THE ENVIRONMENTAL IMPACTS OF AQUACULTURE: A LIFE CYCLE ASSESSMENT COMPARISON OF COMMON AQUACULTURE SYSTEMS TO BEEF, PORK, AND CHICKEN PRODUCTION

By

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To my bride, Valerie

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THE WATER FOOTPRINT OF AQUACULTURE:
A LIFE CYCLE ASSESSMENT COMPARISON OF COMMON AQUACULTURE SYSTEMS TO BEEF, PORK, AND CHICKEN PRODUCTION

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Worldwide aquaculture production nearly equals wild-caught fisheries production, animal agriculture generally uses many more resources for production than do cropping systems, and the demand for animal protein continues to rise as household economies continue to grow. It is important that animal production systems as a whole, and emerging aquaculture systems in particular, seek ecologically sustainable and efficient means of production. Of the resources needed for food production, water is in many cases the scarcest. Agriculture consumes 70% of the world's freshwater on an annual basis, and there is little information available to growers, governments, or consumers on the real water content of human diets.

The objectives of this study were to determine the total consumptive water use, or virtual water, the eutrophication impact potential, and the global warming potential associated with four common systems of aquaculture production [cage-culture of Atlantic Salmon (*Salmo salar*), flow-through culture of Rainbow Trout (*Oncorhynchus mykiss*), pond culture of Channel Catfish (*Ictalurus punctatus*), and recirculating culture of tilapia (*Oreochromis spp.*)] compared with three common systems of terrestrial

animal production (beef, pork, and broiler chickens). To accomplish these objectives, a life cycle assessment (LCA) was conducted for each system using SimaPro 7.1.

The results of the life cycle assessment show that of all the systems analyzed, flow-through production of rainbow trout had the lowest water footprint (570 liters/kg of finished product) compared to cage culture of salmon (700 liters/kg), recirculating culture of tilapia (2950 liters/kg), pond culture of channel catfish (9610 liters/kg), and beef (19,500 liters/kg), pork (10,310 liters/kg), and chicken production (7240 liters/kg). The eutrophication impact potential of trout production was lowest, and was 39.0 mg-equivalents of PO_4^{3-}/kg of production, followed by catfish, chicken, tilapia, pork, salmon, and beef, which each produced 41.0, 46.0, 49.0, 71.0, 87.0, and 244.0 mg-equivalents of PO_4^{3-}/kg, respectively. The global warming potential was lowest for trout production, which is responsible for 2.5 kg-equivalents of CO_2/kg, followed by tilapia, catfish, salmon, pork, chicken, and beef, which produced 3.82, 3.83, 4.2, 5.78, 6.12, and 28.4 kg-equivalents of CO_2/kg, respectively. Sensitivity analyses were performed to test the importance and interaction of different model parameters and in almost every case, the agricultural production of animal feed accounted for the large majority of the environmental impact in these systems. These results also indicate that as the aquaculture industry moves more toward agronomic feed inputs, especially soy, and away from fisheries products its overall environmental impact will increase. This study shows the need for further research into alternative feed ingredients for both fish and terrestrial animals, and should be used to help inform producers, consumers, scientists, and policy makers on the environmental impacts of animal farming systems.

CHAPTER 1
INTRODUCTION

1.1 Food Production and the Environment

World agricultural production can be broken into two major categories; crops, which include cereals, roots and tubers, sugars, pulses, and vegetable oils; and livestock, which includes meat, milk, and other dairy products. In 2006, world agricultural crop production totaled over 3.3 billion tons and occupied over 1.1 billion hectares of land area. In addition to crops, livestock production totaled 0.93 billion tons of meat, milk, and dairy (FAO, 2006a). Major direct and indirect inputs from human and natural systems to the production, processing, and transportation of food include solar energy, land, water, animal feed, fertilizers, pesticides, fossil fuel energy, and labor.

There is no general consensus as to whether world agriculture has reached its carrying capacity for growth (Goodland, 1997). However, it has been suggested (Brown, 1995, 1996; Harris and Kennedy, 1999) that agricultural yield growth is logistical, rather than exponential, because the ecological limits on which it depends are also logistical (soil fertility, nutrient uptake, water availability, etc.), and that human demand has already reached some of these ecological limits (Brown, 1995).

1.1.1 Resource Use in Agriculture

It is estimated that at the end of the 20th century, 1.5 billion hectares of land (11% of the earth's surface) were being used for food production, and that there is potential to develop an additional 1.3 billion hectares for agricultural purposes (Figure 1-1). However, much of this is currently forested (45%), locked up in protected areas (12%), taken up by human settlements (3%), or has characteristics that make it unsuitable for agriculture, such as low soil fertility, soil toxicity, or difficult terrain. (FAO, 2002).

Worldwide, agriculture is responsible for 70% of all fresh water withdrawals. A conservative 2,800 kilocalorie daily diet requires at least 1,000 liters of water for its production on-farm (UNESCO, 2003). However, this number is quite variable depending on the composition of a person's diet (UNESCO, 2003), and it has been estimated that diets in the United States require over 1400 m^3 of water per person per year, or nearly 4000 liters per day. This is 136% higher than the world average (Hoekstra and Chapagain, 2007). When all levels of production, such as processing and transportation, are taken into consideration, food production is responsible for 86% of our global annual water use (Hoekstra and Chapagain, 2007).

Currently, about 38% of the world's grain is used as livestock feed (Brown, 1995). Although livestock watering directly consumes a small percentage of the world's water, livestock consume varying amounts of feed per kilogram of meat produced and therefore indirectly consume large amounts of water (Table 1-1).

Commercial energy use (mainly fossil fuel and wood fuel) in agriculture varies widely throughout the globe. Agriculture in developed and developing countries consumes 13.1 Gigajoules and 4.0 Gigajoules of commercial energy, respectively. It is estimated that the energy used for the processing and transportation of agricultural goods is as much as double the direct energy inputs (FAO, 2000).

In subsistence societies today, about 4 Calories of energy are spent to produce each Calorie of food; this negative yield ratio is possible because of abundant solar energy. Today in the United States, 10 Calories of energy are required to produce each Calorie of food. This extremely negative yield ratio is possible because of a heavy reliance on fossil fuel energy (Giampietro and Pimentel, 1993).

1.1.2 Global Food Security

While the total sum of world food production is important, we can learn much more from knowing how this food is partitioned throughout the globe through production and trade. We can get an even better idea of food partitioning throughout the globe by looking at human diets. The composition of human diets can be broken into seven categories: cereals, roots and tubers, sugar, pulses, vegetable oils, meat, and milk and dairy products. Per capita food consumption varies widely between developed and developing countries. In general, the diets of food insecure populations are imbalanced and consist mainly of roots, tubers, cereals, and some pulses, causing a deficiency in proteins, amino acids, and essential vitamins and minerals. In contrast, diets in developed nations are generally much more balanced, and have high ratios of dietary protein to energy (FAO, 1991). On average, people in industrialized countries consume 15-20% more kilocalories per day than people in developing nations (FAO, 2002) and large populations of people in developing nations are at risk of protein deficiency (Millward and Jackson, 2003).

In the developing world, an estimated 2.5 billion people directly depend on agriculture for their livelihoods, and over the last twenty years, these countries have gone from being net exporters of agricultural goods to being net importers. The importation of cereal grains and livestock to developing countries is expected to continue, and the trade deficit is expected to worsen over the next thirty years (FAO, 2002). Although worldwide production of agriculture will be able to keep up with a growth in demand for at least the short term, there are hundreds of millions of people in poor rural areas who will not be able to meet their protein and energy requirements because of poor farming conditions, lack of resources, or lack of technical innovation (FAO, 2002).

Although many rural poor areas in the developing world face slow to no growth in food security, the rest of the world is seeing brisk economic growth. The most immediate result of this, on a per capita basis, is the increased consumption of protein. It has been projected that over the next twenty to twenty-five years, worldwide demand for meat will increase dramatically because a large portion of the population in developing countries has just entered or is on the verge of entering the income bracket where a large portion of income growth is spent on meat (Keyzer *et al.,* 2005).

While an increase in the availability of protein is a positive thing in the developing world, the increase in cereal feed demand for animal production could put more pressure on populations that are already food insecure (Brown, 1995). There exists a need, therefore, for technical assistance to those populations that are most food insecure in order to develop more robust, balanced farming systems.

1.1.3 Farming Systems and the Environment

A farming system, as any ecosystem, can best be described by how space, matter, diversity, energy, and time are managed, exploited, and distributed for the production of food for human consumption. As stated by Loomis (1976), farming systems will tend to maximize efficiency in the use of their most limiting factors of production. For example, if a farm is most limited by land availability, producers will tend to maximize their use of space, or if by the length of the growing season, farmers will choose crops that maximize the use of short periods of time. While ecological constraints determine which types of cropping systems are feasible on a farm or in a region, actual cropping system dominance has historically been quite dependent on the economic and cultural environment of the society doing the farming (Loomis, 1976). Farming systems throughout history have been made up of very diverse cropping systems. Because these systems mimic natural ecosystems, they optimize nutrient cycles and the accumulation of soil organic matter, create closed loop energy cycles, conserve resources, exhibit resilience to pests, and their levels of productivity can be sustained over time (Altieri, 2001). However, with increased globalization over the last 30 years, and incentives of international capital investment, developing nations have given concessions to multinational corporations. These concessions have primarily been the restructuring of national labor and agriculture along the lines of multinational aims (Watts, 1994). That is to say, multinational corporations themselves are indirectly influencing the activities farmers choose to undertake (Harvey, 1991). Thus, there is an increased rural dependence on cash from the global market while ecological and cultural needs take a back seat to national economic aims. Therefore, the intensity of resource use for farming is not determined by ecological limits, local cultural values, or even local economies, but by external demand for farm produce. The most tangible result of this is a disappearing diversity in farming systems, and thus, a weakened ability to deal with risk (Francis *et al.,* 2006). Farmlands and their adjacent ecosystems become less resilient as farming systems become less diverse. The results are not only an increased vulnerability to financial risk and/or food insecurity, but also a dependence on that same external economy for farming inputs, a decrease in animal and social welfare, the diminishing strength of rural communities, and vulnerability of farmlands and farming lifestyles (Butler and Flora, 2006).

1.1.4 Animal Protein Production

The pragmatic approach to decreasing undernourishment throughout the world has been, for many years, the improved production efficiency of cereal grains. This was well accomplished in certain parts of the world through the Green Revolution. However, there still exists today an epidemic of malnutrition, that is, an inadequacy of certain dietary nutrients. In many cases, this is caused by a lack of digestible protein (Pallett and Ghosh, 1997).

As previously mentioned, large portions of undernourished households worldwide live in rural areas and are heavily dependent on agriculture for their food security. Protein intake in these regions is often very low and is mostly of vegetable origin and is thus less digestible. The scarcity of animal protein in these diets is not by choice, but rather, because animal protein sources are less available, more difficult to produce, difficult to store, and more expensive than vegetable sources. Diets that are low in fish, meat, and dairy products are very common in countries where poverty persists (FAO, 1997). To compound the problem of an already insufficient protein intake, children in the developing world often suffer from chronic infections, which makes their protein need even greater than children in developed countries (FAO, 1997).

Animal foods contain high-quality protein, essential amino acids, and important micronutrients in highly bio-available forms. It has been shown that the inclusion of animal protein even in very small quantities dramatically improves the overall health of undernourished people (Pallett and Ghosh, 1997).

It has also been shown that as income increases in developing countries, the most immediate change in households is the increased consumption of meat products (Schroeder, 1996). Because many developing countries are experiencing continued per capita income and population growth, world livestock demand is expected to increase dramatically in the near future. By 2025, livestock is expected to produce about 30% of the value of global agricultural production and use, directly or indirectly, over 80% of the world's agricultural lands (Haan *et al.,* 2001). With the expected rapid increase in global livestock development, there is a danger that the poorest households worldwide will suffer more greatly than present, the environment might be even further compromised, and global food security may face major challenges (Hann *et al.,* 2001).

Because livestock animals are heterotrophs, they generally require more inputs for their production than grains, pulses, and tubers. Major direct and indirect inputs to livestock production include pastureland, grain, water, fuel for transportation and processing, farm and transportation machinery, and fertilizers and pesticides for feed production. Table 1-1 lists major inputs for major production systems of livestock.

In addition to resource use for livestock production, air, water, and soil are also impacted from pollutants emitted from livestock operations. The burning of fossil fuels, fertilization of feed crops, and the concentration of animal wastes produce compounds that increase global climate change, the potential for acid rain, and eutrophication of natural waters. Common pollutants coming from livestock production are listed in Table 1-2.

1.1.5 Fisheries

The capture of marine fishes and invertebrates is the most diverse of all the food producing sectors. For centuries it was believed that the supply of the oceans was limitless and that human populations would never be able to exhaust this supply. With the advent of the coal-fired steam trawler in the late 1800s, however, fishermen were able to capture fish with a rapidly increasing efficiency of effort and throughout the 20th century fisheries resources began to decline. As catch per unit effort declined, fishing fleets were forced to go further and further offshore and fish for species at lower and lower trophic levels to make fishing economically feasible, and in turn they became even more dependent on large volumes of fossil fuel. In 2000, global fisheries used 620 liters of fuel and emitted over 1.6 tons of CO_2 for every ton of fish that was captured. From an energy efficiency perspective, fisheries consumed 12.5 times the energy than their catch provided (Tyedmers, 2004).

Because of the incredible fishing effort over the last century, nearly all of the world's fisheries have reached a peak harvest and most nations cannot supply the quantity of fish that is demanded, and are even experiencing increases in demand with increasing population and per capita income (U.S. Commission on Ocean Policy, 2004). Global fisheries production reached a peak in the late 1980s at just below 80 million tons and has since experienced a plateau. The world supply of fish in 2005, however, was the highest it had ever been, at 141.6 million tons produced, or 16.6 kilograms per person worldwide (SOFIA, 2006). The growth in production can be attributed to very rapid expansion of the aquaculture industry worldwide, which provided 43% of the world's seafood in 2005 (SOFIA, 2006).

1.2 Aquaculture

Aquaculture has been defined as:

"The farming of aquatic organisms in inland and coastal areas, involving intervention in the rearing process to enhance production and the individual or corporate ownership of the stock being cultivated (FAO, 2008)."

1.2.1 Aquaculture, Past and Present

The practice has been part of household economies for at least 4000 years (Rabanal, 1988), and although historically it has provided a very small percentage of the world's production of seafood, as of 2005 the industry was producing nearly 48 million tons of seafood, it is expected to eventually eclipse commercial fisheries production (SOFIA, 2006). While fisheries production since 1970 has grown at a rate of 1.2%, and the production of terrestrial based meat has grown at a rate of 2.8%, aquaculture worldwide has grown at a rate of 8.8%. Aquaculture has also outpaced the population growth rate. From 1970 until 2004, per capita consumption of aquaculture products grew from 0.7 kilograms per year to 7.1 kilograms per year, and now provides over 5% of the world's animal protein (SOFIA, 2006). It is important to note that China has dominated aquaculture production since its beginnings and today accounts for nearly 70% of world production (SOFIA, 2006).

The world's top producing aquaculture species are listed in Table 1-3. Carps, mostly produced in Asia, comprise the largest group of aquaculture species, and most of their production takes place in Asia. The diversity of organisms produced in aquaculture, however, is staggering compared with the bulk production of terrestrial farming systems. Worldwide, over 240 species of plants and animals were reported in aquaculture production in 2004. In 2002, 91.4% of world aquaculture production took place in the developing world, and the majority of this production was in extensive farming systems with relatively low value species. In 2004, China produced nearly 70% of the world's aquacultured goods. This production accounted for only 51% of the total value for aquacultured species, however. Western Europe, Latin America and the

Caribbean, and North America, however, only accounted for about 7% of world production by volume, but captured over 17% of the global value (SOFIA, 2006).

The dominance of a particular type of aquaculture in a certain area, however, is largely based on the resources available to farmers and the intensity of farming systems. In the developing world, most farming systems are extensive; requiring lower amounts of inputs per kilogram produced, and produce lower value species. In the developed world, however, most aquaculture production takes place in more intensive systems and produce higher value species.

1.2.2 Biology and Physiology of Fish

To understand why and how aquaculture of a particular species develops, it is important to understand the biology and physiology of species produced, and how they fit into particular farming systems. To begin with, fish are ectotherms, that is, their body temperature is regulated by the external environment rather than through their own metabolism or behavior. One of the benefits for ectothermic animals is a low energy requirement for growth and reproduction compared to endotherms, which regulate their body temperature through metabolism of food. Fish and aquatic plants also require less energy for structural support and, when applicable, locomotion, because they are partially supported through the buoyancy of their body in water.

Another difference between fish and terrestrial vertebrates is the manner and forms in which they produce waste. For fish, the major products of metabolism are water, carbon dioxide, and ammonia, with small amounts of other compounds, such as urea, creatine, creatinine, and uric acid. The important point here, though, is that ammonia is the major nitrogenous waste product in fish. Ammonia is a much more bioenergetically efficient waste product because the potential energy left in ammonia in much lower than in uric acid, the main nitrogenous waste product produced by terrestrial vertebrates. Although ammonia is very toxic compared to the uric acid produced by terrestrial vertebrates, there are typically large quantities of water available to dilute it in aquatic ecosystems. Thus, while terrestrial vertebrates assimilate less energy from protein because they have to manufacture a less toxic waste product, fish are able to maximize their use of energy available in food because of the aquatic environment in which they live (Adams and Breck, 1990).

Because of their lower energy requirement for physiological maintenance, fish are able to use a large portion of their dietary energy and protein for growth and reproduction. In addition to this, because fish are produced in three-dimensional volumes of water rather than just two-dimensional areas of land, as in other agricultural systems, they can be produced at much higher densities than other agricultural animals. Also, because of the diversity of aquatic organisms, many aquaculture systems provide agroecological niches for other types of food production. The result of this can be higher food productivity and less vulnerability to risk.

1.2.3 Systems of Production

Throughout the world there is a great diversity of aquaculture production, ranging from very extensive to very intensive systems producing any number of species within the same agricultural area. As previously stated, in the developing world, where inputs for agriculture are more difficult for farmers to acquire, extensive systems of fish production dominate. These systems very often rely on natural ecosystems for some or most of the growth and reproduction of organisms. Where agricultural inputs are more available, such as fossil fuel energy, financial capital, raw material, newer technology, etc., more intensive systems of production are common. In the most intense systems of aquaculture production, every stage in the life cycle of an organism is controlled. Aquaculture can be practiced in open water, raceways, tanks, and cages. The following are examples of each of these commonly found in Western Europe and the Americas.

1.2.3.1 Cage aquaculture

In cage culture, fish are housed in cages or net-pens that are placed in existing bodies of water. Cage culture relies on natural water flow through cages for the provision of quality water and dilution of waste. Major inputs to cage culture are nutritionally complete feeds, juvenile organisms, energy for transportation to and from production facilities, and the raw material for cage production. A typical species produced in cage culture worldwide is the production of Atlantic salmon (*Salmo salar*) in net-pens suspended in bays, fjords, and the open ocean.

1.2.3.2 Pond aquaculture

Pond culture is the production of fish, plants, or invertebrates in natural or manmade open water ponds. Typical inputs into these systems include water, (either from precipitation, other surface water bodies, or groundwater); energy for aeration, harvesting, and feeding; formulated feeds; and labor, among other things. The best example of pond aquaculture in the United States can be seen in the production of channel catfish (*Ictalurus punctatus*). Total U.S. catfish production in 2007 was 412.2 million pounds, live weight (NASS, 2008).

1.2.3.4 Flow-through aquaculture

Flow through aquaculture is the production of aquatic organisms using water that only passes through the production system for a single use. Typically water in these systems is diverted from a clean source of surface water, such as a river, is allowed to run through the production system (typically concrete raceways), and is then returned downstream to the original source, often after receiving some form of primary waste treatment. This system of production is very common in Idaho and North Carolina for the production of rainbow trout (*Oncorhynchus mykiss*). Major inputs to this farming system include feed, fingerlings, infrastructure, and energy for pumping water.

1.2.3.5 Recirculating aquaculture

Recirculating culture is the most intensive of all aquaculture systems, as it requires the management of all aspects of production, especially waste treatment. In these systems, water is pumped from the production environment and treated through mechanical and biological filters to remove waste nutrients. After treatment water is returned to the production environment. Recirculating systems typically recycle 80-95% of their water daily. Typical recirculating systems found in the United States are used to produce high value species such as hybrid striped bass, sturgeon, and tilapia for fresh or even live markets.

1.2.4 Environmental Impacts of Aquaculture Systems

While aquaculture systems range from very extensive to very intensive production, they also vary in the intensity and type of their environmental impact. Recently there has been much discussion on the environmental impacts of aquaculture systems, especially regarding the use of wild-caught fishmeal, antibiotics, and fear of genetic pollution of wild stocks of fish. While these may raise concerns for environmentalists, a careful analysis of each is presented below. The subject of the present study, however, is an analysis of more pertinent potential ecological impacts of aquaculture. These include consumptive water use, fossil fuel energy use, eutrophication potential, acid rain potential, and global warming potential of aquaculture systems.

The term fishmeal generally refers to a nutrient rich meal rendered from wild caught marine fisheries. Fishmeal is most often used as a feed ingredient for domestic animals, including cattle, poultry, swine, and fish. While a portion of the world's fishmeal comes from trimmings of food fish processing, the large majority comes from reduction fisheries, which capture small fish deemed unsuitable for human consumption due to their large portion of bones and oil. World production of fishmeal from the oceans remains somewhat steady at around 6-7 million tons per year. Of this, 46% was used for aquaculture production in 2002. By 2010 this figure is expected to increase to 50% (IFFO, 2006). The remaining portion of fishmeal is used mainly for the production of pigs and poultry (IFFO, 2006).

While agriculture currently uses a sustainable volume of fishmeal, the demand is expected to rise beyond a sustainable catch as the demand for aquaculture products increases. Because fishmeal is high in digestible protein and dietary energy and closely resembles the profile of essential amino acids and fatty acids in wild fish diets, it is very valuable as an ingredient in fish feeds. While the issue of fishmeal as an ingredient in fish feeds is an important one, the present study does not address the issue as a major environmental impact because its solution is quickly being sought through improvements in aquaculture nutrition through the use of alternative feedstuffs.

There has also been recent discussion on the environmental impact of antibiotic use in aquaculture. Widespread use of antibiotics in any setting can cause problems of viral resistance and human health and ecological health problems. The use of prophylactics such as quinolones, which are highly effective antibiotics for human infections, can induce resistance to infection, and remain in sediments for prolonged periods of time, have been banned from use in aquaculture in industrialized countries (Cabello, 2006). Similar policy and legislation should be adopted in the developing world, especially in Chile and China, where such prophylactics are more heavily relied upon for fish production (Cabello, 2006).

While there has been significant discussion and research (Hedrick, 2001; Muir and Howard, 2001, 2002; Wittmann, 1991; Bruggemann, 1993) on the ecological and environmental impacts of transgenic organisms in aquaculture to natural populations of fish, there has been little evidence of ecological impact resulting from domestication through non-transgenic breeding programs (Cognetti *et al.,* 2006). Although little evidence exists to actual genetic pollution to wild stocks, it would be wise for the aquaculture industry and policy makers alike to be precautionary in this area. A good example of due precaution is the legislation derived from the Oslo Agreement, established by the North Atlantic Salmon Conservation Association, which effectively minimizes genetic interaction of domesticated fish with wild stocks (Cognetti *et al.,* 2006). Similar control should be sought for all aquaculture operations that highly alter the genetic variation of animals being produced and are also adjacent to wild populations of the same species.

While the previous impacts have been discussed elsewhere, there is little quantified information available on the resource use and impacts of aquaculture systems to adjacent ecosystems and global climate. This, therefore, is the subject of the present study.

1.3 The Present Study

It was previously stated that farming systems tend to maximize efficiency of the use of their most limiting resource. While this may be true at a farm or regional level, it is often over simplified on a national basis, especially with resources that are not considered an economic good, such as water or topsoil (Hoekstra and Hung, 2005). Although it has been suggested herein that there are major risks in subjecting a nation's agriculture to global demand, it is the concession of this paper that this is somewhat inevitable in today's global economy, and pragmatic solutions must be promoted. In addition, it has been suggested that farming system efficiency can often play a larger role in limiting environmental impact than can the improved efficiency of international transportation of food (Schlich, 2005). It is extremely important, therefore, for nations to understand the total resources used and environmental impacts produced through the production of an agricultural good. A system of accounting for "non-economic" resources such as water, topsoil, or ecological resilience could help shape national agriculture and trade policy in such a way that might provide greater income and food security as well as agro-ecological resilience for a nation's farming systems and rural households.

The present study proposes to quantify the virtual water use, global warming potential, and eutrophication impact potential of aquaculture production compared to common systems of terrestrial animal protein production, namely, those for beef, swine, and poultry. A general description of each system and their type of water use and water treatment are presented in Table 1-4.

Because fish, being aquatic poikilotherms, are more efficient converters of energy and food into body tissue, it is predicted that systems of aquaculture production have less environmental impact in general and less consumptive water use, global warming potential, and eutrophication impact potential, in particular, than other systems of animal protein production. To test this, a Life Cycle Assessment (LCA) of four widely used aquaculture systems was performed.

Table 1-1. Selected inputs required for terrestrial animal production.

Animal	Feed (kg/kg)[1]	Water (m^3/kg)[2]	Energy (MJ/kg)	Land (m^2/kg/year)
Cattle	8	43,000	169.00[3]	20.9[6]
Swine	3	6,000	18.67[4]	8.9[6]
Poultry	2	3,500	39.00[5]	7.3[6]

1. Moffitt, C.M., 2004.
2. Pimentel, *et al.,* 2004.
3. Ogino, *et al.,* 2007.
4. Basset-Mens and van der Werf, 2004.
5. Ellingsen and Aanondsen, 2006.
6. Gerbens-Leenes and Nonhebel, 2002.

Table 1-2. Environmental impact equivalents emitted per kg of livestock production reported in literature.

Animal	Climate Change (kg of CO2 equivalents)	Acidification (g of SO_2 equivalents)	Eutrophication (g of PO_4 equivalents)
Cattle	36.4	340	59.2
Swine	3.24	34.43	19.67
Poultry	2.1[3]	173.0[4]	49.0[4]

1. Ogino *et al.,* 2007.
2. Basset-Mens and van der Werf, 2004.
3. Bennett *et al.,* 2006.
4. Williams *et al.,* 2006.

Table 1-3. Top ten aquaculture species worldwide by volume and growth (SOFIA, 2006).

Species	Volume (million tons)	Species	Ave. Annual Growth Rate (2002-04)
Carps	18.3	Sea urchins	4833.6
Oysters	4.6	Abalones, winlkes, conchs	884.3
Clams	4.1	Frogs and other amphs.	400.1
Misc. freshwater fishes	3.7	Freshwater mollusks	225.8
Shrimps, prawns	2.5	Sturgeons, paddlefish	101.9
Salmonids	2.0	Misc. aquatic inverts.	83.0
Mussels	1.9	Flatfishes	75.5
Tilapias	1.8	Misc. coastal fishes	50.8
Scallops	1.2	Misc. dimersal fishes	37.7
Other marine molluscs	1.1	Shrimps, prawns	28.7

Table 1-4. Four systems of aquaculture production and their type of water use and wastewater treatment.

System Type	Water Use Type	Wastewater Treatment	Energy Consumption
Recirculating[1]	Very Low; Water used to makeup for evaporative and seepage losses and filter back-flushing.	Almost complete; treatment usually consists of mechanical and biological filtration. Requires aeration.	High; Generally require the movement of large quantities of water through filtration media; require aeration.
Pond[2]	Moderate; System usually has large evaporative and seepage losses, made up for by precipitation and/or ground and surface water.	Moderate; Dependent on pond ecosystem for nutrient conversion through production cycle. Usually requires aeration.	Moderately low; Typically require aeration during portions of the production cycle.
Flow-through[3]	Low; While large volumes of water pass through these systems, most is returned to the natural system from which it originated. Losses due to evaporation or seepage in settling ponds.	Moderately Low; Usually includes settling ponds/tanks for removal of solids. Produces some eutrophication potential for natural systems.	Moderately low; Some systems use artificial aeration but are generally dependent on natural water flow for movement and aeration of water.
Cage[4]	Very Low; Cages are set in natural systems and production is dependent on water from these systems. Largest water use comes from harvest of fish biomass.	Low; Usually non-existent; depends on natural system for removal of nutrients by dilution through water movement. In some cases measures are taken toward more intense nutrient management.	Moderately Low/Low; Some systems require transportation to and from by boat but generally do not use artificial aeration. They are also dependent on natural movement of water.

1. Timmons and Losordo, 1994.
2. Tucker and Hargreaves, 2004.
3. Midlen and Redding, 1998., Tucker and Hargreaves, 2004.
4. Beveridge, Malcolm C.M., 1987.

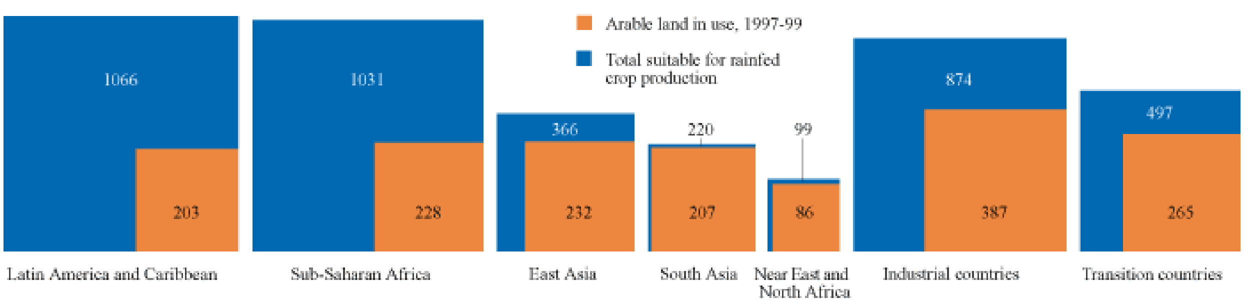


Figure 1-1. Total world arable land use in millions of hectares, (1997-1999) and potential agricultural expansion (FAO, 2002).

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction to Life Cycle Assessments

Life Cycle assessment (LCA) is a tool used for quantifying ecological impacts of a product or a process from its beginning to its end, or from “cradle to grave”. LCA studies can analyze processes from the earliest stages of a production process (i.e. raw materials extraction) to the final stages, (i.e. product and waste disposal). LCA can be used as a decision making tool between one product or process and another, to identify stages or inputs in production that have the greatest environmental impacts, can help guide industry in the development of new products, and can be used to verify an industry or a products environmental claims (Baumann and Tillman, 2004). Guidelines and examples for life cycle assessment have been established in the International Organization for Standardization (ISO) 14040 family of standards.

Life cycle assessment consists of three stages, inventory analysis, impact assessment, and improvement analysis. In the inventory analysis stage, the system being studied is first scoped and then data is collected. The scoping process identifies the reason for the study, the boundaries that will define what will be included in the study, and a list of all assumptions being made. Including certain processes more directly related to a products production and excluding other processes may streamline the scoping process.

Included in the scoping process is the decision on a functional unit (FU) of analysis. This is the amount of a material, product, or service to which the LCA will be applied. For example, if an LCA is being conducted to compare the impacts of cypress mulch versus pine bark, the functional unit chosen may be whatever volume is required for one square meter of coverage. Once the functional unit and scope and boundaries are identified, associated environmental impacts and their stressors are identified (global warming and CO2, fossil-fuel energy use and liters of gasoline, etc.) Once the impacts to be studied are identified, and inventory of these stressors is taken from every stage of the products life cycle that falls within the boundary of the LCA.

Following the inventory analysis, an impact assessment is done in which data from the inventory analysis is used to produce a systematically quantifiable environmental impact. From this impact analysis, one system or process can be compared quantifiably to another system or process to determine relative environmental harm.

After environmental impacts for a product or process are determined, an improvement analysis can be conducted in order to identify those steps in a production process that are responsible for the most environmental impact. Improvement analysis can help guide further product and process development through identifying those input factors that should be focused on when trying to improve environmental impact.

2.2 Environmental Impacts of Aquaculture Production

While consumers are becoming more and more aware of the need to make environmentally conscious decisions at the grocery store, there are very limited ways in which a product may be trusted as more or less environmentally harmful than another. Life cycle assessment of food production is a powerful tool to inform consumers on how environmentally harmful or benign a food product may be. While several life cycle assessments have been conducted to quantify environmental impacts of agriculture, such as global warming potential and air and water toxicity, consumptive water use is very seldom studied even though agricultural practices account for the majority of fresh water use globally (Foster *et al.,* 2006). It has also been proposed that a framework be established for LCA that includes impact categories for abiotic resource depletion, such as consumptive freshwater use (Jolliet *et al.,* 2006).

Because there is widespread anecdotal evidence of environmental impacts from aquaculture operations, it is appropriate to examine the scientific literature that may or may not corroborate claims made in the general media.

2.2.1 Environmental Impact of Aquaculture Feeds

The greatest inputs to fish farming operations are generally formulated feed, developed to maximize growth of fish. Because fish naturally have diets very high in protein, they must also have a high protein diet when raised in an aquaculture setting. Much of the demand for high quality protein for fish feeds has traditionally been met by the world's fishmeal fishery. With the increased growth of aquaculture over the last two decades, however, the entire demand for protein cannot be met by the world's fishmeal supply (Dong *et al.,* 1993) and it has become a major research priority to find high quality, economically feasible replacements for fishmeal in aquaculture diets (Hardy and Kissil, 1997). Much of this demand for sources of protein and fatty acids for aquaculture diets has been met by some conventional oilseed meals, such as soybean, cottonseed, peanut, and canola (rapeseed) (Jauncey and Ross, 1982, Webster *et al.,* 1999, Carter and Hauler, 2000). Proteinacious ingredients of animal origin have also been used to meet demand in fish feeds, and sources include insect larvae, earthworms, bloodmeal, feathermeal, meat meal, and zooplankton (Webster *et al.,* 1999, 2000). It has been shown that the use of conventionally grown oilseed meals in fish feeds, especially soy, has much less environmental impact than the use of fishmeal or fishery/poultry bi-products, when considering the carbon footprint and energy use of agriculture operations versus fisheries and feedstuff reduction operations (Pelletier and Tyedmers, 2007).

2.2.2 Environmental Impacts of Net-Pen Salmon Aquaculture

The majority of environmental impact of salmon farming comes from the production process of feed ingredients, which mostly include rendered fishmeal, grains and animal bi-products (Pelletier and Tyedmers, 2007). In an LCA study (Ellingsen and Aanondsen, 2006) on Norwegian salmon farming, cod fishing, and chicken farming, the feed production stages represented the most environmental impact in the farming operations and the fishing stage represented the largest impact in cod production. Of the three systems, chicken production was the most energy efficient, while salmon farming and cod fishing consumed similar amounts of energy.

Pelletier and Tyedmers (2007) showed that, Atlantic Salmon farming yielded 8-18% of the industrial energy invested as an edible energy output, which is similar to the same data for global fisheries and poultry production, worse than conventional crop production, but better than other animal production. It has been shown that replacement of fishmeal with soybeans in salmon diets will yield 30% of the impacts of Peruvian fishmeal and 44% of the impacts of US menhaden fishmeal (Pelletier and Tyedmers, 2007). Previous research has shown that soy protein contains less digestible energy for salmon than does fishmeal (Storebakken *et al.,* 1998, Carter and Hauler, 2000, Refstie *et al.,* 2001, Opstvedt *et al.,* 2003), but soybean meal and fishmeal have shown similar results in growth performance in several studies where salmon diets contained 20-33% soybean meal (Olli *et al.,* 1995; Carter and Hauler, 2000). Similar to the Pelletier and Tyedmers study, Ellingsen and Aanondsen (2006) showed that conventional salmon farming with fishmeal-based feeds had a higher global warming potential, acidification potential, and toxicity related impacts than conventional chicken production. Salmon fed diets containing no fishmeal or fish oil, but rather plant based protein meals and oils had lower impacts in the same categories because of higher energy use and emissions in fisheries compared to crop production. Attempts to offset environmental impacts of fishmeal by using fisheries and poultry bi-products actually consumes more energy and has higher climate change and acidification potential because of the lower yield of usable product from bi-product inputs (Pelletier and Tyedmers, 2007). It has also been shown that salmon produced with fishmeal and fish oil based diets require more energy inputs and have higher climate change and acidification potentials than conventional pork and poultry production, but that salmon grown on plant based diets required lower energy inputs and had lower climate change and acidification potentials than pork and poultry production (Carlsson-Kanyama, 1998; Spies *et al.,* 2002). It has also been shown (Easton *et al.,* 2002) that farmed salmon being fed commercial diets have higher levels of environmental contaminants (PCBs, PBDEs, PAHs, and Organic Pesticides), than wild salmon. This study, however, did not remark on the origins of contaminates, whether they be from agriculturally produced ingredients or from wild fishmeal sources.

A common concern with salmon farming operations is the escape of salmon from farms into wild salmon populations (Hansen *et al.,* 1991, Hindar *et al.,* 1991, Hutchinson, 1997, Naylor *et al.,* 1998). Fleming *et al.* (2000) showed that the survival of escaped farmed salmon was 16% of that of the native salmon. But while the reproductive success of farmed salmon was diminished compared to the native fish (33%), there was diet overlap between the two groups, which may represent increased resource depletion by the farm origin fish. Although the survival of these fish was quite diminished compared to the wild fish, the genetic invasion of farm-type genotypes is said to pose a significant risk on the genetic variation of the wild population, and this has been corroborated in several studies (Crozier, 2008; Fleming et al, 2000; McGinnity *et al.,* 2003).

Another increasing concern with Salmon production is the concentration of nutrients and particulate matter associated with salmon farming in the areas around net-pens and cages. Because salmon have high protein diets, there is a notable environmental load associated with salmon farming, specifically nutrient loads of nitrogen and ortho-phosphates, both of which can lead to nuisance phytoplankton blooms. In some cases, this nutrient load can be offset through integrated aquaculture techniques, where economically viable seaweeds and algae can be grown within the effluent stream of salmon cages (Troell *et al.,* 1997), and it is widely accepted that at least 80% of effluent nutrients from cage-culture fish farming operations are bio-available for plant or algal growth (Hakansson *et al.,* 1988; Persson, 1988, 1991). However, most cage-based aquaculture today is not integrated with other endeavors, and only about 30% of the nutrients inputted to such systems is harvested as fish biomass (Gowen *et al.,* 1991; Holby and Hall, 1991; Hall *et al.,* 1992). The remainder is released to the surrounding environment as metabolic waste products and uneaten feed. This number, however, is very dependent on feed quality (i.e. digestibility) and farm management strategies (Troell, 1997). It has also been shown in several cases, however, that although an ecosystem may have a higher exposure to eutrophication inducing nutrients, loads from these operations have not been high enough to have a significant or noticeable effect on the natural system (Sowles and Churchill, 2004). It is important to note, however, that the nutrient and particulate matter load and bioavailability and dispersion thereof from cage culture settings are very dependent on site-specific details. Data was collected from 168 different Salmon production sites in Norway and analyzed to determine the relationships between environmental variables, environmental impacts, and management practices at the farm site. Results showed that total organic carbon (TOC) levels in sediments were significantly higher in areas directly adjacent to cages, and 32% of the samples showed significant degradation. These data also showed that no significant effects of the farming operations could be detected on TOC 50-100 meters from the sites. The results of this study showed that periodic abandonment, or fallowing, of sites is one of the best farm management practices for sustainable salmon production (Carroll *et al.,* 2003). Direct energy requirements for net-pen Salmon aquaculture are very low, and are mostly limited to fuel required to operate facilities, and transportation to and from cages. It is estimated that 75% of the total energy required for Salmon production comes from the procuring and growing of feed ingredients (Folke, 1988; Troell et al, 2004; Tyedmers, 2004; Ellingsen and Aanondsen, 2006).

2.2.3 Environmental Impacts of Flow-Through Trout Aquaculture Culture

Similar to Salmon cage-culture, flow-through Rainbow Trout aquaculture has been scrutinized for potential environmental impacts from associated nutrients and organic carbon leaving operations for adjacent natural waters (Dumas *et al.,* 1997; Camargo, 1992; Black, 2001). Camargo (1992) showed that at stations .01, .15., and 1 km downstream from trout farming operations there were potamological effects seen in the macrobenthic community of the river, and that the intensity of these effects diminished from station to station. These changes were a depressed population of “shredders and scrapers" but an increased population of filter feeders, scavengers, and predators. These results show that at a 1 km distance from the trout farm there is a negligible effect of the macrobenthic ecology. A similar study, conducted at Rainbow Trout farms in North Carolina, measured a decreased richness in macrobenthic taxa directly downstream from fish farms, with an increased richness at 1.5 km downstream. However, at 1.5 km downstream there was still a significant depression in taxa richness compared to locations upstream from fish farms, suggesting a diminished water quality from these trout farming operations (Loch *et al.,* 1996). It has also been shown, however, that where regulations are put in place to limit effluent loads from trout operations, farms are able to profitable reduce loads of Nitrogen, Phosphorus and biological oxygen demand by up to 40%, through the use of biological and mechanical filtration, settling ponds, better feeding strategies, and through using feeds lower in phosphorus (MacMillan, 2003). A study of the chemical and microbiological effects of trout farm effluent in Spain, however, showed measurable contamination of chemicals and microbiota as far downstream as 12 km. It is important to note, however, that this study only analyzed the presence of excess chemicals and microbiota downstream and not the extent of any ecological effects from these contaminants (Boaventura *et al.,* 1997).

While flow-through trout aquaculture diverts large amounts of water from natural sources (16,000-120,000 liters/kg produced), this is not considered a consumptive water use because the water is returned to its original source (Boyd *et al.,* 2007). It is important to recognize, in cases such as this and net-pen culture, the distinction between consumptive water use and water quality degradation (Owens, 2008).

The majority of direct energy requirements for flow-through trout production are from mechanical aeration and other facility electricity use. The majority (52%) of the total energy required for trout production comes from the procurement and production of feed ingredients (Papatryphon *et al.,* 2003).

2.2.4 Environmental Impacts of Channel Catfish Pond Aquaculture

Unlike net-pen and flow-through aquaculture, pond aquaculture such as that used for producing channel catfish in the Southeast has limited loss of nutrients and organic matter to natural bodies of water. This is primarily because biological oxygen demand and high levels of nutrients in pond water must be managed in order to ensure fish health and profitability. This is typically done through chemical, physical, and biological processes naturally occurring in production ponds, lessening the amount of feed and fish wastes released to natural waters (Boyd *et al.,* 2007).

The majority of consumptive water use in pond aquaculture is due to evaporation and drainage of pond water, with some loss at the end of a growing period depending on whether or not ponds are drained for harvesting (Boyd *et al.,* 2007). It has been estimated that the direct on-farm water use required for typical catfish production in the Southeast is 1,200- 5,000 liters per kilogram of production (Boyd *et al.,* 2007), but that in arid climates it may be as much as 50% more (Boyd, 2005).

Energy is used in pond aquaculture primarily for pumping water and for mechanical aeration. Typically water is only pumped to make up for that which is lost to evaporation and drainage, and for filling ponds after they have been drained (Boyd, 2007). It has also been reported (Boyd *et al.,* 2007) that pumping water for catfish production requires 296 kilowatt-hours per ton of product. Ponds are typically aerated between May and September for 10 hours per night in the Southeast. Mechanical aeration in catfish farming consumes 950 kilowatt-hours of energy per ton of product (Boyd *et al.,* 2007). It has been shown that the total energy required for pond-grown catfish and tilapia are similar to that used for the production of other common animal-agricultural products, such as eggs, broiler chickens, and pork (Troell *et al.,* 2004; Tyedmers, 2004).

2.2.5 Environmental Impacts of Recirculating Aquaculture Production of Tilapia

Recirculating, tank-based aquaculture has many benefits as a production system, including increased environmental control by the manager, diminished land and water requirements, and manager control of system effluent. It has been estimated that recirculating aquaculture systems use less than 10% of the direct water required by other aquaculture systems and an even smaller percentage of the land required, and that water reuse systems reduce effluent waste by a factor of 500-1000 (Timmons *et al.,* 2001). Tank-based aquaculture, however, relies on larger amounts of input energy to pump water through mechanical and biological filtration and to provide oxygen to fish. It has been estimated that recirculating aquaculture production uses 4-6.5 times the non-renewable energy use of flow-through trout production systems (Aubin *et al.,* 2006), although it is important to point out that this study included energy used cool water to 17°C and maintain the system at this temperature. Further research into the energy requirements for recirculating aquaculture production should be done. And because non-renewable energy use and its related impacts (global warming potential, acidification potential, etc.) are the only major impacts from these systems, with future research into sustainable sources of energy, they represent a great opportunity towards a more environmentally sustainable source of animal protein (Serfling, 2000). It is the opinion of this author that there is a lack of scientific literature on the environmental impacts of recirculating aquaculture systems because they do not fall under the scrutiny of the public eye, as do the other aquaculture production systems.

2.3 Environmental Impacts of Grain and Meat Production

Several researchers (Andersson *et al.,* 1994; Holderbeke *et al.,* 2003; Braschkat *et al.,* 2003; and Rosing and Nielsen, 2003; Hospido *et al.,* 2005) have shown that the largest portion of environmental impact for industrial, processed food production (bread, beer, etc.) comes from the primary grain production on-farm. In addition, it has been shown that on-farm processes account for the majority of the environmental impact associated with milk production, namely, high water and energy consumption and high run-off of nutrients (Hospido *et al.,* 2003; Berlin, 2002; Berlin *et al.,* 2007). Few LCA studies on meat production have extended beyond the agricultural stage, but those studies that have included a broader scope have shown that feed production is the main source of environmental impact in the life cycle of meat products (Foster *et al.,* 2006; Roy *et al.,* 2008a; Roy *et al.,* 2008b). Of the life cycle assessments conducted that compare different types of meat, chicken production is found to have the least environmental impact, followed by pork, and with beef being the least environmentally efficient (Roy *et al.,* 2008a; Roy *et al.,* 2008b). These two studies also showed that the major environmental stressors in beef production were N_2O emission from feed production and methane produced enterically in the guts of cattle, both leading to a high global warming potential for beef. It has been shone that in broiler chicken production, the majority of the environmental impact comes from the agricultural production of feeds and from nutrient run-off and leaching from ammonia evaporation from manure (Katajajuuri, 2007). Several studies have shown that the majority of the environmental impacts of pig production come from the agricultural production of feed ingredients

(Carlsson-Kanyama, 1998; Blonk *et al.,* 1997; van der Werf, *et al.* 2005). These studies have shown that 65-70% of the total energy required, 50% of the global warming potential, and 57% of the eutrophication potential of pig production came from swine feed production. It is important to note, however, that these studies only included beef, pork, and chicken production, and cannot account for other agricultural animals. Because animals generally have a feed conversion ratio greater than 1:1, and because diets of more affluent people contain more meat (Schroeder, 1996), it has been suggested that the diets of more affluent people have a higher environmental impact. It has also been estimated (Gerbens-Leenes and Nonhebel, 2004; Pimentel and Pimentel, 2003) that these diets based on meat have an environmental impact that is 6 times greater than diets based on grains. A list of feed conversion ratios for common agricultural animals is presented in Table 2-1. To illustrate the difference in meat consumption between affluent and poorer nations, Figure 2-1 depicts the growth of and difference between world and U.S. meat consumption over the last 50 years. Figure 2-2 depicts present world and U.S. meat consumption by type, and Figure 2-3 depicts trends in world meat consumption by type. Because animals typically require more than 1 kilogram of feed to provide 1 kilogram of meat, land requirements for meat production are higher for animal production than for grain production. Table 2-2 provides land use requirements for different animal production operations.

It has been estimated that the production of 1 kilogram of beef requires between 12,000 (Chapagain and Hoekstra, 2003) and 100,000 (Pimentel and Houser, 1997) liters of water. The same authors have suggested that the production of pork, chicken, and soybeans, require 2200-6000 liters, 2500-2500 liters, and 1800-2000 liters of water, respectively. A list of consumptive water use for common agricultural products is found in Table 2-3. Because crop agriculture over the last 60 years has become so energy intense, and because animal production in the U.S. has become more and more reliant on concentrated feeds that come from this crop production, the energy intensity of animal agriculture compared to the amount of protein it yields is enormous. Table 2-4 lists typical animals produced for human consumption in the United States, the volume of their current production, and the ratio of input energy to protein yield.

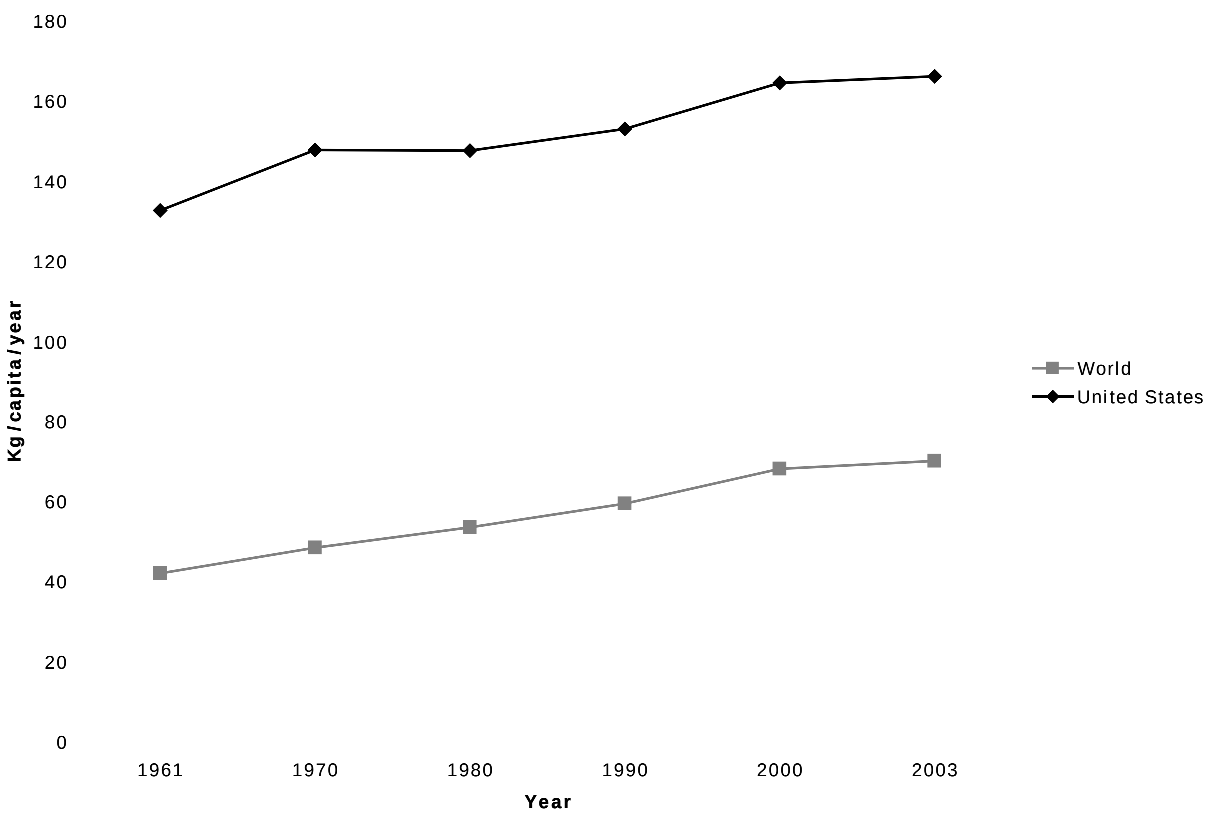


Figure 2-1. World and U.S. meat consumption from 1961 to present. (FAO, 2007).

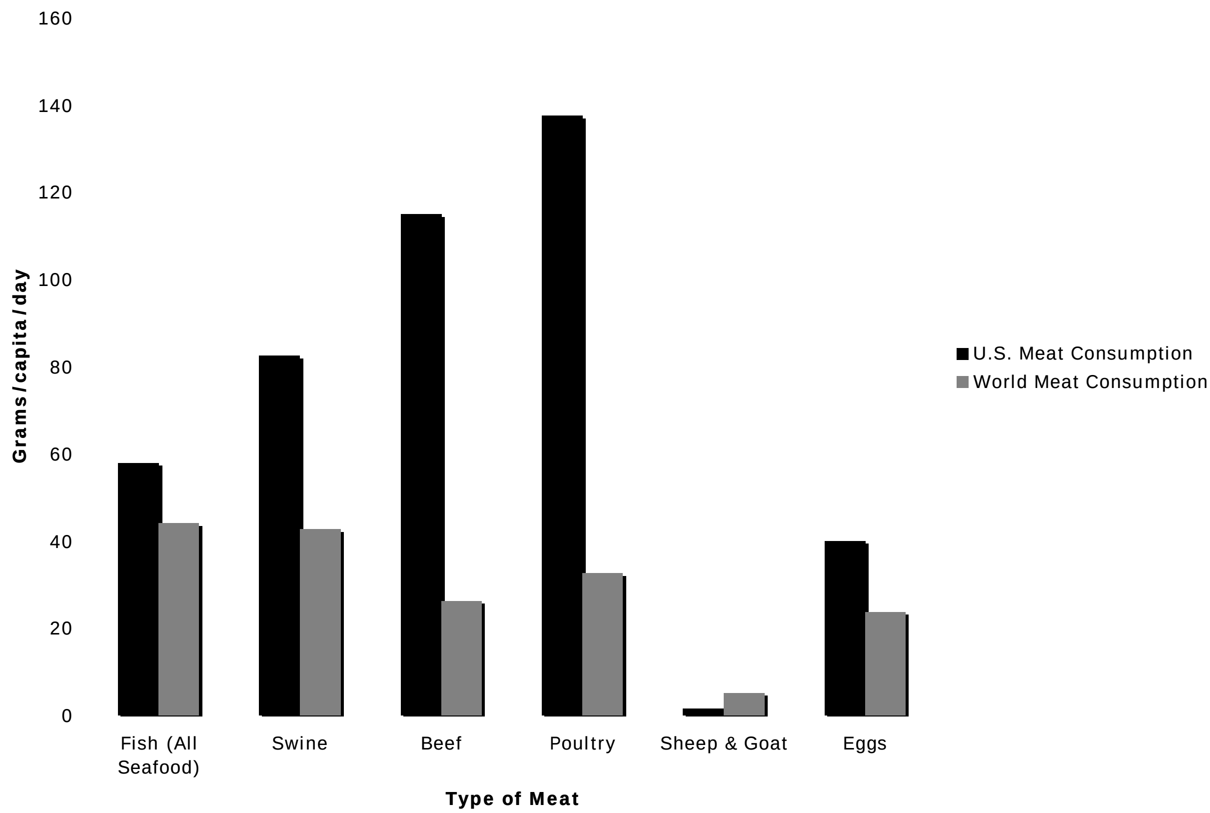


Figure 2-2. Current world and U.S. meat consumption by type. (FAO, 2007).

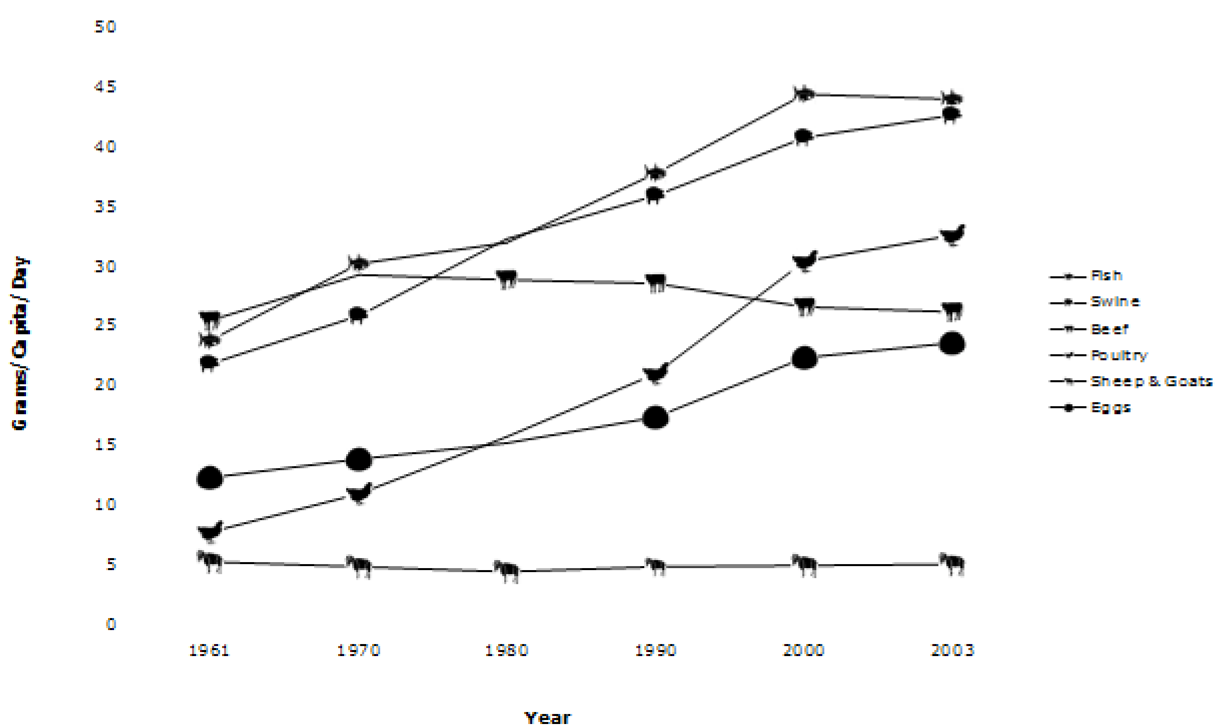


Figure 2-3. Trends in world meat consumption from 1961-2003 by type. (FAO, 2007).

Table 2-1. Feed conversion ratios of traditional terrestrial livestock and typical aquaculture species.

Animal	FCR (kg/kg)	Source
Lamb	9	Snowder & Van Vleck, 2003
Beef cattle	8	Pimentel, *et al.,* 2004.
Goats	11	Casas-Valdez, *et al.,* 2006.
Pigs	4	Pimentel, *et al.,* 2004.
Broiler Chickens	2	Pimentel, *et al.,* 2004.
Catfish	1.5-2.0	Moffitt, 2004.
Warmwater Fish (Recirculating System)	1.5	Masser, *et al.,* 1999.
Salmon	1.1-1.2	Moffitt, 2004.
Trout	1.0	Webster & Lim, 2002.

Table 2-2. Direct land use for different animal protein production systems.

Animal (Type of System)	Direct Land Use (kg/ha)	Reference
Beef (Pastured & Grain Fed)	55-90	Beef Specialist USDA-NASS, 2006
Pigs (Feed house)	13,575	USDA-NASS, 2006.
Broiler Chickens (Feed House)	380,000	Miles, R., 2007.; Jones, *et al.,* 2005.
Finfish (Recirculating Aquaculture Systems)	500,000	Timmons and Losordo, 1994.
Catfish (Ponds)	3500-5600	Durborow, R.M., 2000.
Trout (Flow-through)	450,000-500,000	Hinshaw, *et al.,* 1990.
Salmon (Cage/Net-pen)	100,000-300,000	Turnbull, *et al.,* 2005

Table 2-3. Range of world water requirements for selected agricultural products. (World average in parentheses.)

Agricultural Product	Consumptive Water Use (liters/kg)	Reference
Soybeans	1000-2000 (1789)	Chapagain & Hoekstra, 2004; Pimentel *et al.* 2004
Wheat	900-1500 (1334)	Chapagain & Hoekstra, 2004; USDA, 2006
Corn	489-1744 (909)	Chapagain & Hoekstra, 2004; Benham *et al.,* 1999; Palmer, 2001
Potatoes	630	USDA-NASS, 2006
Sorghum	1300-4053 (2853)	Klocke *et al.,* 1996; Chapagain & Hoekstra, 2004
Rice	1525-4254 (2975)	Snyder, 2000; Chapagain & Hoekstra, 2004
Chicken (broilers)	2198-7736 (3918)	Pimentel, 2003; Chapagain & Hoekstra, 2004
Pork	2211-6947 (4856)	Pimentel, 2003; Chapagain & Hoekstra, 2004
Beef	11,019-43,000 (15497)	Pimentel, 2003; Chapagain & Hoekstra, 2004
Pond based aquaculture	1,200-10,000	Boyd et al., 2007
Raceway aquaculture	16,000-120,000 (non-consumptive)	Boyd et al., 2007

Table 2-4. Common animal products in the U.S., their volume of production, and the ratio of Fossil Fuel Energy input to protein output. (Pimentel and Pimentel, 2003).

Animal products	Volume of Production	Fossil Energy In: Protein out
	$x10^6$	Kcal:grams
Lamb	7	57:1
Beef Cattle	74	40:1
Eggs	77000	39:1
Swine	60	14:1
Dairy	13	14:1
Turkeys	273	10:1
Broiler Chickens	8000	4:1

CHAPTER 3
METHODOLOGY

3.1 Life Cycle Assessment

ISO-compliant LCA methodology was used to calculate the total environmental impacts associated with fish and terrestrial animal production using SimaPro 7.1 (Pré Consultants, 2006).

The results were analyzed using two types of sensitivity analysis, the first was a more typical one-parameter-at-a-time (OAT) analysis, which is only able to determine first order effects of changes in input factors. The second was a global sensitivity analysis using the Morris screening method (Morris, 1991) as outlined by Muñoz-Carpena et al. (2007), which is a more robust, exploratory method used to determine first order importance for each parameter as well as higher order effects of input factors.

3.1.1 Scope, Boundaries, and Functional Unit

Stages included in the life cycle assessment of the each system included the production of agricultural and fisheries feedstuffs, (such as soy, wheat, corn, pasture etc., as well as the capture and rendering of fishmeal), processing of feed ingredients into pelleted fish feed or other animal feed, the on-farm operations associated with animal production, processing of finished animals, the transportation of goods between each process, and the extraction and refinement of energy sources such as coal, oil, and natural gas. Farm construction, decommissioning, and raw materials extraction for non-energy inputs were not included in the scope of this study.

A Level diagram is presented in Figure 1 to display the scope and boundaries of the systems analyzed. Level 3.0 diagrams are also presented in Figures 2 and 3 to provide more detail on inputs and outputs considered for each step in the production processes.

A functional unit of 1 kilogram of processed product is used in order to properly compare all of the systems analyzed.

3.1.2 Data Acquisition

While most of the terrestrial animal production data needed for this study was available from two databases, EcoInvent (Pré, 2006) and LCAFood (Nielsen et al., 2003), available through SimaPro 7.1, very little data is available for aquaculture production in the LCA literature.

In an attempt to best represent the environmental impacts of typical aquaculture products available to consumers, much of the data included in this study were industry wide averages. Such data includes feed conversion ratios, yield, dress-out percentage, mortality, transportation distance of feed and other inputs, water use on farm, crop water requirements of feed ingredients, and transportation and energy use on farm, among others. When this data was not available as primary literature, it came from extension agents, serial extension publications, industry officials, and scholarly books.

3.1.2.1 Fish feed production

Data for the percentage inclusions of different feedstuffs were taken from scientific literature. The data used were selected from the control and reference diets of different nutrition studies and from extension publications and other primary literature, and these were assumed to represent typical aquaculture feeds. Ingredients in these diets included agronomic crops, byproducts of other agro-industries, and wild-caught fishmeal and fish oil. Consumptive water use for both agronomic and fisheries ingredients came from virtual water literature (Chapagain and Hoekstra 2004), and represent average global direct water use during production and processing of each ingredient. However, water consumption data for fishmeal in the paper by Chapagain and Hoekstra was assumed to be the same as poultry, and thus, a certain portion of consumptive water for fishmeal production was taken out and replaced with an actual corroborated volume found in the scientific literature.

3.1.2.2 Transportation

Transportation of inputs and products of each system was based on data from the EcoInvent database available from SimaPro 7.1 and from mean transportation distances from typical sources of production and consumption. For example, transportation distances for fish feeds included the transport of corn and soybeans from the Midwest and portions of fishmeal and fish oil from the Gulf coast, Peru, and Northern Europe, to fish feed processing plants throughout the United States. Transportation of finished products (beef, chicken, pork, and fish) were not included in the scope of the study because it is assumed that the widely dispersed transportation of these products throughout the United States would negate the same data from other animal products in the study.

3.1.2.3 On-farm fish production

Atlantic Salmon: The Salmon production model created for this study was based on typical offshore Salmon production facilities in Maine and Chile. In these systems, juvenile Salmon are produced on-shore in freshwater flow-through or recirculating systems until they smolts, and have reached a size suitable for transport to off-shore cages, or net-pens (Leitritz and Lewis, 1980). These cages are typically made with circular, plastic frames or with square galvanized steel frames, and range from 8,000-13,000 m3 (Rojas and Wadsworth, 2007). The use of materials for cage construction varies based on the eventual location of the cages, and exposure to currents, wind, and storms. Their maximum stocking density is 16-20 kg/m3, depending on environmental conditions specific to regions of production. In these cages Salmon are fed through the use of automatic feeders, and the facility is monitored remotely, and serviced and managed on a daily or weekly basis by personnel (Rojas and Wadsworth, 2007). Fish are fed a diet high in fat and protein, the majority of which comes from fishmeal and fish oil. These systems are open to the natural environment for the release of uneaten feed, nutrients, and organic matter from the net-pens. When Salmon grow to 3-5 kilograms they are considered market size and are harvested (Knapp et al., 1995).

Channel Catfish: The Channel Catfish production model for this study was based on a typical catfish farm found in the Southeastern U.S. Typical pond size is between 8 and 20 acres for embankment ponds (typical in the Mississippi Delta, Louisiana, and Arkansas) and between 2 and 50 acres for watershed ponds, which are more typical in Eastern Mississippi and Alabama (Tucker and Hargreaves, 2004). Ponds are generally stocked at a density of 3500-6000 juvenile fish per acre (Tucker et al., 1994). Fish are harvested when they are 0.6-1.0 kilograms. Catfish diets consist mostly of agriculturally produced ingredients, especially soybean meal, corn, and wheat, and contain very little fishmeal and fish oil, typically about 2.5% (Tucker and Hargreaves, 2004). Sources of water come from groundwater, some surface water, and rainfall. The most significant water losses come from seepage and evaporation. Aeration is provided mechanically during certain parts of the year and at certain times of day usually by the use of tractor power.

Data for average precipitation during the production cycle of Channel catfish were taken from United States Weather Service average annual precipitation for Humphries, Leflore, Sunflower, Washington, and Yazoo Counties in Mississippi, which provide over half of the U.S. Channel catfish supply (NASS, 2005). Agricultural water use data for the Mississippi delta was also available from water management district publications. Both of these sources were used to estimate the total acre-inches of water pumped from groundwater on an annual basis. Production per acre, feed conversion ratios, dressout percentage, and other biological factors came from literature, extension publications, and personal communication with extension agents in the area. Data on the consumptive water use of agricultural crops used for feed production came from extensive amounts of crop water use data available from virtual water literature and the EcoInvent and LCAFood databases available in the SimaPro 7.1 software.

Rainbow Trout: The Rainbow Trout production model was based on typical production found in North Carolina and Idaho. The average farm in these regions produces between 50,000 and 300,000 kilograms of trout each year. In these systems, water is diverted from a natural source, such as a stream or river, and passes through trout raceways, which are around 10 meters long by 2 meters wide and are made of concrete (Hinshaw et al., 1990). Farms are designed so that water enters the first set of raceways at its highest elevation, and then passes to successive raceways by the use of gravitational flow. Depending on the geographical slope of farms, water can be used in 6-20 raceways before it exits the production area of the farm. Typical water flow in each raceway is 75-100 liters per minute per cubic meter of tank volume. Depending on the rate of water flow, tanks are typically stocked at 40-60 kilograms of fish per cubic meter of tank volume (Hinshaw et al., 1990). Rainbow trout diets are similar to that for Salmon production, but may contain more agricultural feed ingredients. The present study uses the same diet for both Salmon and Trout production.

While water is diverted from a natural body and flows through trout operations, it is returned to its source once it flows through the farm. There is a minor water loss at harvest and a slight increase in evaporation from settling ponds than would not occur if the water were never diverted into the farm. However, this quantity is assumed to be negligible in the present study. Water use for fish processing, transportation, and feed production came mostly from scientific literature, especially that related to virtual water in agricultural production, as well as extension and industry publications.

Tilapia: The tilapia production model used for this study was based on data available from economic budgets and literature on recirculating aquaculture production in general and tilapia production in particular. Water exchange rates of recirculating aquaculture production systems range from 5-10% per day, and tilapia are stocked at a density of 100-120 kilograms per cubic meter of tank volume (Losordo and Westers, 1994). The feed conversion ratio in the tilapia model was set at 1.31, and is an average of multiple sources found throughout the literature. Tilapia are harvested at 0.6-1.0 kilograms. The tilapia production industry generally uses feeds that include a larger portion of agriculturally produced ingredients than fishmeal and fish oil. This is because tilapia have a lower protein requirement than higher value species and are able to grow on less digestible feed inputs, such as soybeans, corn, and wheat. Information on energy use in recirculating systems was taken from economic budgets found in the literature and normalized on a power per kilogram of product basis.

Terrestrial Animal Production: Because there is much more existing life cycle assessment research on terrestrial animal production systems, much of the data needed for these models was available through the LCA software SimaPro 7.1. Feed conversion rations came from the scientific literature and were 8:1 for beef, 4:1 for pork, and 2:1 for chicken (Pimentel, 2004). Diets used for these models were typical of mainstream, industrial food production and included mostly soybeans and forage for beef production, wheat, soybeans, and barley for pork production, and soybean, wheat, corn, and blood meal for chicken production. Chemical fertilizer and inorganic chemical use came from data available in the software. Energy used for heat production in animal housing facilities came from natural gas, and traction for grain and forage production came from diesel power.

3.1.3 Environmental Impact Assessment

The resulting inventory provides an extensive list of sources of consumptive water use and compounds that contribute to air and water emissions. From these emissions, and from issues raised in scientific literature and mass media, the three major environmental impacts chosen for quantification in this study were consumptive water use, global warming potential, and eutrophication potential. In the case of consumptive water use, the environmental impact is a direct measure of the volume of water that is used and not returned to its natural source, and this data needs no further treatment to be comparable between systems. In the case of water and air emissions, however, environmental impact was assessed using the Environmental Risk Evaluation Method, (Allan and Shonnard, 2002). In this method, for each compound a dimensionless risk index is calculated by the Equation 1:

$$(DimensionlessRiskIndex)_i = \frac{[(EP)(IIP)]_i}{[(EP)(IIP)]_B}$$

where EP represents the exposure potential, IIP represents inherent impact potential, i is the indexed compound, and B is a benchmark compound. The dimensionless risk index for global warming and eutrophication are referred to as Global Warming Potential (GWP) and Eutrophication Impact Potential (EIP), respectively. The benchmark compound for GWP is CO_2, and is given a value of 1, while the major indexed compounds for GWP are CO_2, CH_4, N_2O, and NO_x, and are given a dimensionless risk index of 1, 21, 310, and 40, respectively. The benchmark compound for EIP is PO_4^{3-}, and is given a dimensionless risk index of 1, while major indexed compounds are PO_4^{3-}, P, NO_X, NO_2, NH_3, and NH_4^+, and are given a dimensionless risk index of 1, 3.06, 0.13, 0.13, 0.35, and 0.33, respectively. Complete lists of indexed compounds and their dimensionless risks for each environmental impact are given in Tables 1 and 2.

The index for the entire system being assessed is then computed Equation 2:

$$I = \sum_i [(DimensionlessRiskIndex)_i \times m_i]$$

where i represents the indexed environmental stressor, the Dimensionless Risk Index is the GWP or EIP of i, and m represents the total mass of i emitted from the system of production. Because all stressors are normalized to the benchmark compound, it is possible to report an impact index that is comparable across systems of production. For GWP, impact is reported as equivalent kilograms of CO_2 per kilogram of finished product (kg-equiv. CO_2/kg) and EIP is reported as equivalent grams of PO_4^{3-} per kilogram of finished product (g-equiv. PO_4^{3-}/kg).

3.2 Sensitivity Analysis

Within life cycle assessment and scientific modeling in general, sensitivity analysis is used to determine the relative importance of individual input factors to model outputs. This type of analysis allows researchers to improve model structure, determine input factors that need to be more accurately represented, and to determine the level of uncertainty in model outputs, among other things (Muñoz-Carpena et al., 2007). Sensitivity analysis is highly important, especially in studies involving environmental impact because results may affect public policy and industry management decisions.

Within the field of life cycle assessment, sensitivity analyses are typically conducted by what are deemed “one-parameter-at-a-time” (OAT) methods, in which only one input factor is changed during each analysis and all other input factors remain constant. This method of analysis is useful because it helps to determine the sensitivity of model outputs to changes in single input parameters. For simpler models, whose input factors produce linear output responses, this method is sufficient to determine sensitivity of input factors (Muñoz-Carpena et al., 2007). However, in more complex models, it is appropriate to analyze output sensitivity to and uncertainty in model input factors simultaneously, which provides results on first-order affects, like those available from OAT methods, but also provides information on higher order affects, like relative importance of input factors and interactions between input factors (Muñoz-Carpena et al., 2007). These analyses of higher order effects are referred to as global sensitivity analyses.

For the sake of the present study, both approaches were taken. The models used to determine consumptive water use for aquaculture systems were analyzed using the global approach, in which all input parameters were analyzed simultaneously to determine both first order effects as well as higher order effects, if any existed. The results of the global sensitivity analysis are presented in the following chapter. The remaining models were analyzed using OAT methods, in which assumptions made for model construction were used to determine those input factors that may be most responsible for uncertainty in model outputs. The input factors that were seemingly most affected by these assumptions were: 1) diets used in aquaculture operations, 2) animal feed conversion ratio, 3) transportation distance, and 4) direct impacts on-farm. Scenarios were designed for the sensitivity analysis based on these assumptions, in which all input factors remain unchanged except the one being tested, which is improved by 20%. Model runs were carried out for each scenario and the results are presented in the following chapter.

For the global sensitivity analyses, probability distribution functions (PDFs) were determined from multiple sources of literature according to the method described by Muñoz-Carpena et al. (2007). Upper and lower bounds were determined, as well as a base value (that value used for the study). These data were analyzed using SimLab v2.2 (Saltelli et al., 2004), by which each input factor is changed simultaneously in regards to its upper and lower bounds, base value, and PDF according to the Morris method as it is outlined by Muñoz-Carpena et al. (2007) and an input set is generated. Each input set is used in a model simulation, and vector outputs from these simulations are used to perform the Morris screening method. The number of simulations (N) used for the Morris method is determined by Equation 3:

$$N = r(k+1)$$

where *r* is the sampling size for search trajectory (*r* = 10 in this case), and *k* is the number of model input parameters. The aquaculture LCA models went through 110-140 runs each. For each model input parameter, two sensitivity measures are calculated: (1) the mean of first-order effects (μ), which estimates the overall effect of the model input on a given output, relative to other model inputs; and (2) the standard deviation of the effects (σ), which calculates the higher-order effects of the model input (such as interactions with other model inputs). From the Morris screening method, the important parameters are selected as those deviating from the μ-σ origin, and the analysis is repeated for only these parameters using the extended FAST method and subsequently, uncertainty is assessed based on the outputs of the extended FAST simulations by constructing PDFs and statistics of calculated errors. For the present study, however, only the initial Morris screening was conducted to compute relative, qualitative importance and interaction of input factors. Details on the extended FAST methods and the Morris method have been published elsewhere by Muñoz-Carpena et al. (2007).

Model input factors and their definitions are presented in Table 3. Their base values, upper and lower bounds, selected PDFs, and sources are listed in Tables 4 through 7.

The results of the global sensitivity analyses are presented in the following chapter, graphically, in which the x-axis represents relative importance of input factors to the models output and the y-axis represents relative interaction between input factors. Therefore, factors that fall toward the origin of the graph are not important in affecting the simulated output nor do they have much interaction with other input factors, and thus are not responsible for uncertainty in model outputs. Factors which fall to the upper left of the figure are highly interactive with other model inputs but are relatively unimportant to model outputs. Factors which fall toward the bottom right of the figure are highly important in affecting model output but have relatively little interaction with other input factors. Finally, factors that fall toward the upper right of the graph represent those inputs that are highly important to model output and have relatively high interaction with other input factors.

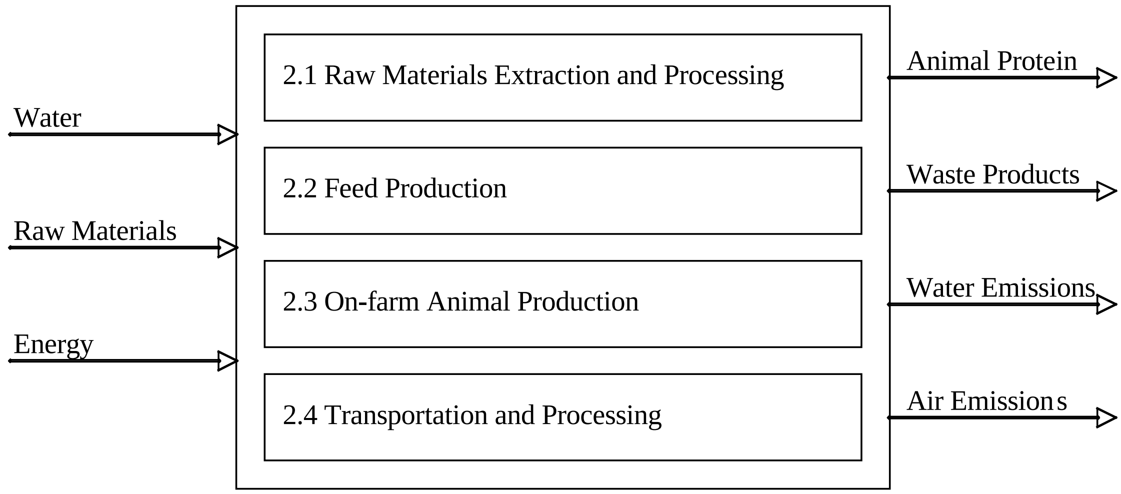


Figure 3-1. Level 1.0 with embedded level 2.0 diagram for animal production systems.

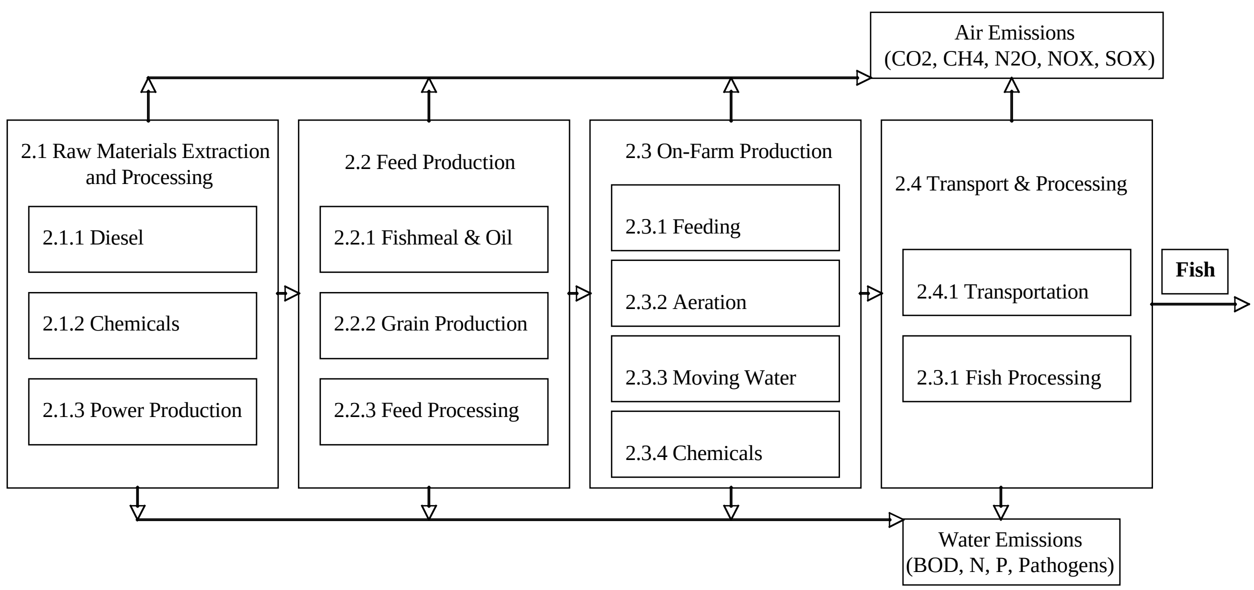


Figure 3-2. Level 3.0 diagram for aquaculture systems.

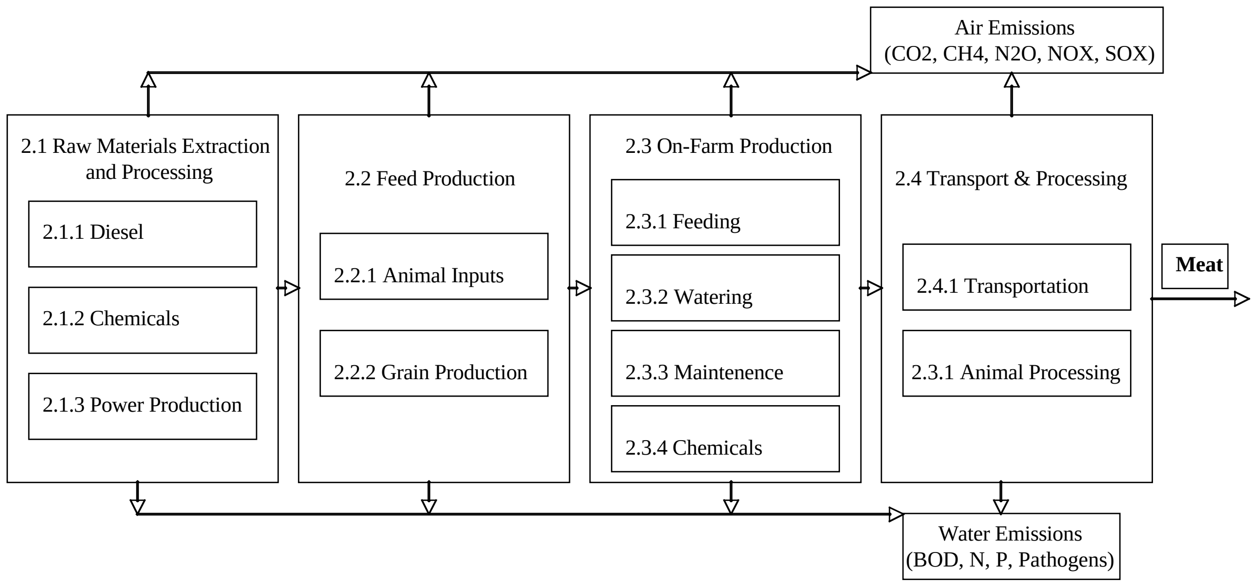


Figure 3-3. Level 3.0 diagram for terrestrial animal production systems.

Table 3-1. Indexed compounds and their dimensionless risk index for the calculation of 100 year global warming potential (Houghton, et al., 1994 and 1996; Guinee, 2002).

Compound	kg-equivalents of CO_2/kg
CO_2	1
CH4	21
1,1,1-Trichloroethylene	110
CCl4- Carbon tetrachloride	1400
N2O- Dinitrogen monoxide	310
SF6- Sulfer hexafluoride	23900
CF4- Tetrafluoromethane	6500
CFC-11	4000
CFC-12	8500
CFC-13	11700
CFC-113	5000
CFC-114	9300
HCFC-22	1700
HCFC-123	93
HCFC-124	480

Table 3-2. Indexed compounds and their dimensionless risk index for the calculation of eutpophication impact potential (Heijungs et al., 1992; Guinee, 2002).

Compound	Gram-equivalents of PO_4^{3-}/g
PO_4^{3-}	1
H_3PO_4	0.97
P	3.06
NO_X	0.13
NO_2	0.13
NH_3	0.35
NH_4^+	0.33
NO_3^-	0.1
HNO_3	0.1
N	0.42
COD	0.022

Table 3-3. Model input factor definitions.

Input parameter	Definition
Fishmeal Water	Total water required for the production of fishmeal and fish oil
Soybean Water	Total water required for the production of soybean meal
Wheat Water	Total water required for the production of wheat middling
Corn Water	Total water required for the production of corn gluten
Canola Water	Total water required for the production of canola
Potato Water	Total water required for the production of potato starch
Molasses Water	Total water required for the production of molasses
Peas Water	Total water required for the production of protein peas
Portion Fishmeal	Percent inclusion of fishmeal in a diet
Portion Soy	Percent inclusion of soybean meal in a diet
Portion Wheat	Percent inclusion of wheat middling in a diet
Portion Corn	Percent inclusion of corn gluten in a diet
Portion Canola	Percent inclusion of canola in a diet
Portion Rest	Percent inclusion of minor feed ingredients (<1%)
FCR	kg of feed needed to produce 1 kg of unprocessed fish
Dressout	Percent of marketable product after processing
Trans	Water use associated with transportation
On-Farm	Direct use of water on-farm for animal production
Feed Processing	Water used for the milling, cooking, and/or extruding of feed
Processing	Water used for fish processing
Electricity	Water use associated with power production

Table 3-4. Model input parameters, upper and lower bounds, probability distribution functions, and sources used for Global Sensitivity Analysis of the Salmon model.

Input Parameter	Base	PDF	Min.	Max	Source
Soybean Water	0.571	Triangular	0.1297	2.753	Chapagain & Hoekstra 2004.
Fishmeal Water	0.022	Uniform	0.018	0.0268	FAO 1986.
Wheat Water	1.34	Triangular	0.465	1.807	Chapagain & Hoekstra 2004.
Corn Water	0.912	Triangular	0.4866	1.4445	Chapagain & Hoekstra 2004.
Potato Water	0.268	Triangular	0.0246	0.140	Chapagain & Hoekstra 2004.
Molasses Water	0.113	Triangular	0.029	0.319	Chapagain & Hoekstra 2004.
Peas Water	0.348	Triangular	0.130	1.035	Chapagain & Hoekstra 2004.
Portion Soy	0.174	Triangular	0	0.6	Mambrini et al 1999, Valente et al, 2007., St-Hilaire et al, 2007., A.M. Escaffre et al, 2007, S. Refstie et al., 1997, Bilgin et al, 2007.
Portion Fishmeal	0.572	Triangular	0.17	0.55	(Same as above)
Portion Wheat	0.15	Triangular	0.084	0.275	(Same as above)
Portion Rest	0.1	Fixed			(Same as above)
FCR	1.2	Triangular	0.84	1.24	Einen & Roem, 1997, Storebakken et al 1998, Refstie et al 1998
Dressout	0.84	Triangular	0.69	0.93	Belle, S. 2005, Johansen & Jobling 1998, Refstie et. al. 1998
Trans	0.2	Triangular	0.16	0.24	EcoInvent Database
Electricity	0.0014	Triangular	0.001	0.002	Bella, S. 2005.
On-farm	0.00075	Triangular	0.0006	0.0009	Assumed
Feed Processing	0.0213	Uniform	0.017	0.0256	Funk 2007.

Table 3-5. Model input parameters, upper and lower bounds, probability distribution functions, and sources used for Global Sensitivity Analysis of the Trout model.

Input Parameter	Base	PDF	Min.	Max	Source
Soybean Water	0.571	Triangular	0.1297	2.753	Chapagain & Hoekstra 2004.
Fishmeal Water	0.022	Uniform	0.018	0.0268	FAO 1986.
Wheat Water	1.34	Triangular	0.465	1.807	Chapagain & Hoekstra 2004.
Corn Water	0.912	Triangular	0.4866	1.4445	Chapagain & Hoekstra 2004.
Potato Water	0.268	Triangular	0.0246	0.140	Chapagain & Hoekstra 2004.
Molasses Water	0.113	Triangular	0.029	0.319	Chapagain & Hoekstra 2004.
Peas Water	0.348	Triangular	0.130	1.035	Chapagain & Hoekstra 2004.
Portion Soy	0.174	Triangular	0	0.6	Mambrini et al 1999, Valente et al, 2007., St-Hilaire et al, 2007., A.M. Escaffre et al, 2007, S. Refstie et al., 1997, Bilgin et al, 2007.
Portion Fishmeal	0.572	Triangular	0.17	0.55	(Same as above)
Portion Wheat	0.15	Triangular	0.084	0.275	(Same as above)
Portion Rest	0.1	Fixed			(Same as above)
FCR	0.94	Triangular	0.70	1.6	Bailey & Alanara, 2006, Okumus & Mazlum, 2002., Caballero et al, 2002
Dressout	0.80	Triangular	0.76	0.84	Reinitz, 1987, Ronsholdt et al 2000, Adelizi et al 1998
Trans	0.16	Triangular	0.152	0.168	EcoInvent Database
Electricity	0.0012	Triangular	0.00	0.0021	Hinshaw et. al., 1990, LCAFood database
On-farm	0.00075	Uniform	0.0006	0.0009	Assumed
Feed Processing	0.0213	Uniform	0.017	0.0256	Funk 2007.

Table 3-6. Model input parameters, upper and lower bounds, probability distribution functions, and sources used for Global Sensitivity Analysis of the Channel Catfish model.

Input Parameter	Base	PDF	Min.	Max	Source
Soybean Water	0.571	Triangular	0.130	2.753	Chapagain & Hoekstra 2004.
Canola Water	1.62	Triangular	0.266	5.00	Chapagain & Hoekstra 2004.
Wheat Water	1.34	Triangular	0.465	1.807	Chapagain & Hoekstra 2004.
Corn Water	0.912	Triangular	0.487	1.444	Chapagain & Hoekstra 2004.
Portion Soy	0.024	Triangular	0	0.4	Robinson & Li 1999.
Portion Canola	0.09	Triangular	0.05	0.1	Robinson & Li 1999.
Portion Wheat	0.17	Triangular	0.1	0.25	Robinson & Li 1999.
Portion Corn	0.326	Triangular	0.303	0.353	Robinson & Li 1999.
FCR	2.2	Triangular	1.97	2.50	Tucker & Hargreaves 2004.
Dressout	0.464	Uniform	0.435	0.493	Tucker & Hargreaves 2004.
Trans	0.25	Triangular	0.238	0.262	EcoInvent Database
Electricity	0.002	Uniform	0.002	0.002	Boyd et al. 2007, Torcellini et al. 2003.
On-farm	5.082	Triangular	3.813	6.098	Catfish Report 2000, Powers 2007, Powers 2006.
Feed Processing	0.021	Uniform	0.017	0.026	Funk 2007.

Table 3-7. Model input parameters, upper and lower bounds, probability distribution functions, and sources used for Global Sensitivity Analysis of the Tilapia model.

Input Parameter	Base	PDF	Min.	Max	Source
Soybean Water	0.571	Triangular	0.1297	2.753	Chapagain & Hoekstra 2004.
Wheat Water	1.34	Triangular	0.465	1.807	Chapagain & Hoekstra 2004.
Corn Water	0.912	Triangular	0.4866	1.4445	Chapagain & Hoekstra 2004.
Portion Soy	0.159	Triangular	0.035	0.5	El-Saidy, et. al 2004., Fontainhas-fernandes et al 1999., Lara-Flores et al 2007., Kut Guroy et al 2007., de Souza et al 2007., Gaber M 2009
Portion Wheat	0.269	Triangular	0.05	0.5	(Same as above)
Portion Corn	0.195	Triangular	0.00	0.367	(Same as above)
Portion Rest	0.3	Fixed			(Same as above)
FCR	1.31	Triangular	1.121	1.509	Abdelghany 2003, Ali et al. 2008, Ridha et al. 2006, Schneider et al. 2004, Schulz et al. 2007.
Dressout	0.376	Uniform	0.357	0.394	Popma & Lovshin, 1995., Hartley-Alcocer, 2007., Botero, 2007., Rutten et. al., 2004., Rutten et. al, 2005., Silva et. al., 2006
Trans	0.20	Triangular	0.19	0.21	EcoInvent Database
Electricity	0.0024	Uniform	0.0023	0.0025	Losordo & Timmons 1994.
On-farm	0.2291	Uniform	0.1636	0.327	Based on Stocking Density and Exchange rates
Feed Processing	0.0213	Uniform	0.017	0.0256	Funk 2007.

CHAPTER 4
RESULTS

4.1 Simulation Results

The results of the environmental impact assessment for total consumptive water use show that finished trout requires 590 liters of water/kg, compared to salmon, tilapia, chicken, catfish, pork, and beef, which consume , 720.0, 2950.0, 7240.0, 9610.0, 10310.0, and 19500.0 L/kg, respectively. In short, trout and salmon have a very low consumptive water use, followed by moderate use for chicken, catfish, and pork, and very high water use for beef. These results are listed in Table 4.1, and are depicted graphically in Figure 4-1.

The results of the impact assessment for global warming potential show that trout has an impact of 2.5 kg-equivalents of CO2/kg of finished product, compared to tilapia, catfish, salmon, pork, chicken, and beef, which produce 3.82, 3.83, 4.2, 5.78, 6.12, and 28.4 kg-equiv. CO2/kg, respectively. That is to say, of the products analyzed, those produced in aquaculture have lower global warming potentials across the board compared to pork, chicken and beef production, which have progressively higher impacts. These results are listed in Table 4.2, and are depicted graphically in Figure 4-2.

The results of the impact assessment for eutrophication impact potential show that trout has an impact of 39.0 mg-equivalents of PO43-/kg of finished product, compared to catfish, chicken, tilapia, pork, salmon, and beef, which are responsible for 41.0, 46.0, 49.0, 71.0, 87.0, and 244.0 mg-equivalents of PO43-/kg, respectively. Of these systems, trout, catfish, chicken, and tilapia can be grouped as having significantly lower eutrophication impact potentials than do pork, salmon, and beef. These results are listed in Table 4.3, and are depicted graphically in Figure 4-3.

4.2 Sensitivity Analysis Results

4.2.1 Sensitivity Analysis (OAT)

The results of the OAT sensitivity analyses used to determine importance of input factors in the global warming potential and eutrophication impact potential models are presented in Tables 4-4 through 4-7. In each system, the global warming potential is most sensitive to changes in animal feed conversion ratio (Tables 4-1 through 4-4). It is those factors that are related to FCR that create the greatest differences in impact between each system. The global warming potentials of the salmon and trout production systems are most sensitive to changes in the feed conversion ratio of the fish because of the high percent inclusion of fishmeal in the fish diets and the high fossil fuel emissions associated with the fishmeal fishery. For catfish and tilapia production, GWP is also most sensitive to changes in feed conversion ratio, but in this case it is due to the high percent inclusion of agricultural products, such as soy and canola, and increased transport weight of feed ingredients because of lower feed conversion efficiency for these fish. It is also important to point out that the GWP of tilapia production is not highly sensitive to changes of on-farm emissions. In this system, which has the highest use of energy on-farm, emissions associated with the production of agricultural feed ingredients and with transportation are more important to the overall global warming potential.

The eutrophication impact potential of salmon and trout production is most sensitive to changes in eutrophication coming from on-farm operations. This should be expected with these systems, as they are more intimately connected with, and their effluents are more directly externalized to the surrounding aquatic environment. The importance of on-farm emissions is higher in salmon production than trout production because all compounds responsible for this impact are made available to the natural environment, whereas in trout production a significant mass of these compounds are removed in settling ponds before water is discharged to the environment.

In the catfish and tilapia systems, EIP is most sensitive to changes in the feed conversion ratio, which is largely due to activities associated with the production of agricultural feed ingredients, primarily soybean meal. In the case of catfish production, on-farm operations do play a small role in the overall EIP, and this is mainly due to seepage and overflow of pond water to groundwater and adjacent surface waters.

4.2.2 Global Sensitivity Analysis

The relative importance of input factors on consumptive water use for each model is presented in Table 4-8, and is based on the value μ, from the Morris method. Figure 4-4 graphically represents the results of each Morris analysis. As previously stated and as expressed by the Morris method, only those factors that are separated from the μ-σ origin are considered important, and therefore the number of important factors for further analysis is diminished significantly. As these figures are read from left to right across the x-axis, the mean variance of a parameter increases. Which is to say, as μ increases, parameters become relatively more important to changes in model outputs. The y-axis represents the standard deviation of that mean variance, which is to say, as parameters are plotted higher on the y-axis, they have a higher level of interaction with other model input parameters. The results of the Morris screening indicate several points which merit discussion.

While on-farm water use is slightly important in the catfish model, it is less important for every other aquaculture system. This can be explained by the greater volume of water used on-farm for catfish production (nearly half of the total) compared to the other systems, which use very little water on-farm relative to the feed production stage (see Figure 4-1). These results indicate that even if major water savings were realized on aquaculture farms, it may not greatly effect the global water consumption of aquaculture as a whole.

The most important parameters, however, were associated with feeding and more specifically with dietary protein sources for fish feeds. For the omnivorous fishes (catfish and tilapia), the most important parameters were associated with agricultural crops used as feed ingredients. Of these, the volume of water required to produce soybean meal (“Soybean Water”), and the percent inclusion of soybean meal (“Portion Soy”) in fish diets were the most important parameters. This is explained by the large range of irrigation requirements for soy production in different regions, and the large, relatively unvarying amount of soybean meal included in catfish diets.

For tilapia production, the percent inclusion and agricultural water requirements for soy and wheat are most important (“Portion Soy”, “Soybean Water”, “Portion Wheat”, and “Wheat Water”), and can be explained by the large inclusion of these ingredients in tilapia diets, a relatively large variance in their percent inclusion across all tilapia diets, and a large variance of the crop water requirements for soy and wheat production from various regions.

The higher-order effects of “Soybean Water” and “Portion Soy” can be explained by the substitutionary relationship between soy and other agriculturally produced feed ingredients. That is to say, if soybean meal is increased or decreased in these diets, it is most likely done so by the replacement or diminishment of some other agricultural input, such as wheat middling or corn gluten.

For the carnivorous fish (salmon and trout), the most important parameters are the portion of fishmeal included in the diet ("Portion FishMeal"), the amount of water used to produce soybeans and wheat ("Soybean Water" and "Wheat Water"), and in the case of the trout model, feed conversion ratio ("FCR").

The importance of the percent inclusion of fishmeal in carnivorous diets can be explained by their high percent inclusion of fishmeal, and the low water consumption of fishmeal as an ingredient. As fishmeal is decreased incrementally in a diet, it is replaced with high water consuming agronomic ingredients, especially soybean meal and wheat. As these agronomic crops increase incrementally with any decrease in fishmeal, the consumptive water use of the system as a whole increases dramatically. More simply, consumptive water use of diets with a high percent inclusion of fishmeal (which has low water requirements) has a low buffering capacity to increases or decreases in agricultural inputs.

In terms of interaction amongst model inputs (Figure 4-4a and 4-4b), the relatively high interaction of 'wheat water' and 'soybean water' in the salmon and trout models is not surprising because wheat middling and soybean meal are both substitutes for fishmeal in Salmonid diets. As fishmeal is decreased it is replaced by some combination of these two ingredients, and because they are also substitutes for one another, they demonstrate a relatively high level of interaction within the model.

In the trout production model FCR is grouped with the most important parameters (Figure 4-4b). It would be expected that any parameters associated with feeding in the trout and salmon models would have similar Morris rankings, because these fish are very similar biologically, however, this is not the case. The high relative importance of FCR in the trout model can be explained by a larger variance of FCR in the trout nutrition literature (Table 3-5), and a relatively narrow range of variance of FCR in the salmon nutrition literature (Table 3-4) causes the diminished importance of FCR in the salmon model. This is due to a greater amount of scientific research toward alternative ingredients for trout feeds compared to salmon nutrition research. Thus, there is a greater amount of variance for FCR in the literature, which leads to a greater variance of FCR in the trout LCA model.

4.3 Summary

4.3.1 Summary of Model Simulations

The results of the life cycle assessment indicate that aquaculture, in general, has a lower consumptive water use than the systems of terrestrial animal protein production, with the exception of catfish, which has a CWU similar to the terrestrial systems. The global warming potential of aquaculture systems are categorically lower than those of terrestrial animal systems, but beef is significantly higher than any other system. For eutrophication impact potential, trout, catfish, chicken, and tilapia had lower impacts compared to the moderate impacts of pork and salmon, and the very high eutrophication impact potential of beef.

4.3.2 Summary of Sensitivity Analysis

There are significant benefits to the use of the Morris screening method over the more typical OAT methods employed for analyzing GWP and EIP models. While the

OAT sensitivity analysis provides a relative sensitivity of model outputs for changes in each model input, it is not robust enough to decipher the role played by higher order effects for each parameter. While the OAT analysis points to FCR as the most important factor for output sensitivity, it does not expose which feed ingredients may or may not play the largest role in FCR itself. By the use of the Morris method, however, higher order effects are also discovered, which show, in the case of consumptive water use, that FCR itself does not play as important of a role as those parameters associated with it, namely, feed composition and crop water requirements.

Table 4-1. Consumptive Water Use in animal production systems.

	Salmon	Trout	Catfish	Tilapia	Beef	Pork	Chicken
Feed	0.51	0.42	4.27	2.54	15.94	8.52	5.66
On Farm	0.00	0.00	5.08	0.23	3.36	1.68	1.43
Transportation	0.20	0.16	0.25	0.20	0.1	0.1	0.13
Processing	0.01	0.01	0.01	0.01	0.1	0.01	0.02
Total	0.72	0.59	9.61	2.95	19.5	10.31	7.24

Note: Values are given in 1000s of liters per kilogram of final product.

Table 4-2. Global warming potential in animal production systems.

	Salmon	Trout	Catfish	Tilapia	Beef	Pork	Chicken
Feed	2.42	2.38	2.5	2.33	6.77	3.22	3.02
On-Farm	0	0.04	0.1	0.50	20.94	2.20	0.88
Transportation	1.75	0.05	1.22	0.95	0.30	0.01	1.65
Processing	0.03	0.03	0.01	0.04	0.4	0.35	0.57
Total	4.2	2.50	3.83	3.82	28.40	5.78	6.12

Note: Values are given in kilogram equivalents of CO_2 per kilogram of final product.

Table 4-3. Eutrophication impact potential in animal production systems.

	Salmon	Trout	Catfish	Tilapia	Beef	Pork	Chicken
Feed	0.012	0.012	0.030	0.044	0.008	0.041	0.031
On-Farm	0.074	0.027	0.011	0.0	0.210	0.028	0.013
Transportation	0.0	0.0	0.0	0.005	0.0	0.0	0.002
Processing	0.0	0.0	0.0	0.0	0.026	0.002	0.0
Total	0.087	0.039	0.041	0.049	0.244	0.071	0.046

Note: Values are given in gram equivalents of PO_4^{3-} per kilogram of final product.

Table 4-4. Sensitivity analysis of the salmon LCA by changes in input factors.

Input Factor	Change in GWP	Change in EIP
Inclusion of soy	3.33%	1.73%
Inclusion of fishmeal	8.33%	1.04%
Feed conversion ratio	11.55%	2.89%
Total transportation distance	8.33%	0%
On-farm impact	0%	17.11%

Table 4-5. Sensitivity analysis of the trout LCA by changes in input factors.

Input Factor Changed	Change in GWP	Change in EIP
Inclusion of soy	7.01%	4.1%
Inclusion of fishmeal	15.16%	1.08%
Inclusion of wheat	1.7%	1.08%
Feed conversion ratio	19.04%	6.15%
Total transportation distance	1.14%	0%
On-farm impact	0.32%	13.74%

Table 4-6. Sensitivity analysis of the catfish LCA by changes in input factors.

Input Factor	Change in GWP	Change in EIP
Inclusion of soy	7.36%	10.05%
Inclusion of corn	2.40%	2.72%
Inclusion of wheat	1.57%	1.48%
Feed conversion ratio	13.05%	14.85%
Total transportation distance	6.37%	0%
On-farm impact	0.5%	5.2%

Table 4-7. Sensitivity analysis of the tilapia LCA by changes in input factors.

Input Factor	Change in GWP	Change in EIP
Inclusion of soy	2.26%	6.78%
Inclusion of fishmeal	3.25%	0.8%
Inclusion of wheat	1.61%%	3.34%
Inclusion of canola	3.29%	3.24%
Feed conversion ratio	12.55%	18.2%
Total transportation distance	6.51%	1.71%
On-farm impact	1.0%	0%

Table 4-8. Ranking of sensitive parameters calculated by the Morris method.

	W-S	W-W	W-C	W-Can	%FM	%S	%Can	%W	%C	FCR	DO	T	Dir	FP
Salmon	3	2	--	--	1	4	--	--	--	5	6	-	--	--
Trout	1	1	--	--	1	5	--	--	--	1	6	-	--	--
Catfish	1	--	4	3	--	--	--	--	--	5	6	-	2	--
Tilapia	2	4	6	--	--	1	--	2	--	5	7	-	8	--

W-S: CWU of soybean production
W-W: CWU of wheat production
W-C: CWU of corn production
W-Can: CWU of canola production
%FM: % inclusion of fishmeal
%S: % inclusion of soybean meal
%Can: % inclusion of canola
%W: % inclusion of wheat
%C: % inclusion of corn
FCR: Feed conversion ratio
DO: Dressout
T: Transportation
Dir: Direct on-farm water use
FP: Feed processing

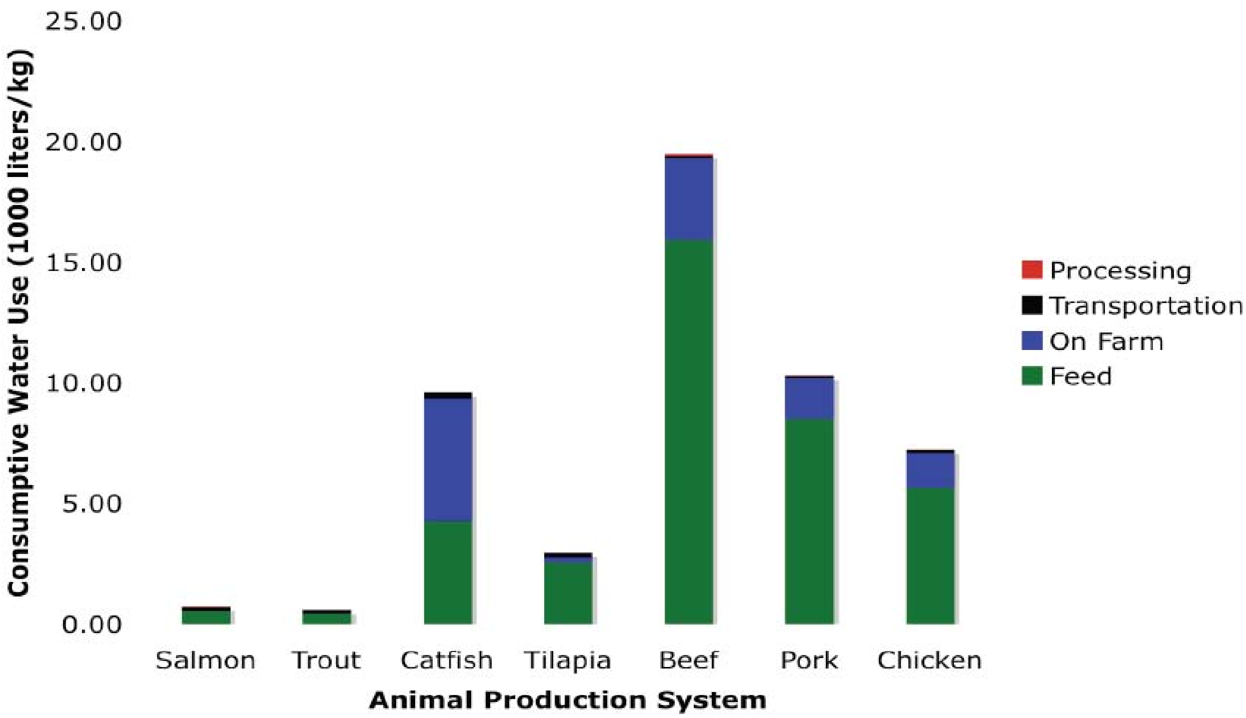


Figure 4-1. Consumptive water use in animal protein production by type and by life cycle stage.

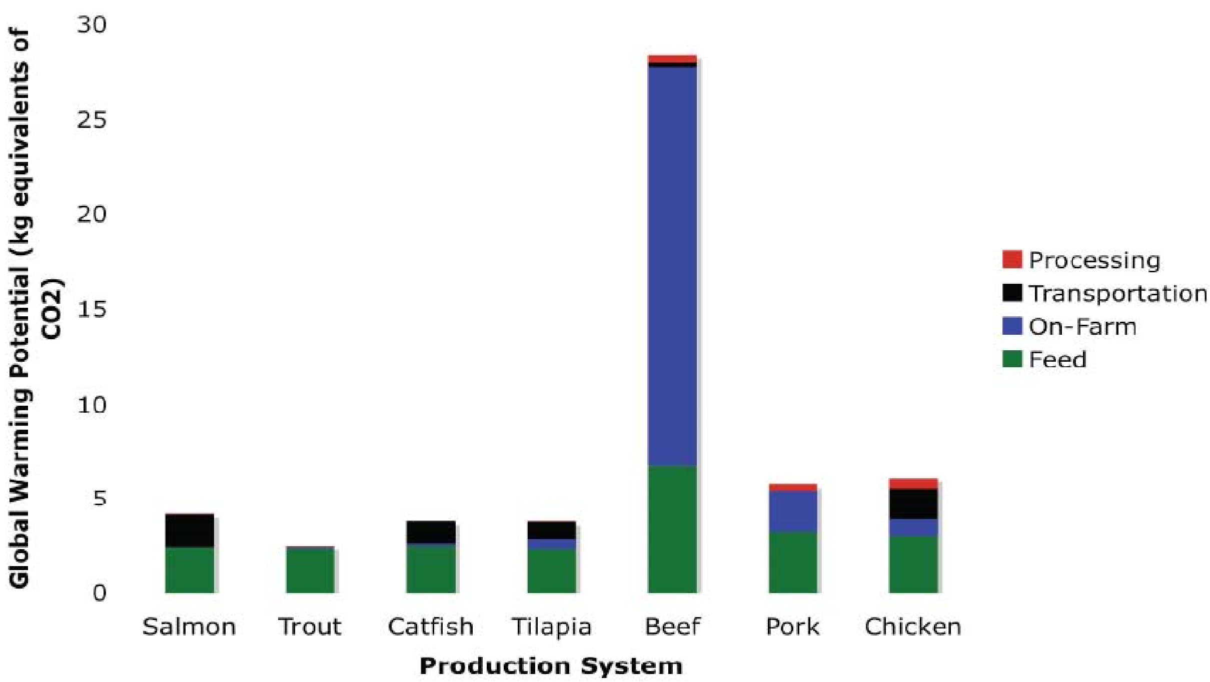


Figure 4-2. Global warming potential by type and life cycle stage, given in kg equivalents of CO_2/kg of finished product.

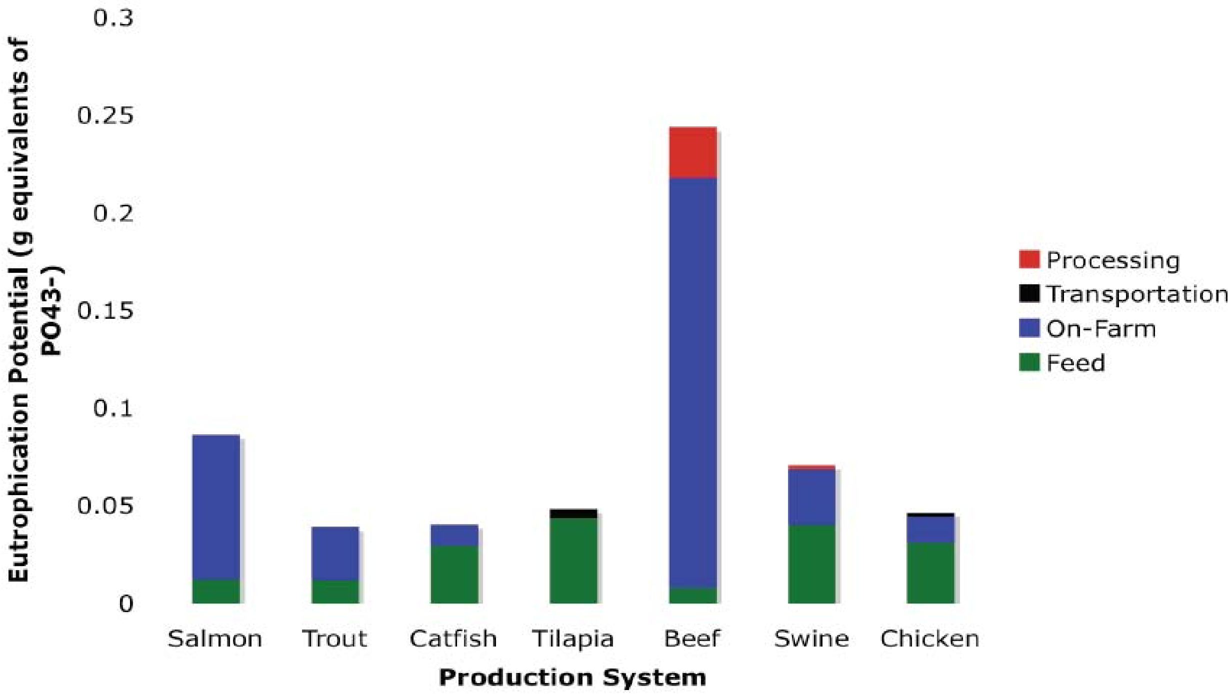


Figure 4-3. Eutrophication impact potential by type and life cycle stage, given in gram equivalents of CO_2/kg of finished product.

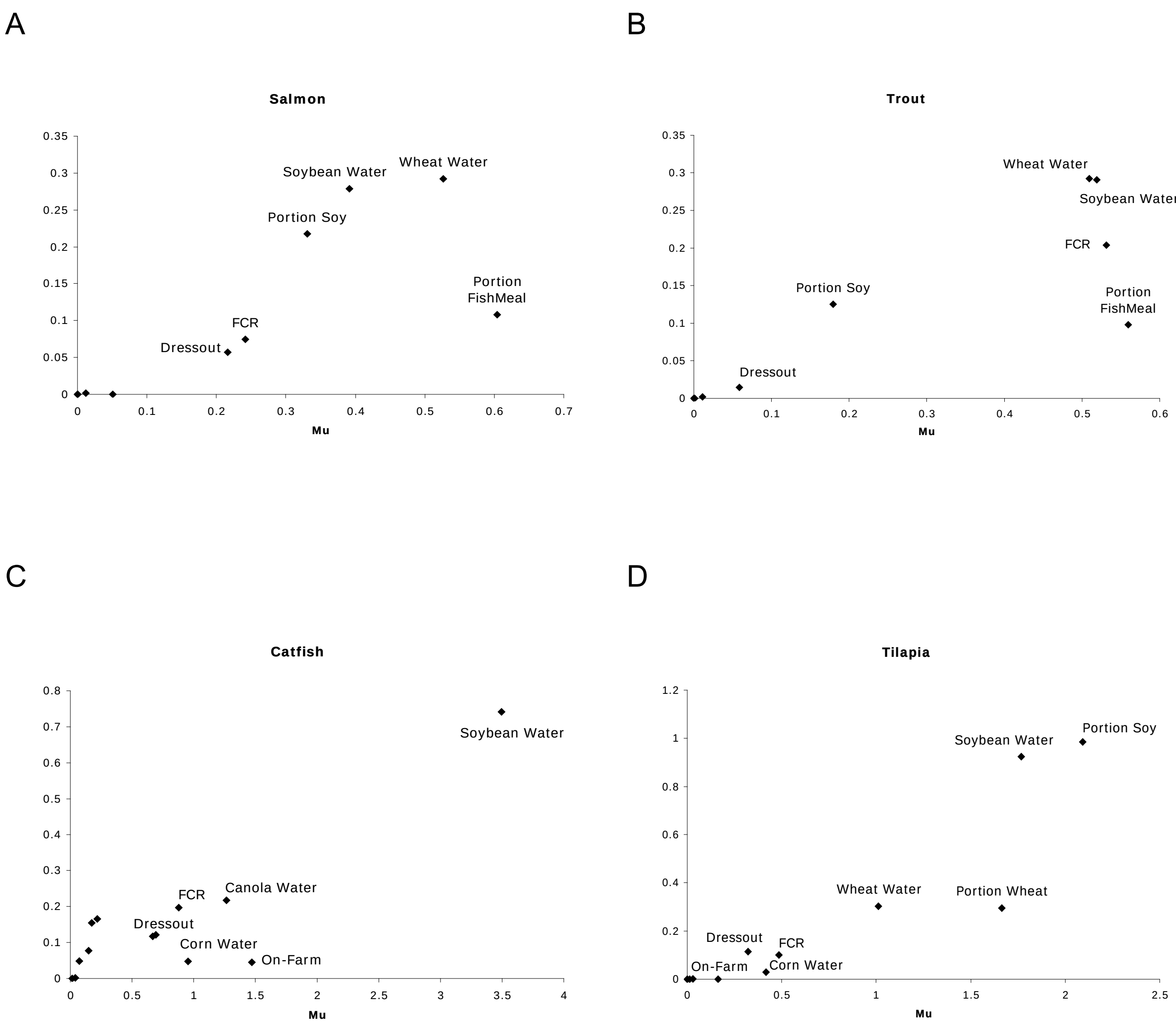


Figure 4-4. Global sensitivity analysis results for consumptive water use of (A) salmon, (B) trout, (C) catfish, and (D) tilapia production.

CHAPTER 6
CONCLUSIONS

The results of this study show that the aquaculture products analyzed in this study are, in general, more water efficient, have lower global warming potentials, and have similar eutrophication impact potentials compared to pork and chicken production, and that all the systems analyzed had much lower impacts than beef production for every impact category. For all of the systems analyzed, the majority of the impact came from stages of direct agriculture, whether animal protein or animal feed production.

The major consumptive water use in all of the terrestrial animal production systems was that associated with animal feed production, and is even further exacerbated by the higher FCRs, lower dressout percentages, and higher use of agriculturally based feed ingredients for terrestrial animal production. Since these terrestrial production systems have developed over long periods of time, it is likely that they currently produce at a maximum efficiency of resource use, and future improvements of that efficiency will be slight.

The results of the environmental impact assessment for global warming potential show that aquaculture production systems generally have a lower impact than terrestrial systems, and systems analyzed had a much lower impact than beef production. This is largely due to the enteric production of methane in the guts of cattle. The diminished global warming potential of aquaculture production compared to chicken and pork production is primarily due to a more efficient feed conversion ratio, as well as a diminished use of fossil fuel energy on-farm, primarily used in the terrestrial systems for heating production houses. Among the aquaculture systems, the majority of the global warming potential comes from emissions associated with feed production. For salmon and trout production, the emissions associated with the wild capture and rendering of fishmeal play the most major role in this impact, whereas for tilapia and catfish production it is the emissions associated with the production of agricultural crops for use as feed ingredients, especially soy. Among the other stages of production, on-farm emissions played a significant role in the global warming potential of tilapia production, and this can be explained by the relatively higher use of energy on-farm for the movement and filtration of water for re-use. This portion of the impact, however, was not as high as that associated with transportation throughout the production cycle, which is primarily due to the distances between sites of feed ingredient production, feed milling locations, and sites of fish production, and was significant for all aquaculture systems except for trout production, which is generally located close to all feed ingredient sources except for fishmeal and fish oil fisheries. Transportation also played an increased role in the global warming potential of salmon production because of the travel to and from off-shore net-pens for daily and weekly maintenance, which could be considered a part of on-farm operations, as well as the shipping of finished products from major production areas, namely Chile, Northern Europe, and the Northeastern U.S. Transportation plays a significant role in catfish production because of its relative distance to sources of feed ingredients produced in the Midwestern U.S. and the live transportation of finished fish to processing plants nearby.

The results of the analysis for eutrophication impact potential indicate that, with the exception of beef production, all other systems are somewhat similar in their impact. In salmon, trout, and beef production, which are more exposed to adjacent natural environments, the majority of this impact is associated with on-farm operations, especially effluents arising from animal waste production. This impact can be managed to a degree by using strategies from best management practices. For example, in flow-through Trout production, settling ponds are used to remove the majority of biochemical oxygen demand (BOD) and settleable solids before water is returned to natural systems. This is the primary reason EIP is lower for trout production than for salmon. Mechanical and biological filtration can also be used to remove suspended solids and nutrients, and sterilization techniques can be used, such as ozonation and UV radiation to kill harmful loads of pathogens. In Salmon culture, cage systems can be integrated with the production of economically viable seaweeds and algae, more efficient feeding techniques can be employed, areas can be laid fallow for periods of time to allow for ecological recovery, and feeds can be developed with higher protein digestibility and lower phosphorus content.

For the remaining systems of production, the majority of the EIP comes from emissions associated with feed production, especially agricultural products. As shown in the results of the LCA of aquaculture feeds in Appendix B, soybean meal has the highest associated eutrophication impact potential, and fishmeal has the lowest. All other feed ingredients are also significantly lower than that of soybean meal.

The results of the global sensitivity analysis show that the most important factors in the consumptive water use of aquaculture systems were those associated with the production of feed ingredients and the percent inclusion of different feed ingredients in diets for fish. These factors were also highly interactive, which may cause some uncertainty in model results but can also be explained by of the role feed ingredients can play as substitutes for one another. The most valuable information gained from the global sensitivity analysis is a more clear understanding that the choice of feed ingredients for aquaculture diets is significantly more important than other stages in fish production, direct water use on aquaculture farms. Currently the aquaculture industry is moving further and further away from fishmeal and fish oil as feed ingredients because of the high economic cost associated with these ingredients because they are currently harvested at a maximum while aquaculture continues to expand rapidly. As the industry turns to crop producers for proteinaceous feed ingredients, the consumptive water use of the aquaculture industry will certainly rise.

From the sensitivity analysis of global warming potential associated with aquaculture production, it is shown that choice of feed ingredients plays a major role in the impact on global warming. As shown in the life cycle assessment of aquaculture feeds in Appendix B soybean production has the highest global warming potential of all feed ingredients analyzed, followed closely by fisheries products. This is significant because as the aquaculture industry moves further away from the use of fisheries products as feed ingredients, they use an increasing amount of soybean meal, which increases this impact. Other agricultural crops analyzed for this impact had significantly lower global warming potentials, and, at least in regards to this impact, are better ingredient choices for fish production.

As the fishmeal fishery continues to be harvested at a maximum, constant tonnage, and as aquaculture continues its rapid growth, the industry continues to move further away from fishmeal as a protein source and further toward agriculturally produced alternatives, especially soybean meal. Because of the state of the world’s fisheries, this is typically seen as an improvement to overall environmental impact of aquaculture. The results of this study show, however, that as soybean meal replaces fishmeal in aquaculture diets, the consumptive water use, global warming potential, and eutrophication impact potential of aquaculture systems increases. This is both due to water use and emissions associated with crop production as well as a lower digestibility of plant products than fisheries products. While the effects of global warming potential should be diminished if non-soy agricultural crops replace fisheries products in fish diets, it has also been shown in the literature that as this occurs, animal feed conversion efficiency decreases. The result is an increased use of feed per kg of product. What follows is a need for a concerted effort among the entire innovation system, that is, industry, government, and academia, toward more efficient and sustainable sources of feed for fish production, because it is in this area of production that the most change can be affected for the environment.

While the three systems of terrestrial animal protein production analyzed in this study are highly mechanized and well developed from years of improvement through research, aquaculture is a relatively new and emerging agricultural operation. These aquaculture systems will continue to develop in response to economic and environmental constraints. As aquaculture research and development progresses, we can expect to see more efficient fish diets, breeding programs that will yield more efficient growth of fish, and engineering technologies that should lower environmental impact potentials across all systems and stages of aquaculture production. It is encouraging that although there are environmental impacts associated with fish production, the biology and physiology of the animals themselves provide a head start to more environmentally efficient means of animal protein production.

The use LCA for quantifying the environmental impacts of a production system is extremely useful, especially in the food production system, because it helps to quantify externalized impacts that are not well understood and typically do not affect a firm financially. As the breadth of agricultural LCA research increases, scientifically informed decision making should be used to help producers, consumers, scientists, and policy makers to decrease the environmental impacts of our animal food production system.

APPENDIX A
LIST OF ASSUMPTIONS

- It was assumed that reference diets found in scientific literature are representative of industry average diets for aquaculture systems.
- All biological management factors, such as animal feed conversion ratio (FCR), dressout, and stocking densities were taken from the literature and are assumed to be economically viable numbers.
- Some data for agriculture inputs for feed production are “top-down” numbers, meaning that statistical data from the national or regional level have been broken down to represent specific processes on-farm.
- Some data for aquaculture production came from “bottom-up” calculation, in which data from limited resources were used to represent regional or industry-wide levels.
- This study did not quantify data for the production of capital goods, such as buildings and machinery.
- Packaging was not included in these analyses for any life cycle stage.
- Chemicals used for cleaning capital resources were not included in these analyses.
- All water taken from “natural” sources and not returned directly is considered consumptive water use. The quality or renewability of the source is not considered.
- The first stages in the animal life cycle (fish larvae-juvenile, calf, chick, and piglet) are not included in this study. Aquaculture hatcheries are assumed to be similar in their resource use and impacts across systems of production and substantial data for young terrestrial animal production was not readily available.
- Any of the studied emissions leaving the farm boundaries are assumed to contribute to environmental impacts, i.e. this study assumes that “natural” areas begin at farm boundaries.
- Water use on farm for catfish production was taken from those counties that produce the large majority of catfish in the United States.
- Feed ingredients across production systems come from the same source, i.e. soybean meal for catfish and beef production all comes from the Midwestern U.S., fishmeal all comes from Peruvian and Gulf Coast waters.
- Water occupied by raceways and cages for trout and salmon production, respectively, is considered non-consumptive.

- Evaporation rates of raceways and settling ponds are not significantly different from natural sources of water for trout production.
- Clay lined settling ponds in trout production are considered to remain in the farming system boundary and therefore have no eutrophication potential.
- The distance between the water source for trout production and the place it is returned to the natural source is not affected by the loss of water to the farming system.
- Trout are assumed to have the same diet as salmon.
- Direct water use on-farm for trout and salmon production was primarily due to biological water harvested in fish biomass.
- Feed mills are assumed to be within 150 miles of aquaculture farms.
- Fish processing plants are assumed to be within 10 miles of aquaculture farms.
- Finished products found in retail markets are assumed to best represent environmental impact of each product.

APPENDIX B
LIFE CYCLE ASSESSMENT OF AQUACULTURE FEEDS

In order to accurately determine the consumptive water use required for fish production, an LCA of fish diets was conducted. The results of the LCA for each diet are depicted in Table 4-4 and Figures 4-11 through 4-22.

The results of the LCA of aquaculture diets reveals that the Salmonid diet (used for Salmon and Rainbow Trout production), has the lowest consumptive water use, 342.1 liters per kilogram of feed, compared to the Channel Catfish and Tilapia diets, which have a consumptive water use of 924.5 and 1018.2 liters per kilogram of feed, respectively. This can be attributed to its higher inclusion of fisheries products, which have a very low consumptive water use (0.02 liters/kg) compared to agricultural crops.

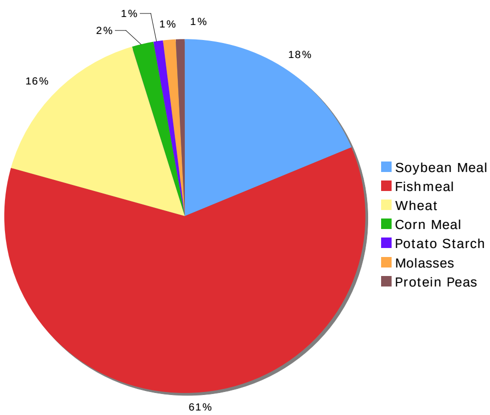
While the global warming potential associated with feeding in aquaculture was similar for each system, the feeds themselves differ in their impact. The results of the environmental assessment of aquaculture feeds show that tilapia feed has the lowest global warming impact, and produces 0.969 kg equivalents of CO2 for every kg of feed. Catfish was the next lowest, with a GWP of .988 kg equivalents of CO2 per kg of feed, and salmonid feed has the highest GWP, which is 1.173 kg equivalents of CO2 per kg of feed.

Among feed ingredients, soybean meal has a significantly greater eutrophication impact potential than all others. Because of this, the catfish diet has the largest EIP (12.11 mg-equivalents PO_4^{3-}/kg), mainly because of its high percent inclusion of soy. This is followed by the EIP of the tilapia diet (6.95 mg-equivalents PO_4^{3-}/kg), which has a high input of agricultural ingredients and a low input of fishmeal, which has the lowest EIP of all the ingredients. The salmonid diet had the lowest EIP (6.04 mg-equivalents

PO_4^{3-}/kg) because of its high use of fishmeal and diminished use of agricultural crops as feed ingredients.

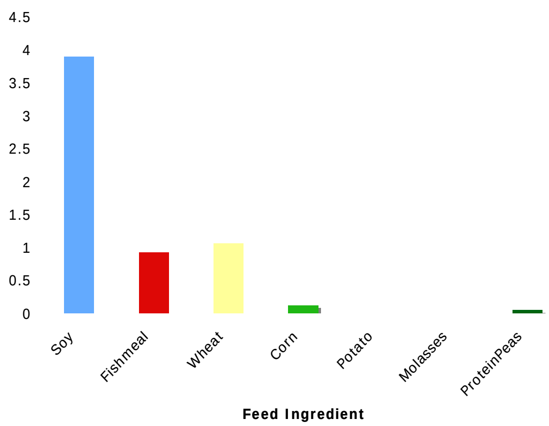
Consumptive water use, global warming potential and eutrophication impact potential of aquaculture feeds by ingredient.

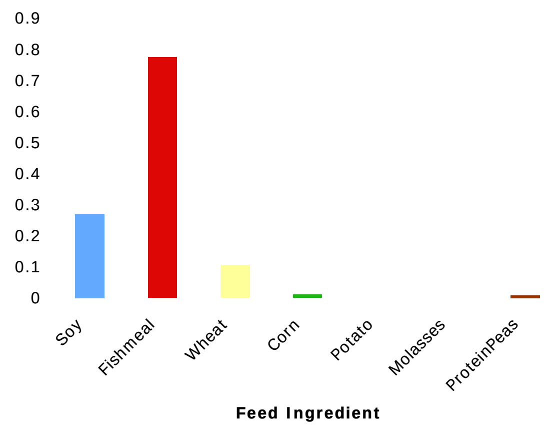
	Fishmeal (%)	Soybean Meal (%)	Canola (%)	Wheat Middling (%)	Corn Gluten (%)	Potato Starch (%)	Sunflower Meal (%)	Molasses (%)	Protein Peas (%)	**Total CWU (L/kg)**	**Total GWP (kg-equiv CO_2/kg)**	**Total EIP (mg-equiv PO_4^{3-}/kg)**
Salmonid	57	17.3		14.9	1.8	0.9		1.0	0.7	**342.1**	**1.17**	**6.04**
Catfish	2.4	36.5	11.5	17.0	32.6					**924.5**	**0.99**	**12.1**
Tilapia	18.8	11.5	29.7	17.9	13.1		2.3	1.1	5.6	**1018.2**	**0.97**	**6.95**



Proportion of ingredients used in the LCA of the Salmonid diet.

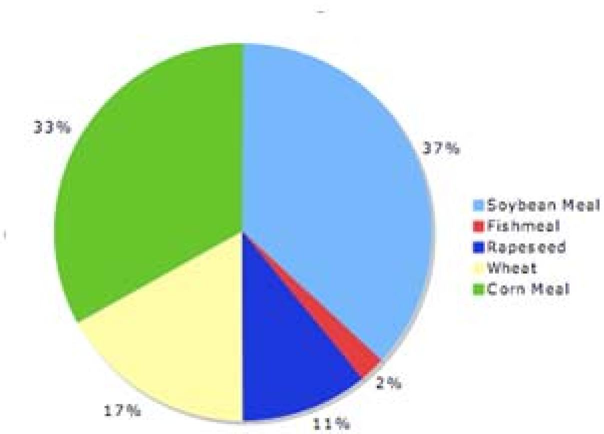
Consumptive water use of Salmonid feed by ingredient.



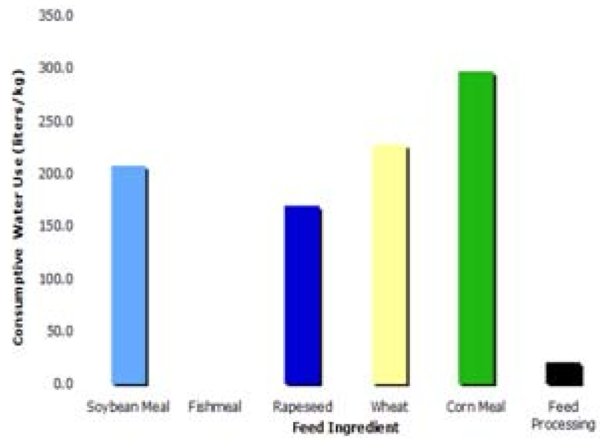


Eutrophication impact potential of Salmonid feed by ingredient.

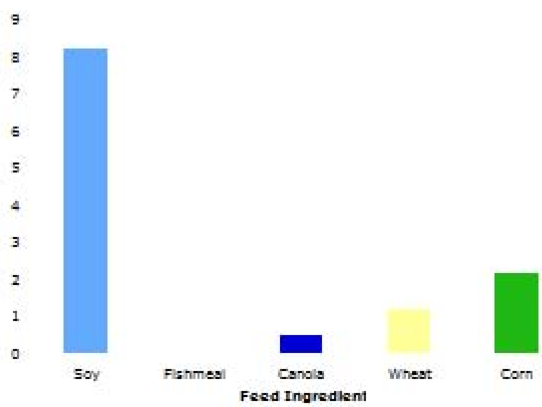
Global warming potential of Salmonid feed by ingredient.



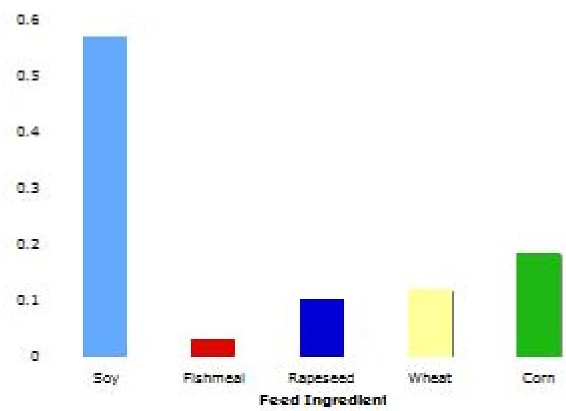
Proportion of ingredients used in the LCA of the catfish diet.



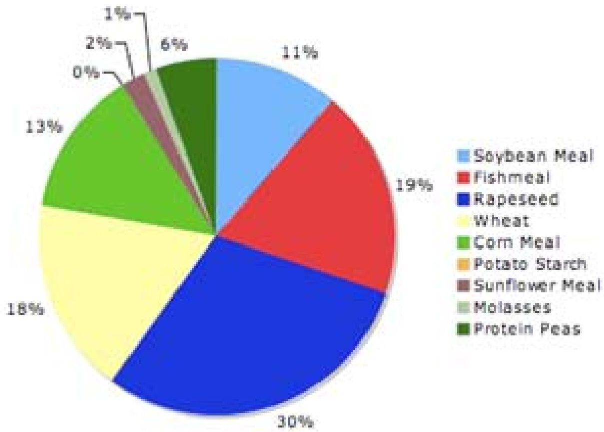
Consumptive water use of catfish feed by ingredient.

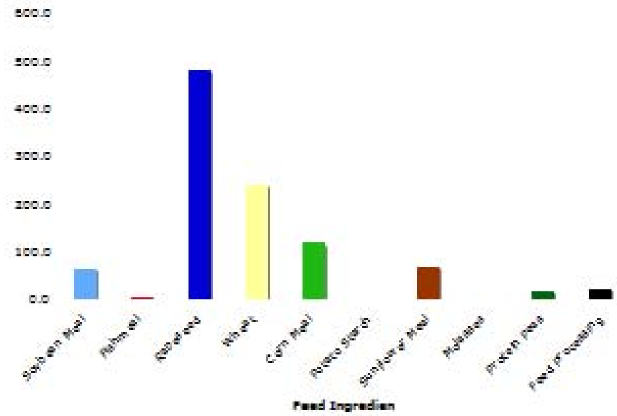


Eutrophication impact potential of catfish feed by ingredient.



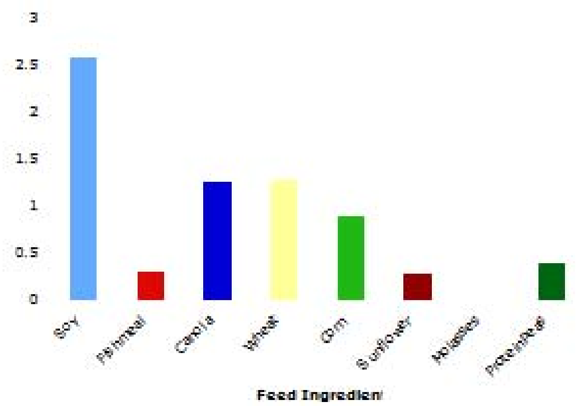
Global warming potential of catfish feed by ingredient.

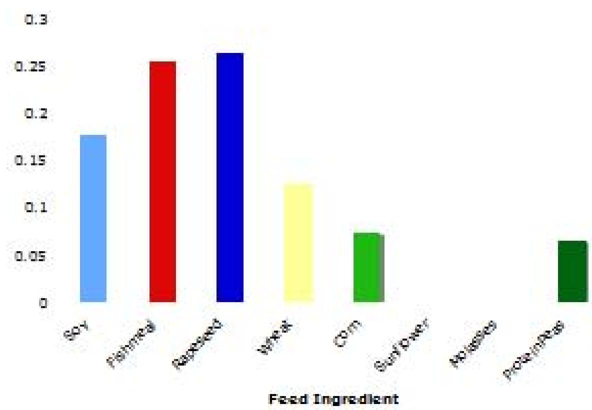




Proportion of ingredients used in the LCA of the tilapia diet.

Consumptive water use of tilapia feed by ingredient.





Eutrophiction impact potential of tilapia feed by ingredient.

Global warming potential of tilapia feed by ingredient.

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