

*Table H-1. Analysis of the Material Inputs to the Fabrication and Maintenance of Saltwater Grow-Out Site Infrastructure per Tonne of Salmon Produced*

| | | Input | Fabrication Input | Repair & | Total | Inputs (kg) per tonne | |
|---|---|---|---|---|---|---|---|
| | Input | Longevity | per 24 month | Maint. | Inputs per | salmon produced | |
| Inputs | Mass (kg) | (years) | cycle (kg)[a] | Factor[b] | cycle (kg) | Atlantics[c] | Chinook[d] |
| Steel[e] | 63,500 | 15 | 8,467 | 25% | 10,583 | 4.5 | 7.8 |
| | | | | | | | |
| Zinc[f] | 3,600 | 15 | 480 | 25% | 600 | 0.26 | 0.44 |
| | | | | | | | |
| Polyethylene for float shells | 8,000 | 15 | 1,067 | 25% | 1,333 | | |
| Polystyrene for float cores | 3,400 | 15 | 453 | 25% | 567 | | |
| Nylon - main fish netting | 22,700 | 5 | 9,080 | 25% | 11,350 | | |
| Nylon - extra fish netting[g] | 5,675 | 5 | 2,270 | 25% | 2,838 | | |
| Nylon - predator netting | 2,300 | 5 | 920 | 25% | 1,150 | | |
| Nylon - extra pred. netting[g] | 575 | 5 | 230 | 25% | 288 | | |
| Nylon - bird netting | 450 | 5 | 180 | 25% | 225 | | |
| Nylon - anchor ropes | 9,000 | 5 | 3,600 | 25% | 4,500 | | |
| Foam for shed floatation[h] | 6,500 | 20 | 650 | 25% | 813 | | |
| | | | | Total all plastics: | 23,063 | 9.9 | 17.1 |
| Concrete anchors[i] | 99,000 | 20 | 9,900 | 0% | 9,900 | | |
| Concrete for shed float[h] | 105,200 | 20 | 10,520 | 25% | 13,150 | | |
| | | | | Total all concrete: | 23,050 | 9.9 | 17.1 |

Source: All material input quantities, except for that required for extra fish netting and predator netting, along with the expected working life of the various components was provided by Mr. Doug Louvier, president Wavemaster Canada Ltd. (pers. comm. 1998).

Notes: a. The typical saltwater production cycle for both chinook and Atlantic salmon is 24 months long (British Columbia Environmental Assessment Office 1997).
Therefore values in this column are derived by dividing the component mass by the expected number of production cycles that the component is expected to last (eg. the functional life expectancy of the component in years divided by two).
b. In order to account for the material which must be invested to maintain the system components over the course of their functional life, a repair and maintenance factor of 25% has been added to all components except for the anchors which are assumed to be functionally unreparable.
c. The average stocking density used for Atlantic salmon is 13.5 kg/m$^3$ (British Columbia Environmental Assessment Office 1997).
d. The average stocking density used for chinook salmon is 7.5 kg/m$^3$ (British Columbia Environmental Assessment Office 1997).
e. Steel inputs include all material for cage frame members, walkways, and railing.
f. Zinc is used to hot galvanise all steel components after they have been welded together.
g. In order to account for the back-up fish and predator netting which an operating site must have on hand to allow for net repairs and cleaning, an additional 25% of these two component inputs has been included in the analysis.
h. The floating platform upon which the feed shed/bunkhouse building is erected is comprised of a concrete shell filled with foam.
i.A total of 22 anchors, each weighing 4500kg, are required to hold the system in place.

# *Appendix I: Estimating the Average Trophic Level at Which Wild Salmon Feed*

For each of the five species of Pacific salmon native to British Columbia, estimates were made of the average trophic level of their diet while in the marine environment. This was done using published stomach content analyses, covering a range of live stages and locations from around the north Pacific[254]. All stomach content analyses used reported diet components either as a percentage by weight or by volume of the total stomach contents. After assigning appropriate trophic level values to each of the types of prey encountered[255], a weighted average trophic level of the total diet described was calculated for each of the stomach content analyses. For each species of salmon, I then calculated an overall mean of the individual diet trophic levels, along with the upper and lower 95% confidence limits (Tables I-1, I-2, I-3, I-4, and I-5).

[254] When a single reference reported more than one stomach content analysis for a given species of salmon, either reflecting different sampling years, seasons, locations or size of salmon being examined, I treated each analysis separately.

[255] Because stomach content analyses varied in the level of detail used to describe the organisms found in salmon stomachs (for example some analyses reported fish remains to the species level while others simply reported all fish remains as fish), I have, where necessary, re-organized the reported diet components into the following aggregate classes: squid, fish, euphausiids, copepods, amphipods, decapods, pteropods, polychaetes, appendicularia, cirripedia, larvacea, jellyfish, chaetognaths, and other.

*Table I-1. Summary of Chinook Salmon Stomach Content Analyses and Estimated Average Trophic Level of Prey*

| | | | | Diet Composition (% by weight or volume) | | | | | | | | | Mean | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of | | Mean | and mean trophic level of food category | | | | | | | | | Trophic | |
| Sample | Stomachs | | Size of | Sqd | Fish | Ephs | Cpds | Amph | Deca | Pter | Poly | Other | Level | |
| Year | exam. | empty | Fish | 3.5 | 3.0 | 2.2 | 2.0 | 2.3 | 2.5 | 2.5 | 2.5 | 2.7 | of Diet | Source |
| 1975 | 166 | n/a | | | 63.1 | 4.0 | 0.3 | 11.2 | 20.7 | 0.4 | | 0.3 | 2.78 | a |
| 1976 | 37 | n/a | | | 28.5 | 0.7 | | 25.8 | 16.0 | 3.4 | 1.2 | 24.2 | 2.64 | a |
| 1980-85 | 39 | 2 | 10.4 cm | | 74.5 | 4.7 | | 1.6 | 9.0 | | | | 2.90 | b |
| 1980-85 | 68 | 1 | 13.0 cm | | 77.5 | 1.3 | | 2.4 | 8.3 | | | | 2.92 | b |
| 1980-85 | 115 | 8 | 15.0 cm | | 90.2 | 2.0 | | 1.8 | 2.5 | | | | 2.96 | b |
| 1980-85 | 113 | 9 | 16.9 cm | | 88.6 | 4.7 | | 1.1 | 2.4 | | | | 2.94 | b |
| 1980-85 | 116 | 7 | 18.9 cm | | 92.9 | 2.1 | | 0.6 | 2.3 | | | | 2.97 | b |
| 1980-85 | 99 | 6 | 20.9 cm | | 93.0 | 3.2 | | 0.5 | 1.2 | | | | 2.96 | b |
| 1980-85 | 89 | 2 | 22.9 cm | | 93.7 | 0.7 | | 0.4 | 3.8 | | | | 2.97 | b |
| 1980-85 | 76 | 3 | 24.8 cm | | 92.1 | 1.4 | | 0.3 | 2.5 | | | | 2.97 | b |
| 1980-85 | 38 | 1 | 26.9 cm | | 86.7 | 5.3 | | 0.5 | 4.6 | | | | 2.93 | b |
| 1980-85 | 90 | 9 | 31.6 cm | | 82.9 | 9.1 | | 0.4 | 4.2 | | | | 2.90 | b |
| 1955 | 61 | 21 | 54.9 cm | 2.0 | 97.6 | | | | | | | 0.4 | 3.01 | c |
| 1955 | 89 | 32 | 56.9 cm | 6.0 | 80.8 | | | | 13.3 | | | | 2.96 | c |
| 1955 | 93 | 6 | 62.7 cm | 20.3 | 31.4 | 33.0 | | | 15.0 | | 0.1 | 0.2 | 2.76 | c |
| 1955 | 71 | 2 | 67.1 cm | 19.1 | 23.5 | 47.7 | | | 9.5 | | | 0.3 | 2.67 | c |
| 1955 | 119 | 3 | 70.1 cm | 13.5 | 61.4 | 23.9 | | | 1.0 | | | 0.2 | 2.87 | c |
| 1955 | 89 | 9 | 66.0 cm | 2.0 | 89.4 | 8.4 | | | | | | 0.2 | 2.94 | c |
| 1955 | 109 | 21 | 64.1 cm | 0.7 | 96.5 | 2.1 | | | | | | 0.7 | 2.98 | c |
| 1955 | 89 | 29 | 66.4 cm | 4.2 | 95.7 | | | | | | | | 3.02 | c |
| 1955 | 187 | 50 | 56.8 cm | 5.9 | 93.9 | | | | | | | 0.2 | 3.03 | c |
| 1955 | 97 | 21 | 54.7 cm | 1.9 | 98.1 | | | | | | | | 3.01 | c |
| 1991 | 24 | n/a | 2,019 g | 56.0 | 20.0 | 23.0 | | | | | | | 3.10 | d |
| 1992 | 16 | n/a | 2,418 g | 34.0 | | 63.0 | | | | 1.0 | | 1.0 | 2.65 | d |
| 1957 | 164 | 27 | 82 cm | 1.3 | 60.1 | 3.2 | | | | | | 34.9 | 2.88 | f |
| 1958 | 210 | 35 | 82 cm | 13.8 | 68.1 | 1.0 | | | | | | 17.1 | 3.01 | f |
| 1939 | 338 | 0 | | 0.1 | 94.2 | 5.6 | | | | | | 0.1 | 2.96 | g |
| 1940 | 467 | 0 | | 0.2 | 97.6 | 1.6 | | 0.3 | 0.3 | | | | 2.98 | g |
| 1941 | 578 | 0 | | 1.2 | 94.8 | 0.8 | | | 3.2 | | | | 2.98 | g |
| 1957 | 9 | | 63 cm | | 6.0 | 94.0 | | | | | | | 2.25 | h |
| 1957 | 35 | | 64 cm | | 95.3 | 2.7 | | | 1.0 | | | 1.0 | 2.97 | h |
| 1957 | 16 | | 64 cm | | 44.5 | 53.8 | | | | | | 1.7 | 2.56 | h |
| 1957 | 53 | | 71 cm | | 75.4 | 19.2 | | | 4.8 | | | 0.6 | 2.82 | h |
| 1957 | 29 | | 54 cm | | 83.1 | 16.3 | | | 0.2 | | | 0.4 | 2.87 | h |
| 1957 | 57 | | 76 cm | | 97.5 | 2.2 | | | 0.1 | | | 0.2 | 2.98 | h |
| 1957 | 6 | | 59 cm | | 100 | | | | | | | | 3.00 | h |
| 1957 | 67 | | 71 cm | | 93.4 | 4.7 | | | | | | 1.9 | 2.96 | h |
| 1957 | 5 | | 26 cm | | 85.0 | | | | 2.5 | | | 12.5 | 2.95 | h |
| 1957 | 32 | | 76 cm | | 99.5 | 0.2 | | | | | | 0.3 | 3.00 | h |
| | | | | | | Mean Trophic Level of All Chinook Diets: | | | | | | | 2.90 | |
| | | | | Standard Deviation of All Chinook Diet Mean Trophic Levels: | | | | | | | | | 0.1591 | |
| | | | | Upper 95% Confidence Limit of Mean Prey Trophic Level: | | | | | | | | | 2.95 | |
| | | | | Lower 95% Confidence Limit of Mean Prey Trophic Level: | | | | | | | | | 2.85 | |

Diet component notes: Sqd: denotes squid to which I have assigned a mean trophic level of 3.5.
Fish: represents the sum of all fish species and life stages (including eggs) reported. I have assigned a mean trophic level of 3.0 to this prey category.
Ephs. denotes euphausiids to which I have assigned a mean trophic level of 2.2 reflecting an assumed average diet composition of 80% phytoplankton and 20% zooplankton.

Cpds. denotes copepods to which I have assigned an average trophic level of 2.0 reflecting a diet that is composed almost entirely of phytoplankton and bacteria-rich detritus (Pauly and Christensen 1996).
Amph. denotes amphipods to which I have assigned a mean trophic level of 2.5.
Deca. represents the sum of all decapod life stages reported. I have assigned a mean trophic level of 2.5 to this prey category.
Pter. denotes pteropods to which I have assigned a mean trophic level of 2.5.
Poly. denotes polychaetes to which I have assigned an average trophic level of 2.5.
Other represents all other prey items documented which may include insects (particularly in stomach content analyses of juvenile fish) and an unidentifiable fraction in some analyses.

Source Notes: a. Healey 1980, b. Brodeur 1991, c. Merkel 1957, d. Tadokoro 1996, e. Reid 1961, f. Pritchard and Tester 1944, g. Prakash 1962

*Table I-2. Summary of Coho Salmon Stomach Content Analyses and Estimated Average Trophic Level of Prey*

| | | | | | Diet Composition (% by weight or volume) | | | | | | | | Mean | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of | | Mean | | and mean trophic level of food category | | | | | | | | Trophic | |
| Sample | Stomachs | | Size of | Sqd | Fish | Ephs | Cpds | Amph | Deca | Pter | Poly | Other | Level | |
| Year | exam. | empty | Fish | 3.5 | 3.0 | 2.2 | 2.0 | 2.3 | 2.5 | 2.5 | 2.5 | 2.7 | of Diet | Source |
| 1975 | 482 | n/a | Juv. | | 34.6 | 4.4 | 0.2 | 26.6 | 28.0 | 5.3 | | 0.9 | 2.61 | a |
| 1976 | 52 | n/a | Juv. | | 28.9 | 0.3 | | 41.7 | 11.1 | 10.5 | 3.6 | 3.7 | 2.57 | a |
| 1955 | 144 | 19 | 10 cm | | 70.0 | 3.0 | 6.0 | 3.0 | 9.0 | | | 7.0 | 2.83 | b |
| 1980-85 | 86 | 5 | 12.1 cm | | 50.4 | 23.2 | | 5.2 | 11.2 | | | | 2.69 | c |
| 1980-85 | 308 | 11 | 14.1 cm | | 61.6 | 12.8 | | 3.5 | 7.9 | | | | 2.81 | c |
| 1980-85 | 256 | 24 | 15.9 cm | | 73.8 | 7.6 | | 3.0 | 6.7 | | | | 2.87 | c |
| 1980-85 | 240 | 10 | 17.9 cm | | 70.2 | 8.2 | | 5.2 | 6.5 | | | | 2.85 | c |
| 1980-85 | 190 | 7 | 19.9 cm | | 69.3 | 10.6 | | 3.3 | 7.8 | | | | 2.84 | c |
| 1980-85 | 121 | 5 | 21.8 cm | | 55.0 | 16.5 | | 6.0 | 6.9 | | | | 2.75 | c |
| 1980-85 | 81 | 3 | 23.9 cm | | 64.4 | 10.5 | | 3.2 | 3.0 | | | | 2.85 | c |
| 1980-85 | 50 | 1 | 26.0 cm | | 76.1 | 6.7 | | 2.8 | 8.0 | | | | 2.88 | c |
| 1980-85 | 56 | 3 | 27.9 cm | | 60.8 | 24.0 | | 3.4 | 2.9 | | | | 2.75 | c |
| 1980-85 | 162 | 10 | 32.5 cm | | 83.6 | 6.5 | | 1.6 | 1.8 | | | | 2.92 | c |
| 1964 | 4 | 2 | 37 cm | | | 15.0 | | 5.0 | 80.0 | | | | 2.45 | d |
| 1958 | 73 | 20 | 58 cm | 47.8 | 21.0 | 31.4 | | | | 0.2 | | | 2.99 | e |
| 1991 | 85 | n/a | 1,796 g | 88.0 | 1.0 | 1.0 | | 5.0 | | 4.0 | | 1.0 | 3.37 | f |
| 1992 | 23 | n/a | 1,635 g | 78.0 | 2.0 | 5.0 | 1.0 | 12.0 | | 1.0 | | 1.0 | 3.25 | f |
| 1957 | 200 | 66 | 69 cm | 0.7 | 69.8 | 5.9 | | | | | | 23.0 | 2.89 | g |
| 1958 | 222 | 73 | 69 cm | | 57.8 | 5.6 | | 7.7 | 1.0 | | | 27.5 | 2.81 | g |
| 1939 | 45 | 0 | | | 95.7 | 0.4 | | | 3.8 | 0.1 | | | 2.98 | h |
| 1940 | 126 | 0 | | | 70.4 | 9.1 | | 12.5 | 6.9 | | | 1.1 | 2.80 | h |
| 1941 | 86 | 0 | | 0.6 | 81.4 | 0.4 | | 9.0 | 8.6 | | | | 2.89 | h |
| 1957 | 18 | 0 | 47 cm | | 58.0 | 13.8 | | 24.3 | 3.9 | | | | 2.70 | i |
| 1957 | 48 | 0 | 53 cm | | 26.8 | 27.8 | | 29.8 | 15.1 | | | 0.5 | 2.49 | i |
| 1957 | 16 | 0 | 58 cm | | 69.7 | 5.6 | | 0.2 | 24.5 | | | | 2.83 | i |
| 1957 | 57 | 0 | 52 cm | | 71.8 | 0.1 | | 19.2 | 8.2 | | | 0.7 | 2.82 | i |
| 1957 | 41 | 0 | 62 cm | | 86.0 | 0.8 | | 0.1 | 12.7 | | | 0.4 | 2.93 | i |
| 1957 | 13 | 0 | 52 cm | | 21.4 | 18.8 | | 43.9 | 15.0 | | | 0.9 | 2.46 | i |
| 1957 | 85 | 0 | 64 cm | | 95.8 | 3.4 | | | 0.5 | | | 0.5 | 2.97 | i |
| 1957 | 5 | 0 | 49 cm | | 12.5 | 43.7 | | | 25.0 | | | 18.8 | 2.47 | i |
| 1957 | 45 | 0 | 66 cm | | 75.2 | 22.1 | | | 2.3 | | | 0.4 | 2.81 | i |
| | | | | | | | Mean Trophic Level of All Coho Diets: | | | | | | 2.81 | |
| | | | | Standard Deviation of All Coho Diet Mean Trophic Levels: | | | | | | | | | 0.2042 | |
| | | | | Upper 95% Confidence Limit of Mean Prey Trophic Level: | | | | | | | | | 2.88 | |
| | | | | Lower 95% Confidence Limit of Mean Prey Trophic Level: | | | | | | | | | 2.74 | |

Diet component notes:

Sqd: denotes squid to which I have assigned a mean trophic level of 3.5.
Fish: represents the sum of all fish species and life stages (including eggs) reported. I have assigned a mean trophic level of 3.0 to this prey category.
Ephs. denotes euphausiids to which I have assigned a mean trophic level of 2.2.
Cpds. denotes copepods to which I have assigned an average trophic level of 2.0 reflecting a diet that is composed almost entirely of phytoplankton and bacteria-rich detritus (Pauly and Christensen 1996).
Amph. denotes amphipods to which I have assigned a mean trophic level of 2.5.
Deca. represents the sum of all decapod life stages reported. I have assigned a mean trophic level of 2.5 to this prey category.
Pter. denotes pteropods to which I have assigned a mean trophic level of 2.5.
Poly. denotes polychaetes to which I have assigned an average trophic level of 2.5.
Other represents all other prey items documented which may include insects (particularly in stomach content analyses of juvenile fish) and an unidentifiable fraction in some analyses.

Source Notes: a. Healey 1980, b. Manzer 1969, c. Brodeur 1991, d. Manzer 1968, e. LeBrasseur 1966, f. Tadokoro 1996, g. Reid 1961, h. Pritchard and Tester 1944, i. Prakash 1962

*Table I-3. Summary of Sockeye Salmon Stomach Content Analyses and Estimated Average Trophic Level of Prey*

| | | | | | | Diet Composition (by weight or volume) | | | | | | | | | Mean | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of | | Mean | | | and mean trophic level of food category | | | | | | | | | Trophic | |
| Sample | Stomachs | | Size of | Sqd | Fish | Ephs | Cpds | Amph | Deca | Pter | App | Larv | Jlly | Other | Level | |
| Year | exam. | empty | Fish | 3.5 | 3.0 | 2.2 | 2.0 | 2.3 | 2.5 | 2.5 | 2.0 | 2.5 | 3.0 | 2.7 | of Diet | Source |
| 1955 | 98 | 7 | 9 cm | | 24.0 | 1.0 | 48.0 | 3.0 | 5.0 | | | 14.0 | | 7.0 | 2.39 | a |
| 1986 | 60 | 0 | 13 cm | | 2.1 | 29.4 | 2.8 | 4.9 | 0.5 | | | 59.8 | | 0.5 | 2.40 | b |
| 1987 | 148 | 5 | 13 cm | | 1.3 | 21.0 | 36.1 | 2.1 | 7.8 | 3.8 | | 27.4 | | 0.5 | 2.26 | b |
| 1975 | 26 | n/a | Juv. | | 10.5 | 8.4 | 0.6 | 54.2 | 15.4 | | | | | 10.9 | 2.44 | c |
| 1976 | 11 | n/a | Juv. | | | | 7.3 | 66.9 | 1.4 | | | | | 24.2 | 2.38 | c |
| 1967-68 | 996 | 79 | Juv. | | 30.8 | 42.0 | 5.1 | 1.6 | | 6.2 | | | | | 2.50 | d |
| 1964 | 87 | 43 | 43 cm | 27.0 | 71.0 | | | | 1.0 | | | | | 1.0 | 3.13 | e |
| 1958 | 137 | 28 | 48 cm | 27.1 | 5.2 | 29.2 | 0.5 | 18.0 | | | | | | 19.9 | 2.71 | f |
| 1958 | 451 | 53 | 58 cm | 29.7 | 17.7 | 33.4 | 2.2 | 9.5 | | 1.3 | | | | 5.7 | 2.77 | f |
| 1955 | 91 | 40 | 56 cm | 4.9 | 0.3 | 1.3 | | 64.6 | 26.0 | 2.9 | | | | | 2.42 | g |
| 1955 | 117 | 32 | 55 cm | 2.0 | 4.0 | 4.0 | 1.0 | 85.0 | 1.0 | 3.0 | | | | | 2.35 | g |
| 1955 | 104 | 13 | 54 cm | 1.0 | 11.0 | 31.0 | 49.5 | 4.0 | | 5.0 | | | | | 2.22 | g |
| 1991 | 42 | n/a | 1,633 g | 12.0 | 2.0 | 35.0 | 7.0 | 2.0 | | 21.0 | 5.0 | | 11.0 | 11.0 | 2.54 | h |
| 1992 | 21 | n/a | 1,922 g | 62.0 | 5.0 | 5.0 | 6.0 | 16.0 | | | | | 4.0 | 2.0 | 3.09 | h |
| | | | | | | | | Mean Trophic Level of All Sockeye Diets: | | | | | | | 2.54 | |
| | | | | | Standard Deviation of All Sockeye Diet Mean Trophic Levels: | | | | | | | | | | 0.2832 | |
| | | | | | | Upper 95% Confidence Limit of Mean Prey Trophic Level: | | | | | | | | | 2.69 | |
| | | | | | | Lower 95% Confidence Limit of Mean Prey Trophic Level: | | | | | | | | | 2.39 | |

Diet component notes:

Sqd: denotes squid to which I have assigned a mean trophic level of 3.5.
Fish: represents the sum of all fish species and life stages (including eggs) reported. I have assigned a mean trophic level of 3.0 to this prey category.
Ephs. denotes euphausiids to which I have assigned a mean trophic level of 2.2.
Cpds. denotes copepods to which I have assigned an average trophic level of 2.0 reflecting a diet that is composed almost entirely of phytoplankton and bacteria-rich detritus (Pauly and Christensen 1996).
Amph. denotes amphipods to which I have assigned a mean trophic level of 2.5.
Deca. represents the sum of all decapod life stages reported. I have assigned a mean trophic level of 2.5 to this prey category.
Pter. denotes pteropods to which I have assigned a mean trophic level of 2.5.
App. denotes appendicularians to which I have assigned a mean trophic level of 2.0.
Larv. denotes larvacea to which I have assigned a mean trophic level of 2.5.
Jlly. denotes jellyfish to which I have assigned a mean trophic level of 3.0.
Other represents all other prey items documented which may include insects (particularly in stomach content analyses of juvenile fish) and an unidentifiable fraction in some analyses.

Source Notes: a. Manzer 1969, b. Healey 1991a, c. Healey 1980, d. Hartt and Dell 1986, e. Manzer 1968, f. LeBrasseur 1966, g. Allen and Aron 1958, h. Tadokoro 1996

*Table I-4. Summary of Pink Salmon Stomach Content Analyses and Estimated Average Trophic Level of Prey*

| | | | | | Diet Composition (% by weight or volume) | | | | | | | | | Mean | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of | | Mean | | and mean trophic level of food category | | | | | | | | | Trophic | |
| Sample | Stomachs | | Size of | Sqd | Fish | Ephs | Cpds | Amph | Deca | Pter | Cirr | Larv | Other | Level | |
| Year | exam. | empty | Fish | 3.5 | 3.0 | 2.2 | 2.0 | 2.3 | 2.5 | 2.5 | 2.0 | 2.5 | 2.7 | of Diet | Source |
| 1955 | 537 | 27 | 8 cm | | 5.0 | 3.0 | 31.0 | 1.0 | 4.0 | | 6.0 | 40.0 | 8.0 | 2.34 | a |
| 1986 | 825 | 2 | 12 cm | | 0.9 | 10.0 | 2.2 | 5.1 | 0.9 | | 0.2 | 80.4 | 0.3 | 2.45 | b |
| 1987 | 1157 | 29 | 12 cm | | 0.9 | 20.2 | 26.2 | 1.9 | 25.0 | 7.5 | 0.7 | 16.6 | 1.0 | 2.31 | b |
| 1976 | 22 | n/a | Juv. | | 1.7 | 7.1 | 7.8 | 37.4 | 10.9 | 1.7 | | | 32.5 | 2.44 | c |
| 1964 | 24 | 9 | 31 cm | | 1.0 | 1.0 | | 97.0 | | | | | 1.0 | 2.31 | d |
| 1970 | 53 | n/a | Juv. | | 14.0 | 2.0 | 46.0 | 4.0 | | | 16.0 | | 18.0 | 2.28 | e |
| 1964-66 | 170 | n/a | Juv. | | 3.0 | 1.0 | 77.0 | | 1.0 | | 8.0 | 3.0 | 7.0 | 2.10 | f |
| 1963 | 255 | n/a | Juv. | 5.0 | 2.0 | 50.0 | 19.0 | 7.0 | | 5.0 | | 1.0 | 11.0 | 2.32 | g |
| 1974 | 385 | n/a | Juv. | | 11.0 | | 73.0 | 2.8 | | | | | 13.2 | 2.21 | h |
| 1974 | 418 | n/a | Juv. | | 3.4 | | 89.5 | 2.6 | | | | | 4.5 | 2.07 | h |
| 1977 | 623 | n/a | Juv. | | 3.5 | 3.2 | 82.8 | 2.2 | 0.8 | | | | 7.5 | 2.10 | h |
| 1977 | 214 | n/a | Juv. | | 7.2 | 11.5 | 72.0 | | 4.7 | | | | 4.6 | 2.15 | h |
| 1955 | 46 | 15 | 50 cm | 6.7 | 13.7 | 0.3 | | 56.9 | 12.2 | 10.1 | | | | 2.52 | i |
| 1955 | 132 | 14 | 49 cm | 1.7 | 20.5 | 7.6 | 1.0 | 49.0 | 16.7 | 3.5 | | | | 2.49 | i |
| 1955 | 111 | 4 | 48 cm | 3.1 | 17.0 | 20.2 | 41.7 | 12.5 | | 5.5 | | | | 2.32 | i |
| 1958 | 167 | 17 | 50 cm | 6.1 | 62.5 | 10.9 | 0.6 | 6.7 | | 3.3 | | | 9.9 | 2.84 | j |
| 1991 | 226 | n/a | 1,073 g | 14.0 | 12.0 | 37.0 | 11.0 | 8.0 | | 13.0 | | | 4.0 | 2.53 | k |
| 1992 | 7 | n/a | 1,318 g | 20.0 | 26.0 | 23.0 | 5.0 | 25.0 | 1.0 | | | | | 2.69 | k |
| 1952 | 97 | 2 | Immat.? | 5.4 | 8.8 | 65.9 | 1.7 | 10.6 | | | | | 7.6 | 2.39 | l |
| 1956 | 1061 | n/a | Immat.? | 28.9 | 44.8 | 11.0 | 1.7 | 5.7 | | 6.2 | | | 1.7 | 2.96 | m |
| 1957 | 175 | n/a | Immat.? | 0.6 | 2.7 | 36.5 | 30.0 | 7.8 | | | | | 22.4 | 2.29 | m |
| 1958 | 356 | n/a | Immat.? | 41.7 | 19.3 | 18.6 | 5.4 | 10.9 | | 1.1 | | | 3.0 | 2.91 | m |
| 1959 | 204 | n/a | Immat.? | 0.7 | 16.0 | 37.3 | 16.2 | 13.7 | | 3.9 | | | 12.2 | 2.39 | m |
| 1960 | 176 | n/a | Immat.? | 57.0 | 16.2 | 11.3 | 1.8 | 6.5 | | 0.7 | | | 6.1 | 3.11 | m |
| 1961 | 178 | n/a | Immat.? | 1.1 | 21.8 | 52.4 | 6.8 | 1.7 | | 5.8 | | | 10.4 | 2.45 | m |
| 1962 | 196 | n/a | Immat.? | 8.2 | 19.0 | 21.8 | 9.5 | 13.2 | | 13.4 | | | 14.9 | 2.57 | m |
| 1963 | 198 | n/a | Immat.? | 1.5 | 10.1 | 46.4 | 17.7 | 12.6 | | 5.4 | | | 6.3 | 2.33 | m |
| 1964 | 254 | 114 | Immat.? | 26.9 | 7.3 | 0.4 | | 24.0 | | 31.6 | | | 9.8 | 2.78 | n |
| 1965 | 290 | 64 | Immat.? | 2.2 | 17.7 | 35.2 | 5.0 | 4.0 | | 3.8 | | | 32.1 | 2.54 | n |
| 1966 | 447 | 67 | Immat.? | 21.6 | 6.2 | 22.8 | 16.0 | 14.6 | | 7.8 | | | 11.0 | 2.59 | n |
| 1966 | 107 | 13 | Immat.? | 91.3 | 6.5 | 0.7 | | 1.2 | | | | | 0.3 | 3.44 | o |
| 1966 | 79 | 6 | Immat.? | | 53.2 | 16.4 | | 27.5 | | | | | 2.9 | 2.67 | o |
| 1948 | 400 | 388 | Mat.? | | 87.8 | 4.6 | | 4.8 | | | | | 2.8 | 2.92 | p |
| 1949 | 833 | 733 | Mat.? | 1.5 | 50.2 | 11.1 | | 6.2 | | 0.1 | | | 30.9 | 2.78 | p |
| 1949 | 125 | 93 | Mat.? | 0.1 | 38.6 | 52.3 | | 7.6 | | | | | 1.4 | 2.52 | p |
| 1965 | 79 | n/a | Mat.? | | 0.4 | 0.2 | | 95.6 | | | | | 3.6 | 2.32 | q |
| 1965 | 229 | n/a | Mat.? | 1.8 | 0.7 | 34.3 | 2.2 | 54.4 | | | | | 6.6 | 2.31 | q |
| 1965 | 277 | n/a | Mat.? | 12.0 | 0.2 | 43.3 | 0.4 | 37.8 | | | | | 6.3 | 2.43 | q |
| 1965 | 585 | n/a | Mat.? | 6.5 | 0.5 | 33.4 | 1.0 | 52.6 | | | | | 6.0 | 2.37 | q |
| | | | | | | | | Mean Trophic Level of All Pink Diets: | | | | | | 2.50 | |
| | | | | | Standard Deviation of All Pink Diet Mean Trophic Levels: | | | | | | | | | 0.2942 | |
| | | | | | Upper 95% Confidence Limit of Mean Trophic Level of Prey: | | | | | | | | | 2.59 | |
| | | | | | Lower 95% Confidence Limit of Mean Trophic Level of Prey: | | | | | | | | | 2.41 | |

Diet component notes:

Sqd: denotes squid to which I have assigned a mean trophic level of 3.5.

Fish: represents the sum of all fish species and life stages (including eggs) reported. I have assigned a mean trophic level of 3.0 to this prey category.

Ephs. denotes euphausiids to which I have assigned a mean trophic level of 2.2.

Cpds. denotes copepods to which I have assigned an average trophic level of 2.0 reflecting a diet that is composed almost entirely of phytoplankton and bacteria-rich detritus (Pauly and Christensen 1996).

Amph. denotes amphipods to which I have assigned a mean trophic level of 2.5.

Deca. represents the sum of all decapod life stages reported. I have assigned a mean trophic level of 2.5 to this prey category.
Pter. denotes pteropods to which I have assigned a mean trophic level of 2.5.
Cirr. denotes cirripedia to which I have assigned a mean trophic level of 2.0.
Larv. denotes larvacea to which I have assigned a mean trophic level of 2.5.
Other represents all other prey items documented which may include insects (particularly in stomach content analyses of juvenile fish) and an unidentifiable fraction in some analyses.

Source Notes: a. Manzer 1969; b. Healey 1991a; c. Healey 1980; d. Manzer 1968; e. Kaczynski *et al.* 1973 as reported in Takagi *et al.* 1981, Table 10; f. Bailey *et al.* 1975 as reported in Takagi *et al.* 1981, Table 10; g. LeBrasseur and Barner 1964 as reported in Takagi *et al.* 1981, Table 10; h. Shershnev *et al.* 1982 as reported in Heard 1991, Table 19; i. Allen and Aron 1958; j. LeBrasseur 1966; k. Tadokoro 1996; l. Maeda 1954 as reported in Takagi *et al.* 1981, Table 9; m. Ito 1964 as reported in Takagi *et al.* 1981, Table 9; n. Takeuchi 1972 as reported in Takagi *et al.* 1981, Table 9; o. Kanno and Hamai 1971 as reported in Takagi *et al.* 1981, Table 9; p. Pushkareva 1951 as reported in Takagi *et al.* 1981, Table 9; q. Fukataki 1967 as reported in Takagi *et al.* 1981, Table 9.

*Table I-5. Summary of Chum Salmon Stomach Content Analyses and Estimated Average Trophic Level of Prey*

| | | | | | | Diet Composition (% by weight or volume) | | | | | | | | | | | Mean | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of | | Mean | | | | and mean trophic level of food category | | | | | | | | | | Trophic | |
| Sample | Stomachs | | Size of | Sqd | Fish | Ephs | Cpds | Amph | Deca | Pter | App | Chae | Poly | Cirr | Larv | Jlly | Other | Level | |
| Year | exam | empty | Fish | 3.5 | 3.0 | 2.2 | 2.0 | 2.3 | 2.5 | 2.5 | 2.0 | 3.0 | 2.5 | 2.0 | 2.5 | 3.0 | 2.7 | of Diet | Source |
| 1955 | 410 | 20 | 7 cm | | 4.0 | 4.0 | 19.0 | 2.0 | 5.0 | | | | | 2.0 | 51.0 | | 9.0 | 2.41 | a |
| 1986 | 246 | 1 | 12 cm | | 2.0 | 10.2 | 1.9 | 3.9 | 0.4 | | | | | | 81.1 | | 0.5 | 2.46 | b |
| 1987 | 580 | 12 | 13 cm | | 2.0 | 4.4 | 20.9 | 2.6 | 1.1 | 3.6 | | 0.3 | | 0.2 | 64.3 | | 0.6 | 2.39 | b |
| 1975 | 465 | n/a | Juv. | | 12.3 | 13.2 | 7.7 | 41.2 | 9.4 | | | 2.8 | 5.6 | | 2.3 | | 5.0 | 2.42 | c |
| 1976 | 14 | n/a | Juv. | | 2.1 | 7.2 | 5.6 | 65.6 | 14.1 | 0.8 | | | 3.7 | | | | 0.9 | 2.33 | c |
| 1955 | 19 | 3 | 56 cm | 17.1 | 10.6 | 3.0 | 2.0 | 12.1 | 35.8 | 19.1 | | | | | | | | 2.68 | d |
| 1955 | 49 | 3 | 57 cm | 23.3 | 11.7 | 15.7 | 5.9 | 30.1 | 3.8 | 9.4 | | | | | | | | 2.65 | d |
| 1955 | 88 | 5 | 55 cm | 1.1 | 19.0 | 50.1 | 10.1 | 7.8 | 0.8 | 11.1 | | | | | | | | 2.39 | d |
| 1958 | 361 | 22 | 55 cm | 1.3 | 24.0 | 0.5 | 0.7 | 0.3 | | 14.7 | | | | | | | 58.4 | 2.74 | e |
| 1991 | 267 | n/a | 1,238 g | 2.0 | 1.0 | 9.0 | 4.0 | 4.0 | | 3.0 | 15.0 | 1.0 | | | | 6.0 | 56.0 | 2.54 | f |
| 1992 | 168 | n/a | 1,527 g | 13.0 | 4.0 | 34.0 | 10.0 | 13.0 | | | | 2.0 | | | | 10.0 | 13.0 | 2.56 | f |
| | | | | | | | | | | | Mean Trophic Level of All Chum Diets: | | | | | | | 2.51 | |
| | | | | | | | Standard Deviation of All Chum Diet Mean Trophic Levels: | | | | | | | | | | | 0.137 | |
| | | | | | | | Upper 95% Confidence Limit of Mean Trophic Level of Prey: | | | | | | | | | | | 2.59 | |
| | | | | | | | Lower 95% Confidence Limit of Mean Trophic Level of Prey: | | | | | | | | | | | 2.43 | |

Diet component notes:

Sqd: denotes squid to which I have assigned a mean trophic level of 3.5.

Fish: represents the sum of all fish species and life stages (including eggs) reported. I have assigned a mean trophic level of 3.0 to this prey category.

Ephs. denotes euphausiids to which I have assigned a mean trophic level of 2.2.

Cpds. denotes copepods to which I have assigned an average trophic level of 2.0 reflecting a diet that is composed almost entirely of phytoplankton and bacteria-rich detritus (Pauly and Christensen 1996).

Amph. denotes amphipods to which I have assigned a mean trophic level of 2.5.

Deca. represents the sum of all decapod life stages reported. I have assigned a mean trophic level of 2.5 to this prey category.

Pter. denotes pteropods to which I have assigned a mean trophic level of 2.5.

App. denotes appendicularians to which I have assigned a mean trophic level of 2.0.

Chae. denotes chaetognaths to which I have assigned a mean trophic level of 3.0.

Poly. denotes polychaetes to which I have assigned a mean trophic level of 2.5.

Cirr. denotes cirripedia to which I have assigned a mean trophic level of 2.0.

Larv. denotes larvacea to which I have assigned a mean trophic level of 2.5.

Jlly. denotes jellyfish to which I have assigned a mean trophic level of 3.0.

Other represents all other prey items documented which may include insects (particularly in stomach content analyses of juvenile fish) and an unidentifiable fraction in some analyses.

Source Notes: a. Manzer 1969, b. Healey 1991a, c. Healey 1980, d. Allen & Aron 1958, e. LeBrasseur 1966, Tadokoro 1996

## *Appendix J: Calculation of the Proportion of SEP Operational Inputs Dedicated to the Production of Each Species of Salmon*

As a starting assumption, I postulated that there is a very close relationship between the amount of manufactured feed consumed by a population of juvenile salmon being reared in Salmon Enhancement Program (SEP) facilities and the amount of total operational inputs dedicated to rearing that population until their release. If this assumption is valid, then an estimate can be made of the proportion of the SEP operational material and energy inputs required to produce a given population, based on the proportion of the total amount of feed that that population of salmon consumes. Using data, provided by the SEP of the number and average weight upon release for unfed fry, fed fry and yearling smolts released from all of their operational facilities for 1994, '95 and '96 (Table J-1), I calculated the proportion of the total feed used that is consumed by each species in each year (Table J-2).

*Table J-1. Total Number and Average Weight of Unfed Fry, Fed Fry and Yearling Smolts Released from all SEP Operational Facilities, 1994-1996*

| | Release | Unfed Fry | | Fed Fry or Smolts | | Yearlings | | Total Releases |
|---|---|---|---|---|---|---|---|---|
| Species | Year | Number | Ave. wt (g) | Number | Ave. wt (g) | Number | Ave. wt (g) | |
| Chinook | 1994 | 292,965 | 0.95 | 37,109,329 | 6.09 | 956,969 | 14.79 | 38,359,263 |
| Chinook | 1995 | 1,020,614 | 0.62 | 42,657,973 | 5.44 | 1,005,460 | 19.55 | 44,684,047 |
| Chinook | 1996 | 113,892 | 0.74 | 35,724,383 | 6.89 | 294,412 | 15.68 | 36,132,687 |
| Coho | 1994 | 406,994 | 0.33 | 2,345,007 | 3.33 | 9,075,410 | 20.48 | 11,827,411 |
| Coho | 1995 | 5,494,725 | 0.33 | 1,616,310 | 3.38 | 9,205,971 | 19.81 | 16,317,006 |
| Coho | 1996 | 1,522,715 | 0.3 | 1,374,330 | 3.63 | 8,855,431 | 19.86 | 11,752,476 |
| Chum | 1994 | 98,046,139 | 0.37 | 85,162,248 | 1.23 | | | 183,208,387 |
| Chum | 1995 | 82,419,982 | 0.36 | 94,502,120 | 1.11 | | | 176,922,102 |
| Chum | 1996 | 32,336,763 | 0.38 | 78,466,467 | 1.22 | | | 110,803,230 |
| Sockeye | 1994 | 223,900,823 | 0.16 | 4,256,639 | 1.12 | | | 228,157,462 |
| Sockeye | 1995 | 151,654,906 | 0.16 | 4,940,282 | 0.74 | | | 156,595,188 |
| Sockeye | 1996 | 107,705,769 | 0.16 | 2,390,314 | 1.06 | | | 110,096,083 |
| Pink | 1994 | 34,540,385 | 0.22 | 932,502 | 0.46 | | | 35,472,887 |
| Pink | 1995 | 7,185,144 | 0.21 | 1,981,042 | 0.62 | | | 9,166,186 |
| Pink | 1996 | 29,926,853 | 0.21 | 1,762,467 | 0.72 | | | 31,689,320 |

*Table J-2. Total Feed Derived Weight Gain and Proportion of Weight Gained by each Species Released from all SEP Operational Facilities, 1994-1996*

| Species | Release Year | Total Weight Gain Through Feeding (kg)[a] | Percentage of Weight Gain Through Feeding |
|---|---|---|---|
| Chinook | 1994 | 203,986 | 43% |
| Coho | 1994 | 189,905 | 40% |
| Chum | 1994 | 73,240 | 16% |
| Sockeye | 1994 | 4,086 | 1% |
| Pink | 1994 | 224 | 0% |
| | 1994 Total: | 471,441 | |
| Chinook | 1995 | 224,645 | 46% |
| Coho | 1995 | 184,262 | 38% |
| Chum | 1995 | 70,877 | 15% |
| Sockeye | 1995 | 2,865 | 1% |
| Pink | 1995 | 812 | 0% |
| | 1995 Total: | 483,461 | |
| Chinook | 1996 | 224,103 | 48% |
| Coho | 1996 | 177,789 | 38% |
| Chum | 1996 | 65,912 | 14% |
| Sockeye | 1996 | 2,151 | 0% |
| Pink | 1996 | 899 | 0% |
| | 1996 Total: | 470,854 | |

Notes: a. Values in this column were calculated using the data presented in Table J-1. For each species in each year, the total fed weight gain was calculated by adding the product of the fed weight gain increment for fed fry/smolts by the corresponding numbers of fed fry/smolts released to the product of the fed weight gain increment for yearlings by the corresponding numbers of yearlings released for each species for each year. For example, the calculation of the total fed weight gain for chinook salmon released in 1994 appears as:

$$((6.09-0.95) \times 37{,}109{,}329) + ((14.79-0.95) \times 956{,}969) = 203{,}986{,}402 \text{ grams.}$$

From Table J-2, the proportion of feed that goes into producing each species in SEP operational facilities has remained fairly consistent over the three years from 1994 to 1996. Furthermore, chinook and coho in combination consistently account for well over 80% of the feed derived weight gain associated with all juvenile salmon production from SEP facilities while chum represent approximately 15% and sockeye and pink in combination account for at most 1%.

Therefore, based on my original assumption, I posit that over 80% of the operating inputs and hence biophysical costs associated with SEP operational facilities are dedicated to chinook and coho production. About 15% is dedicated to chum production and a negligible amount, on the order of 1%, is dedicated to sockeye and pink production.

# *Appendix K: Analysis of the Direct Material, Labour and Energy Inputs to Chinook and Coho Smolt Production to Two SEP Hatcheries*

Managers of two SEP hatcheries, Tenderfoot Creek hatchery and Robertson Creek hatchery, were surveyed regarding the labour, feed and operating energy inputs to chinook and coho smolt production from their facilities. Considering chinook and coho production separately, the data from the two hatcheries were averaged and normalised per million smolts produced using mass of smolts produced as the weighting factor (Table K-1).

*Table K-1. Summary of the Material, Labour and Energy Inputs to Chinook and Coho Salmon Smolt Production from Two SEP Hatcheries and Average Inputs per Million Smolts Produced*

| | | | | | Average Inputs to Produce | | | |
|---|---|---|---|---|---|---|---|---|
| | Robertson Creek[a] | | Tenderfoot Creek[b] | | Chinook smolts per | | Coho Smolts per | |
| **Inputs** | **Chinook** | **Coho** | **Chinook** | **Coho** | **$10^6$ pieces** | **tonne** | **$10^6$ pieces** | **tonne** |
| Labour (person-days) | 2,160 | 270 | 1,155 | 385 | 332 | 60 | 550 | 28 |
| Feed (kg) - "Dry"[c] | 7,600 | 0 | | | 762 | 137 | 0 | 0 |
| - Semi-moist[d] | 16,800 | 4,200 | 1,649 | 1,031 | 1,850 | 332 | 4,396 | 220 |
| - CMP/OMP[e] | 9,000 | 18,000 | 10,287 | 6,429 | 1,934 | 347 | 20,529 | 1,026 |
| Electricity in kWh | 127,200 | 413,400 | 333,744 | 500,616 | | | | |
| Electricity in MJ[f] | 457,920 | 1,488,240 | 1,201,478 | 1,802,218 | 166,439 | 29,845 | 2,765,090 | 138,255 |
| Gasoline in litres | 7,358 | 3,679 | 6,587 | 2,196 | | | | |
| Gasoline in MJ[g] | 237,296 | 118,648 | 23,713 | 7,906 | 26,179 | 4,694 | 106,347 | 5,317 |
| Furnace oil in litres | 12,240 | 1,530 | | | | | | |
| Furnace oil in MJ[h] | 474,422 | 59,303 | | | 47,585 | 8,533 | 49,834 | 2,492 |
| Propane in litres | 3,804 | | | | | | | |
| Propane in MJ[i] | 96,082 | | | | 9,637 | 1,728 | 0 | 0 |
| **Smolt Output** | | | | | | | | |
| Numbers of smolts | 8,370,000 | 890,000 | 1,600,000 | 300,000 | | | | |
| Mass of smolts (kg) | 46,000 | 17,800 | 9,600 | 6,000 | | | | |

Notes: a. Data provided by Mr. Glen Rasmussen, manager, Robertson Creek hatchery, August, 1997. Data covers the 1996 calendar year. The data presented only represents inputs to chinook and coho smolt production. Steelhead smolt production inputs are not included.

b. All data, with the exception of feed use data, provided by Mr. David Celli, manager, Tenderfoot Creek hatchery, July, 1997. Data presented is the average of the 1995-96 and 1996-97 fiscal years. Feed use data for the Tenderfoot Creek hatchery provided by Ms. Diane Plotnikoff, SEP feed purchasing agent, October, 1997. Feed data is the average of 1995-96 and 1996-97 fiscal years.

c. "Dry" feed is assumed to contain approximately 8% moisture. This feed is equivalent to the feed being used by the private commercial hatcheries providing smolts to the salmon farming industry.

d. Semi-moist feed typically contains 20% moisture.

e. CMP denotes Canadian Moist Pellet while OMP denotes Oregon Moist Pellet. These are both standard moist pellet feeds that typically contain 30% moisture.

f. One kWh of electricity equals 3.6MJ.

g. The energy content of gasoline is 32.25 MJ/l. Derived from Rose and Cooper (1977, p. 281).

h. The energy content of furnace oil is 38.76 MJ/l. Derived from Rose and Cooper (1977, p. 281).

i. The energy content of liquid propane is 25.26 MJ/l. Derived from Friedrich and Hayden (1974, p. 48).

A variety of feed types, reflecting a range of moisture contents, are currently being used to rear chinook and coho smolts in SEP facilities (Table K-1)[256]. In order to simplify the analysis, it was necessary to convert the three forms of feed being used into a single type. As my analysis of the inputs to salmon farming included a detailed analysis of the material, labour and energy inputs associated with producing contemporary "dry" salmon feed, I opted to convert the moist and semi-moist feeds into their "dry" feed equivalents based on their dry matter content. As a result, I estimate that chinook smolt production requires the equivalent of 3,843 kg of dry feed per million smolts released or 690 kg of dry feed per tonne of smolts released. Similarly, I estimate that coho smolt production requires the equivalent of 19,422 kg of dry feed per one million smolts released or 971kg of dry feed equivalent per tonne of smolts released.

[256] The "dry" feeds being used are essentially the same feeds that contemporary private hatcheries that supply the salmon farming industry are using. They have a moisture content of about 8%. The semi-moist feeds that are used have a moisture content of about 20% whle the moist feeds have a moisture content of about 30%.

# *Appendix L: Releases and Final Distribution of SEP Origin Chinook and Coho Salmon, 1985 to 1994*

Table L-1 presents the total number of juvenile chinook and coho salmon that were released from SEP facilities annually over the decade from 1985 to 1994 along with the average releases for the period.

*Table L-1. Juvenile Chinook and Coho Releases from all SEP Facilities, 1985 to 1994*

| Brood Year | Total Chinook Releases | Total Coho Releases |
|---|---|---|
| 1985 | 42,761,623 | 19,126,042 |
| 1986 | 53,840,001 | 22,594,254 |
| 1987 | 63,693,726 | 17,814,064 |
| 1988 | 64,528,141 | 22,020,733 |
| 1989 | 63,636,836 | 23,186,351 |
| 1990 | 66,220,850 | 22,429,564 |
| 1991 | 59,139,749 | 22,127,770 |
| 1992 | 57,518,170 | 18,707,124 |
| 1993 | 50,709,598 | 19,140,481 |
| 1994 | 54,867,222 | 21,927,933 |
| Averages: | 57,691,592 | 20,907,432 |

Source: Extracted from a data file of total SEP releases from 1977 to 1995 provided to me by Mr. Greg Steer, SEP Evaluation Coordinator, April, 1996.

For SEP origin coho and chinook salmon respectively, Tables L-2 and L-3 present estimates of:

- the number of returning adult fish that end up being caught by the British Columbia commercial, aboriginal and recreational fisheries along with the number taken in various American based fisheries and the number of fish that escape to spawn,
- the proportion of total returning SEP origin fish that are harvested by the British Columbia commercial fishery, and
- the proportion of the total British Columbia commercial catch that is of SEP origin for each year from 1985 to 1994.

*Table L-2. Fate of SEP Origin Adult Coho Returns, 1985-1994*

| Catch Year | British Columbia Based Catch of SEP Origin Fish Comm. | Sport | Indian | Total US Catch of SEP Fish | Escapement of SEP Fish | Total SEP Returns | BC Comm. Harvest of SEP Fish as a % of Total Returns | | Total BC Comm. Catch | SEP Origin Fish as a % of Total Comm. Catch |
|---|---|---|---|---|---|---|---|---|---|---|
| 1985 | 277,213 | 239,456 | 13,943 | 36,573 | 221,834 | 789,019 | 35.1% | | 2,950,000 | 9.4% |
| 1986 | 388,827 | 206,865 | 6,604 | 57,881 | 273,086 | 933,263 | 41.7% | | 4,904,000 | 7.9% |
| 1987 | 379,199 | 309,779 | 14,586 | 49,791 | 328,376 | 1,081,731 | 35.1% | | 3,359,000 | 11.3% |
| 1988 | 312,649 | 408,592 | 15,884 | 36,117 | 295,984 | 1,069,226 | 29.2% | | 2,745,000 | 11.4% |
| 1989 | 352,702 | 215,343 | 13,704 | 60,418 | 293,071 | 935,238 | 37.7% | | 3,434,000 | 10.3% |
| 1990 | 334,706 | 213,773 | 7,464 | 46,652 | 247,213 | 849,808 | 39.4% | | 3,872,000 | 8.6% |
| 1991 | 398,226 | 59,264 | | 80,860 | 294,876 | 833,226 | 47.8% | | 3,509,000 | 11.3% |
| 1992 | 369,934 | 218,572 | | 44,173 | 285,385 | 918,064 | 40.3% | | 2,962,000 | 12.5% |
| 1993 | 230,989 | 267,334 | | 34,625 | 248,986 | 781,934 | 29.5% | | 1,895,000 | 12.2% |
| 1994 | 287,588 | 100,145 | | 27,851 | 38,909 | 454,493 | 63.3% | | 2,559,771 | 11.2% |
| | | | | | | Average: | 39.9% | | Average: | 10.6% |

Note: All catch and escapement values are pieces of fish not tonnes.

*Table L-3. Fate of SEP Origin Adult Chinook Returns, 1985-1994*

| Catch Year | British Columbia Based Catch of SEP Origin Fish Comm. | Sport | Indian | Total US Catch of SEP Fish | Escapement of SEP Fish | Total SEP Returns | BC Comm. Harvest of SEP Fish as a % of Total Returns | | Total BC Comm. Catch | SEP Origin Fish as a % of Total Comm. Catch |
|---|---|---|---|---|---|---|---|---|---|---|
| 1985 | 61,536 | 42,484 | 0 | 34,489 | 55,809 | 194,318 | 31.7% | | 870,000 | 7.1% |
| 1986 | 64,714 | 46,869 | 0 | 26,265 | 57,182 | 195,030 | 33.2% | | 813,000 | 8.0% |
| 1987 | 47,145 | 42,125 | 0 | 29,839 | 88,038 | 207,147 | 22.8% | | 768,000 | 6.1% |
| 1988 | 57,531 | 46,881 | 0 | 41,096 | 130,450 | 275,958 | 20.8% | | 725,000 | 7.9% |
| 1989 | 101,727 | 82,656 | 0 | 64,176 | 156,045 | 404,604 | 25.1% | | 650,000 | 15.7% |
| 1990 | 139,448 | 68,054 | 0 | 104,054 | 223,940 | 535,496 | 26.0% | | 668,000 | 20.9% |
| 1991 | 175,094 | 96,238 | | 120,373 | 224,915 | 616,620 | 28.4% | | 640,000 | 27.4% |
| 1992 | 196,181 | 86,362 | | 111,128 | 262,743 | 656,414 | 29.9% | | 682,000 | 28.8% |
| 1993 | 169,836 | 108,978 | | 87,099 | 245,309 | 611,222 | 27.8% | | 622,000 | 27.3% |
| 1994 | 53,829 | 46,687 | | 43,197 | 57,105 | 200,818 | 26.8% | | 431,390 | 12.5% |
| | | | | | | Average: | 27.3% | | Average: | 16.2% |

Note: All catch and escapement values are in pieces of fish not tonnes.

Over the decade from 1985 to 1994, approximately 40% of the returning adult coho that started life in SEP facilities are captured in the British Columbia based commercial fishery (Table L-2). However, these SEP origin fish only account for an average of approximately 10.6% of the total annual commercial catch of coho (Table L-2). The remaining almost 90% of the commercially caught coho were either spawned in the wild or originate from an enhancement facility in another jurisdiction.

Similarly, Over the period from 1985 to 1994, only about 27% of the returning adult chinook that originated in SEP facilities end up being captured by the British Columbia based commercial fishery (Table L-3). These SEP origin fish, however, only make up a little over 16%, on average, of the total annual commercial chinook catch (Table L-3). The remaining approximately 84% of commercially caught chinook in British Columbia were either of wild origin or were the product of enhancement activities in other jurisdictions.

## *Appendix M: British Columbia Commercial Salmon Catch by Species and Gear Type, 1985 to 1994*

Table M-1 presents the landings, in round weight tonnes, of chinook and coho salmon by commercial gillnetters, purse seiners and trollers in British Columbia from 1985 to 1994. Table M-2 presents similar data sets for commercially caught sockeye and pink salmon while Table M-3 presents landing data for commercially caught chum salmon and for all five species of salmon combined.

*Table M-1. British Columbia Commercial Catch of Chinook and Coho Salmon, 1985 to 1994*

| | Chinook salmon harvest in tonnes and % of total by: | | | | | | | | Coho salmon harvest in tonnes and % of total by: | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gillnet | | Seine | | Troll | | Total | | Gillnet | | Seine | | Troll | | Total |
| Year | tonnes | % | tonnes | % | tonnes | % | tonnes | | tonnes | % | tonnes | % | tonnes | % | tonnes |
| 1985 | 525 | 9.6 | 733 | 13.4 | 4,211 | 77.0 | 5,469 | | 857 | 9.5 | 1,410 | 15.7 | 6,710 | 74.7 | 8,977 |
| 1986 | 516 | 10.3 | 580 | 11.6 | 3,911 | 78.1 | 5,007 | | 981 | 7.4 | 1,776 | 13.4 | 10,481 | 79.2 | 13,238 |
| 1987 | 270 | 5.1 | 355 | 6.8 | 4,623 | 88.1 | 5,248 | | 380 | 4.5 | 985 | 11.7 | 7,050 | 83.8 | 8,415 |
| 1988 | 485 | 8.2 | 298 | 5.0 | 5,138 | 86.8 | 5,921 | | 417 | 5.9 | 620 | 8.8 | 6,040 | 85.3 | 7,077 |
| 1989 | 789 | 15.1 | 557 | 10.6 | 3,889 | 74.3 | 5,235 | | 687 | 7.8 | 1,194 | 13.6 | 6,871 | 78.5 | 8,752 |
| 1990 | 631 | 12.1 | 402 | 7.7 | 4,195 | 80.2 | 5,228 | | 675 | 6.4 | 1,055 | 10.0 | 8,839 | 83.6 | 10,569 |
| 1991 | 890 | 17.6 | 408 | 8.1 | 3,760 | 74.3 | 5,058 | | 614 | 6.1 | 790 | 7.9 | 8,649 | 86.0 | 10,053 |
| 1992 | 460 | 8.6 | 296 | 5.5 | 4,580 | 85.8 | 5,336 | | 479 | 6.5 | 574 | 7.8 | 6,275 | 85.6 | 7,328 |
| 1993 | 625 | 13.0 | 267 | 5.5 | 3,924 | 81.5 | 4,816 | | 383 | 8.9 | 326 | 7.6 | 3,607 | 83.6 | 4,316 |
| 1994 | 395 | 11.1 | 192 | 5.4 | 2,990 | 83.6 | 3,576 | | 791 | 10.3 | 677 | 8.8 | 6,248 | 81.0 | 7,716 |
| Mean '85-'94 | 559 | 11.1 | 409 | 8.0 | 4,122 | 81.0 | 5,089 | | 626 | 7.3 | 941 | 10.5 | 7,077 | 82.1 | 8,644 |
| Mean '85, '88 '91 & '94 | 574 | 11.6 | 408 | 8.0 | 4,025 | 80.4 | 5,006 | | 670 | 7.9 | 874 | 10.3 | 6,912 | 81.8 | 8,456 |

*Table M-2. British Columbia Commercial Catch of Sockeye and Pink Salmon, 1985 to 1994*

| | Sockeye salmon harvest in tonnes and % of total by: | | | | | | | | Pink salmon harvest in tonnes and % of total by: | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gillnet | | Seine | | Troll | | Total | | Gillnet | | Seine | | Troll | | Total |
| Year | tonnes | % | tonnes | % | tonnes | % | tonnes | | tonnes | % | tonnes | % | tonnes | % | tonnes |
| 1985 | 13,461 | 42.6 | 14,735 | 46.7 | 3,373 | 10.7 | 31,569 | | 4,012 | 10.6 | 25,996 | 69.0 | 7,692 | 20.4 | 37,700 |
| 1986 | 11,073 | 35.9 | 12,944 | 42.0 | 6,816 | 22.1 | 30,833 | | 4,217 | 14.3 | 23,679 | 80.3 | 1,609 | 5.5 | 29,505 |
| 1987 | 6,619 | 44.0 | 6,283 | 41.8 | 2,133 | 14.2 | 15,035 | | 4,464 | 16.6 | 15,415 | 57.3 | 7,042 | 26.2 | 26,921 |
| 1988 | 7,591 | 63.6 | 3,693 | 30.9 | 659 | 5.5 | 11,943 | | 1,745 | 5.4 | 25,559 | 79.3 | 4,913 | 15.2 | 32,217 |
| 1989 | 12,475 | 36.3 | 17,266 | 50.2 | 4,642 | 13.5 | 34,383 | | 2,687 | 8.7 | 19,068 | 61.5 | 9,250 | 29.8 | 31,005 |
| 1990 | 13,022 | 35.1 | 15,770 | 42.5 | 8,341 | 22.5 | 37,133 | | 2,839 | 10.8 | 19,307 | 73.6 | 4,094 | 15.6 | 26,240 |
| 1991 | 10,407 | 41.3 | 10,312 | 40.9 | 4,492 | 17.8 | 25,211 | | 2,937 | 8.4 | 25,828 | 73.6 | 6,331 | 18.0 | 35,096 |
| 1992 | 12,912 | 61.9 | 6,956 | 33.4 | 988 | 4.7 | 20,856 | | 2,528 | 17.0 | 10,093 | 67.7 | 2,292 | 15.4 | 14,913 |
| 1993 | 18,536 | 43.6 | 19,281 | 45.3 | 4,712 | 11.1 | 42,529 | | 1,846 | 11.5 | 9,491 | 59.1 | 4,709 | 29.3 | 16,046 |
| 1994 | 10,326 | 33.5 | 13,613 | 44.2 | 6,889 | 22.3 | 30,828 | | 714 | 21.1 | 1,972 | 58.3 | 697 | 20.6 | 3,383 |
| Mean '85-'94 | 11,642 | 43.8 | 12,085 | 41.8 | 4,305 | 14.4 | 28,032 | | 2,799 | 12.4 | 17,641 | 68.0 | 4,863 | 19.6 | 25,303 |
| Mean '85, '88 '91 & '94 | 10,446 | 45.2 | 10,588 | 40.7 | 3,853 | 14.1 | 24,888 | | 2,352 | 11.4 | 19,839 | 70.0 | 4,908 | 18.6 | 27,099 |

*Table M-3. British Columbia Commercial Catch of Chum Salmon and All Species Combined, 1985 to 1994*

| | Chum salmon harvest in tonnes and % of total by: | | | | | | | | Harvest of all salmon in tonnes and % of total by: | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gillnet | | Seine | | Troll | | Total | | Gillnet | | Seine | | Troll | | Total |
| Year | tonnes | % | tonnes | % | tonnes | % | tonnes | | tonnes | % | tonnes | % | tonnes | % | tonnes |
| 1985 | 6,211 | 26.3 | 15,769 | 66.7 | 1,666 | 7.0 | 23,646 | | 25,219 | 23.4 | 58,676 | 54.5 | 23,669 | 22.0 | 107,564 |
| 1986 | 9,216 | 36.6 | 14,152 | 56.2 | 1,828 | 7.3 | 25,196 | | 26,130 | 25.1 | 53,156 | 51.1 | 24,652 | 23.7 | 103,938 |
| 1987 | 4,236 | 38.5 | 6,413 | 58.3 | 352 | 3.2 | 11,001 | | 16,026 | 24.0 | 29,465 | 44.2 | 21,203 | 31.8 | 66,694 |
| 1988 | 8,966 | 29.6 | 20,218 | 66.7 | 1,113 | 3.7 | 30,297 | | 19,281 | 22.0 | 50,401 | 57.6 | 17,866 | 20.4 | 87,548 |
| 1989 | 3,955 | 42.4 | 4,846 | 52.0 | 521 | 5.6 | 9,322 | | 20,616 | 23.2 | 42,936 | 48.4 | 25,174 | 28.4 | 88,726 |
| 1990 | 6,049 | 35.2 | 10,800 | 62.9 | 331 | 1.9 | 17,180 | | 23,257 | 24.1 | 47,338 | 49.1 | 25,801 | 26.8 | 96,396 |
| 1991 | 4,541 | 44.4 | 5,202 | 50.8 | 493 | 4.8 | 10,236 | | 19,410 | 22.7 | 42,543 | 49.7 | 23,725 | 27.7 | 85,678 |
| 1992 | 6,722 | 37.4 | 10,715 | 59.6 | 527 | 2.9 | 17,964 | | 23,183 | 34.9 | 28,641 | 43.1 | 14,674 | 22.1 | 66,498 |
| 1993 | 7,153 | 41.4 | 9,199 | 53.3 | 921 | 5.3 | 17,273 | | 28,549 | 33.6 | 38,566 | 45.4 | 17,874 | 21.0 | 84,989 |
| 1994 | 8,951 | 44.1 | 10,972 | 54.0 | 397 | 2.0 | 20,320 | | 21,178 | 32.2 | 27,426 | 41.7 | 17,220 | 26.2 | 65,824 |
| Mean '85-'94 | 6,600 | 37.6 | 10,829 | 58.0 | 815 | 4.4 | 18,244 | | 22,285 | 26.5 | 41,915 | 48.5 | 21,186 | 25.0 | 85,385 |
| Mean '85, '88 | | | | | | | | | | | | | | | |
| '91 & '94 | 7,167 | 36.1 | 13,040 | 59.6 | 917 | 4.4 | 21,125 | | 21,272 | 25.1 | 44,761 | 50.9 | 20,620 | 24.1 | 86,653 |

# Appendix N: Industrial Product Price Index for Miscellaneous Manufactured Chemical Products for Sporting, Fishing and Hunting Equipment

Table N-1 provides the Canadian industrial product price index for miscellaneous manufactured chemical products used for sporting, fishing and hunting purposes (CANSIM data series #P3647). I believe that this price index is the most appropriate available for converting expenditures made on commercial salmon fishing gear.

*Table N-1. Canadian Industrial Product Price Index for Miscellaneous Manufactured Chemical Products Used for Sporting, Fishing and Hunting Purposes (CANSIM data series #P3647) (1992=100)*

| Year | |
|---|---|
| 1985 | 73.4 |
| 1986 | 81.4 |
| 1987 | 85.5 |
| 1988 | 90.4 |
| 1989 | 92.9 |
| 1990 | 94.4 |
| 1991 | 100.1 |
| 1992 | 100.0 |
| 1993 | 101.4 |
| 1994 | 104.4 |
| 1995 | 107.5 |
| 1996 | 112.1 |
| 1997 | 114.1 |
| 1998 | 112.4 |

Source: Retrieved over the internet from the CANSIM database through the Computing in the Humanities and Social Sciences (CHASS) data center at the University of Toronto on December 28, 1998. Web site address: http://datacenter.chass.utoronto.ca.5680/cgi-bin/cansim/

## *Appendix O: Material, Labour and Energy Inputs to Build and Maintain Salmon Fishing Vessels*

Tables O-1, O-2, and O-3 respectively present the major material, labour and energy inputs required to build and maintain:

- an aluminium-hulled purse seiner that is 18 m long, with a beam width of 6 m and a depth (excluding the keel) of 2.8 m,
- a fibreglass-hulled gillnetter that is 10 metres long, and
- an aluminium-hulled gillnetter that is 10 metres long.

*Table O-1. Estimates of the Major Material, Labour and Energy Inputs to Build and Maintain a Typical Aluminium Hulled Purse Seiner per Tonne of Salmon Landed*

| Inputs | Initial Input Quantity | Expected Working Life (years)[a] | Repair & Maintenance Factor[b] | Total Input per year[c] | Input to Salmon Fishing per year[d] | Input per Tonne of Salmon Landed[e] |
|---|---|---|---|---|---|---|
| Aluminum | | | | | | |
| - for the bare vessel[f] (kg) | 18,000 | 30 | 25% | 750 | | |
| - for all other equipment[g] (kg) | 6,500 | 10 | 50% | 975 | | |
| | | | Total Aluminum: | **1,725** | **1,139** | **14.3** |
| All steel and iron components[g] (kg) | 9,200 | 10 | 50% | **1,380** | **911** | **11.4** |
| All other components[g] (kg) | 1,200 | 10 | 50% | **180** | **119** | **1.49** |
| Electricity to weld the bare boat[f] (MJ) | 1,296,000 | 30 | 25% | **54,000** | **35,640** | **447** |
| Labour to fabricate the complete vessel[f] (pers-days) | 1,250 | 30 | 25% | **52** | **34** | **0.43** |

Notes: a. Values in this column indicate the assumed functional working life of various vessel components. Based on the average age of the seine vessels as of 1998 (calculated from data provided by Mr. Brian Moore, Fisheries and Oceans Canada), I have assumed that the bare vessel itself will have a functional working life of 30 years. For all other inputs, including all mechanical systems, fishing equipment, etc., I have assumed that they will need to be replaced after 10 years following the results of Rochereau (1976) analysis of the functional life of trawl vessel components.

b. Values indicate the additional proportion of the various inputs that have to be included to accommodate routine repair and maintenance. For all inputs to all passive vessel components, I have assumed a 25% repair and maintenance factor while all inputs to "active" components were assigned a 50% repair and maintenance factor.

c. Calculated by first dividing the initial input quantity by the functional working live of a given component and then multiplying by the appropriate repair and maintenance factor.

d. The proportion of the inputs attributable to salmon fishing specifically were calculated by multiplying values in column 5 by 66%, the average salmon fishing income to total income ratio for purse seiners for the years 1985, '88, '91 and '94 from Gislason (1997).

e. Average inputs per tonne of salmon landed were calculated by dividing values in column 6 by 79.8 tonnes, the average landings of salmon by all licensed purse seiners over the period from 1985 to 1994 (from Department of Fisheries and Oceans' Summary of B.C. commercial catch statisitics and Gislason 1997, Exhibit A-1)

f. Initial input quantities from Mr. Jim Walker, ex-manager of Shore Boats Ltd. pers. comm. 1998.

g. Initial input quantities from Mr. Chris Cue, Seine operations manager, Canadian Fishing Company Ltd. pers. comm. 1998.

*Table O-2. Estimates of the Major Material, Labour and Energy Inputs to Build and Maintain a Typical Fibreglass Gillnetter per Tonne of Salmon Landed*

| Inputs | Initial Input Quantity[a] | Expected Working Life (years)[b] | Repair & Maintenance Factor[c] | Total Input per year[d] | Input to Salmon Fishing per year[e] | Input per Tonne of Salmon Landed[f] |
|---|---|---|---|---|---|---|
| Aluminum | | | | | | |
| - Fuel & water tanks (kg) | 540 | 30 | 50% | 27 | | |
| - Fishing equipment (kg) | 330 | 10 | 50% | 50 | | |
| | | Total Aluminum (kg): | | **77** | **70** | **6.7** |
| Steel | | | | | | |
| - Main Engine (kg) | 890 | 10 | 50% | 134 | | |
| - Transmission & propeller (kg) | 220 | 10 | 50% | 33 | | |
| - Fishing equipment (kg) | 390 | 10 | 50% | 59 | | |
| - Anchor, anchor winch & chain (kg) | 210 | 10 | 50% | 32 | | |
| - Stove (kg) | 50 | 10 | 50% | 8 | | |
| - Hardware & other steel inputs (kg) | 1,000 | 30 | 25% | 42 | | |
| | | Total Steel (kg): | | **306** | **281** | **26.8** |
| Lead in batteries (kg) | 100 | 10 | 0% | **10** | **9** | **0.88** |
| Mixed metals (controls, steering) (kg) | 390 | 10 | 50% | **59** | **54** | **5.1** |
| Fibreglass resin (kg) | 1,210 | 30 | 25% | **50** | **46** | **4.4** |
| Glass | | | | | | |
| - Fibreglass matting, etc. (kg) | 1,540 | 30 | 25% | 64 | | |
| - Windows (kg) | 100 | 30 | 25% | 4 | | |
| | | Total Glass (kg): | | **68** | **63** | **6.0** |
| Wood | | | | | | |
| - 60 sheets of 1/2" plywood ($m^3$) | 2.27 | 30 | 25% | 0.09 | | |
| - 530 linear metres of 2x4 lumber ($m^3$) | 2.78 | 30 | 25% | 0.12 | | |
| | | Total Wood ($m^3$): | | **0.21** | **0.19** | **0.018** |
| Labour (person-days) | 375 | 30 | 25% | **16** | **14** | **1.4** |

Notes: a. All initial input quantities from Mr. Bob Pearson, Pearson Marine and Industrial Ltd., pers. comm. 1998

b. Values in this column indicate the assumed functional working life of various vessel components. Based on the average age of the gillnet vessels as of 1998 (calculated from data provided by Mr. Brian Moore, Fisheries and Oceans Canada), I have assumed that the bare vessel itself will have a functional working life of 30 years. For all other inputs, including all mechanical systems, fishing equipment, etc., I have assumed that they will need to be replaced after 10 years following the results of Rochereau (1976) analysis of the functional life of trawl vessel components.

c. Values indicate the additional proportion of the various inputs that have to be included to accommodate routine repair and maintenance. For all inputs to all passive or non-moving vessel components, I have assumed a 25% repair and maintenance factor while all inputs to "active" components were assigned a 50% repair and maintenance factor.

d. Calculated by first dividing the initial input quantity by the functional working live of a given component and then multiplying by the appropriate repair and maintenance factor.

e. The proportion of the inputs attributable to salmon fishing specifically were calculated by multiplying values in column 5 by 92%, the average salmon fishing income to total income ratio for gillnetters for the years 1985, '88, '91 and '94 (from Gislason 1997).

f. Average inputs per tonne of salmon landed were calculated by dividing values in column 6 by 10.54 tonnes, the average landings of salmon by all licensed gillnetters over the period from 1985 to 1994 (from Department of Fisheries and Oceans' Summary of B.C. commercial catch statisitics and Gislason 1997, Exhibit A-1)

*Table O-3. Estimates of the Major Material, Labour and Energy Inputs to Build and Maintain a Typical Aluminium Hulled Gillnetter per Tonne of Salmon Landed*

| Inputs | Initial Input Quantity | Expected Working Life (years)[a] | Repair & Maintenance Factor[b] | Total Input per year[c] | Input to Salmon Fishing per year[d] | Input per Tonne of Salmon Landed[e] |
|---|---|---|---|---|---|---|
| Aluminum | | | | | | |
| - Hull, decks, holds & cabin (kg)[f] | 2,250 | 30 | 25% | 94 | | |
| - Fuel & water tanks (kg)[g] | 540 | 30 | 25% | 23 | | |
| - Fishing equipment (kg)[g] | 330 | 10 | 50% | 50 | | |
| | | Total Aluminum (kg): | | **166** | **152** | **14.5** |
| Steel | | | | | | |
| - Main Engine (kg)[g] | 890 | 10 | 50% | 134 | | |
| - Transmission & propeller (kg)[g] | 220 | 10 | 50% | 33 | | |
| - Fishing equipment (kg)[g] | 390 | 10 | 50% | 59 | | |
| - Anchor, anchor winch & chain (kg)[g] | 210 | 10 | 50% | 32 | | |
| - Stove (kg)[g] | 50 | 10 | 50% | 8 | | |
| - Hardware & other steel inputs (kg)[g] | 500 | 30 | 25% | 21 | | |
| | | Total Steel (kg): | | **285** | **262** | **25.0** |
| Lead in batteries (kg)[g] | 100 | 10 | 0% | **10** | **9** | **0.88** |
| Mixed metals (controls, steering) (kg)[g] | 390 | 10 | 50% | **59** | **54** | **5.1** |
| Glass windows (kg)[g] | 100 | 30 | 25% | **4** | **4** | **0.37** |
| Electricity to weld the hull, etc. (MJ)[f] | 324,000 | 30 | 25% | **13,500** | **12,420** | **1,183** |
| Labour (person-days)[f] | 375 | 30 | 25% | **16** | **14** | **1.4** |

Notes: a. Values in this column indicate the assumed functional working life of various vessel components. Based on the average age of the gillnet vessels as of 1998 (calculated from data provided by Mr. Brian Moore, Fisheries and Oceans Canada), I have assumed that the bare vessel itself will have a functional working life of 30 years. For all other inputs, including all mechanical systems, fishing equipment, etc., I have assumed that they will need to be replaced after 10 years following the results of Rochereau (1976) analysis of the functional life of trawl vessel components.

b. Values indicate the additional proportion of the various inputs that have to be included to accommodate routine repair and maintenance. For all inputs to all passive or non-moving vessel components, I have assumed a 25% repair and maintenance factor while all inputs to "active" components were assigned a 50% repair and maintenance factor.

c. Calculated by first dividing the initial input quantity by the functional working live of a given component and then multiplying by the appropriate repair and maintenance factor.
d. The proportion of the inputs attributable to salmon fishing specifically were calculated by multiplying values in column 5 by 92%, the average salmon fishing income to total income ratio for gillnetters for the years 1985, '88, '91 and '94 (from Gislason 1997).
e. Average inputs per tonne of salmon landed were calculated by dividing values in column 6 by 10.54 tonnes, the average landings of salmon by all licensed gillnetters over the period from 1985 to 1994 (from Department of Fisheries and Oceans' Summary of B.C. commercial catch statisitics and Gislason 1997, Exhibit A-1)
f. Initial input quantities from Mr. Jim Walker, ex-manager of Shore Boats Ltd. pers. comm. 1998.
g. Initial input quantities from Mr. Bob Pearson, Pearson Marine and Industrial Ltd., pers. comm. 1998.