The Fishprint of Aquaculture



Can the Blue Revolution be Sustainable?

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December, 2005

Generous support for this work was provided by the Packard Foundation



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I. Synopsis

Ocean fisheries are in deep trouble. Global fishery catches from marine ecosystems peaked in the mid 1980s and have been declining ever since despite increasing fishing effort (MEA 2005). A 2003 global assessment found that today's biomass of large, predatory fish is only about 10% of pre-industrial levels (Myers and Worm 2003). The mean trophic level of fish caught in large portions of world's oceans continues to decline (Loh and Wackernagel 2004). In 2004, the United Nations "State of the World's Fisheries" report found that "52 percent of the oceans' wild fish stocks are fully exploited." (FAO 2004).

In response to the decline of wild fisheries, there has been a dramatic increase in aquaculture — more commonly known as fish farming. Over 40% of all fish consumed is now derived from aquaculture (FAO 2003). While many view aquaculture as the blue equivalent to the Green Revolution in agriculture, the environmental effects of aquaculture are poorly understood just as the environmental effects of fertilizers, pesticides, and genetically engineered lines were poorly understood as the Green Revolution began over thirty years ago. For example, aquaculture is often invoked as a means to protect wild fish stocks despite the fact that wild fish stocks are themselves a significant input into many aquaculture systems.

One tool that can help policy makers and fish ranchers better understand the environmental impacts of aquaculture is the ecological fishprint. Like its terrestrial equivalent – the ecological footprint – the ecological fishprint is a tool for gauging whether or not our use of global fisheries is sustainable. As applied to aquaculture, ecological fishprinting compares the resources put into an aquaculture system versus the resources or fish production harvested from the system. It incorporates the inputs, including ecosystem area needed to produce fish and fish feed and oil fed to the fish, and the outputs, including amount of fish produced and area affected by waste production.

Fishprinting is a relatively modern accounting tool that can be used to help distinguish between sustainable and unsustainable aquaculture practices. While currently there is no standard methodology used for fishprinting, results from existing studies show that aquaculture systems targeting low trophic level species are much more sustainable than systems targeting higher trophic level species. For example, one methodology – spatial to weight fishprinting – has conclusively proven that salmon aquaculture, a resource intense practice, results in a huge net

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¹ While existing ecological footprint methods ostensibly address impacts on marine ecosystems, it is widely recognized that the methods fail to account for observed declines in fish stocks and other obvious signs of ecosystem degradation. As a result, many have called for an alternative methodology for marine ecosystems. The fishprint is being developed to meet this need.

loss of fish protein on the market and in the sea. Even when applying environmentally friendly technologies, other spatial to spatial fishprint methodologies have proven that extensive, low trophic level species are more sustainable.

As fishprinting science matures, it can be used to inform the policy debate over major expansion of aquaculture systems in the United States and abroad. As a comprehensive accounting system that tracks the energy and natural resource requirements of different aquaculture systems, fishprinting can play a vital role in determining which species should be cultured and which should not in order to sustain the blue revolution and alleviate the escalating pressure on wild fisheries.

The remainder of this report is organized as follows. Section II documents the recent explosion in the scope and scale of global aquaculture operations. In Section III, a typology of aquaculture systems is discussed along with a preliminary sustainability assessment. Section IV reviews the environmental impacts of different aquaculture systems. Section V describes three major fishprinting methods that have been applied to aquaculture, and Section VI discusses future refinements to these methods. Policy implications are set forth in Section VIII. The report ends with conclusions in Section VIII.

II. The Aquaculture Explosion

Approximately 950 million people in the world, mainly the underprivileged, depend on fishery products as an important part of their diet and their primary source of protein (Costa-Pierce 2003). This means that for those 950 million people a threat to the world's fisheries means a direct threat to their livelihoods.

In 2004, the United Nations "State of the World's Fisheries" report stated that, "52 percent of the oceans' wild fish stocks are fully exploited. Of the rest, 23 percent are lightly or moderately exploited and still offer some scope for further fisheries expansion, 16 percent are overexploited, 7 percent are depleted, and 1 percent are recovering from depletion, meaning they have no room for further expansion" (FAO 2004). This means that well over half of all fisheries are currently being fished at unsustainable rates. Some would consider this large number a direct threat to the livelihoods of those individuals who depend on fish protein as part of their diet.

Many look to aquaculture as a means to decrease pressure on wild fisheries and to combat the loss of protein. Aquaculture is the deliberate husbandry of aquatic organisms for human use, including mollusks, crustaceans, seaweed, and other aquatic life. The Food and Agriculture Organization (FAO) reports that, "Global aquaculture production has grown at 11 percent a year over the past decade and is projected to continue increasing." Farmed fish account for about 40% of fish directly consumed, and in 2003, 54.7 million tons of fish were produced via aquaculture at a value of 67 billion US dollars up from 60 billion dollars in 2002 (FAO 2003).

Aquaculture is an age-old tradition in many cultures around the world. The history of aquaculture dates back to fifth century ancient Chinese manuscripts, and was alluded to in Egyptian hieroglyphics. These cultural practices included harvesting young immature fish, often carp, and growing them in environmentally friendly polycultures that did not require additional outside inputs. Yet today, the field of aquaculture is radically different. While some fisheries still maintain the ancient Chinese practices, advanced knowledge of fish life cycles and increased economic pressure has led to highly unsustainable aquaculture practices, which include farming

some of the largest fish found in the sea. These unsustainable farms not only impact the surrounding environment, but the input of fish protein for production often exceeds the fish protein output. As fisheries around the world continue to be exploited and fish protein continues to decline, it is essential to understand the impacts of the various forms and types of aquaculture on both nature and society.

III. Aquaculture Systems and Sustainability Evaluation

Aquaculture systems fall into three major categories: intensive, semi-intensive and extensive. Table 1 summarizes important distinctions between these systems, and ranks each in accordance with its degree of sustainability as suggested by various fishprinting methods discussed in later sections of this report.

Table 1: Overview of Types of Aquaculture						
Type of Practice	Sustainability Level	Major Marketplace	Economic Value	Where Grown	Examples Carp;	Protein Return on Investment*
Extensive	Most sustainable	Locally sold	Low Value	In-shore ecosystems	tilapia; mollusks	11-100%
					Often extensive species	
Semi- Intensive	Somewhat sustainable	Mainly locally sold Sold in	Medium Value	In-shore ecosystems In-shore and off-shore	that are fed fish feed.	2-10%
Intensive	Not sustainable	global markets	HIGH value	marine environments	Salmon; tuna; cod	1.4-3%

^{*} Estimated numbers (Tyedmers 2005)

Extensive techniques reflect the more traditional aquaculture practices, which are the most sustainable. They require little to no outside inputs, but yield less per unit area. These species are low level trophic species, primary producers and herbivores; they transfer energy from net primary photosynthesis fairly efficiently resulting in a higher productivity output per unit input. Research completed on both commercial and cultured fisheries reported that an extensive carp culture is the most efficient source of fish protein, often returning 100% of edible protein on energy invested (Tyedmers 2005). Globally, extensive aquaculture accounts for nearly 25% of all finfish culture.

Current trends in extensive aquaculture systems include carp in Asia, especially China, Africa and Central America, and tilapia in China, Central and South America; yet these systems are also the most vulnerable to semi-intensive practices, and when farmed at high densities cumulative impacts on the environment could occur.

Semi-intensive techniques employ a combination of elements from both extensive and intensive practices. They stem from extensive practices and are normally a result of increased inputs, including the addition of supplemental feeds, antibiotics, mechanized water circulation, treatment or aeration of water systems, fertilization or increased direct labor inputs.

The premier example of an extensive system converted to a semi-intensive system is the polyculture systems in China. In the late 1980s these extensive systems accounted for over half of the world's aquaculture production. But when the Chinese government switched to a market-driven economy, a shift occurred to culture only one or two species with a high market demand and value.

This commercialization of aquaculture in China and around the world has triggered people to feed lower trophic level species fish meal and fish oil. Due to the nature of food webs and conversion efficiencies, as a fish moves up the food web the fraction between protein consumed per protein produced decreases. This is measured through energy conversion estimates, which range from low trophic level producers and primary consumers at roughly 10% to higher trophic level conversion factors estimated to be as little as 4%. Thus, feeding former primary, or herbivore, species fish meal increases their overall trophic level and moves the species up the food web, resulting in a semi-intensive fishery. Overall energy return for semi-intensive systems is now estimated to be 5-20%, and today, about 20% of carp and 35% of tilapia are fed some sort of modern compound feed (Naylor 2000a).

Despite the varying impacts of extensive and semi-intensive methods, both still produce low value species for subsistence and local market consumption. They are both most likely located in in-shore habitats and are mainly produced on family and cooperative farms in developing countries.

On the other hand, intensive aquaculture techniques are used to commercially produce larger marine finfish. These fish are medium and high value commodities sold on regional and global markets. They also require a large amount of fish meal, oil, and energy because they are higher trophic level species or omnivores and carnivores.

Intensive practices are emerging most rapidly in developed countries and often without the development of necessary regulations. The most common intensive fisheries include salmon (Atlantic, Chinook), shrimp, moi, tuna (bluefin, albacore), eel, amberjack, tilapia (Nile, Red and various hybrids), and snapper (Red, mutton). To get a better understanding of the intensity of these fisheries, a study in 2000 concluded that 5.16 kg of wild fish are processed into fish meal in order to produce one kilogram of marine finfish (Naylor 2000a). It is estimated that 1.9 kg of wild fish input is needed for every kilogram of fish raised on compound feeds (Naylor 2000a). A similar study estimated an edible protein return on investment for intensive systems at around 1.4-3% (Tyedmers 2005). These low energy return numbers should start to raise red flags in the aquaculture industry, but instead production of intense species is rapidly increasing.

Aquaculture systems are also distinguished by water setting and number of species. Water settings include freshwater, brackish water, in-shore marine, and off-shore marine aquaculture. Freshwater fisheries include carp, catfish, and other freshwater finfish, usually grown in ponds. They are largely extensive and are practiced widely in China and other parts of East Asia. Brackish water systems vary in salinity levels due to seasonal fluctuations and marine water influxes. Often in enclosed coastal and inland water bodies along rivers and estuaries, tiger shrimp is one of the largest brackish water fisheries.

Marine aquaculture, also known as mariculture, water systems in-shore and off-shore maintain a constant high quantity salinity level. In-shore mariculture systems include clams, oysters and other mollusks, which are wild-caught or hatchery-reared seed grown on the sea floor or on

suspended nets, ropes, or other structures (Naylor 2001). Off-shore mariculture often refers to large intensive fisheries in off-shore fish pens.

Depending upon the number of species cultured in a given area, an aquaculture system can be described as a monoculture, integrated culture or polyculture system. Monoculture is the farming of one species, and is most likely intensive because it employs high stocking densities and large energy input. A prime example is shrimp and salmon raised in British Colombia. Raising these species requires large pens, huge fish meal and fish oil inputs and a large amount of waste discharged directly into the environment.

Integrated culture involves the use of multiple systems and organisms grown together to maximize production and/or alleviate wastes. These intensive integrated systems are fairly recent developments in the aquaculture industry and are based on traditional extensive polyculture systems. In most cases these integrated systems are associated with the use of bivalves, seaweeds, or mangroves as a method of bio-filtration to mediate the effects of effluent from intensive shrimp and salmon farms (Neori 2004). An integrated example includes shellfish, seaweed, and gourami in rice paddies (Nunes 2003). The use of an integrated culture system is one technology used today to decrease the environmental impacts that are discussed below.

Polyculture is the farming of several species of aquatic organisms, often including both plants and animals within the same area. These traditional and customarily sustainable freshwater practices are prevalent in developing countries. The most abundant example is the carp culture in China. "In traditional Chinese pond polyculture, the silver carp feeds on phytoplankton in the water column, the bighead (carp) consumes zooplankton, the grass carp eats supplemental vegetation, the black carp eats mollusks, and the mud carp and common carp eat benthos/detritus," (Ye 2001).

IV. Aquaculture Environmental Impacts

Due to the significant growth rate of aquaculture in the United States (U.S.) and abroad, an understanding of the potential impacts of aquaculture on the environment is essential. Table 2 outlines six of the major environmental impacts of aquaculture and assesses the relevance of each impact to the three major types of aquaculture systems.

Table 2: Environmental Impacts by Aquaculture Types						
Type of Practice Extensive	Modifies Habitat Moderate	Use Wild Fish for Feed N/A	Fed Fish Meal and Fish oil N/A	Increases Influx of Wastes in Nearby Areas Low	Threatens wild populations Low	Potential Pathogen Invasion in Surrounding Areas Moderate
Semi- Intensive Intensive	Moderate Moderate	N/A Moderate	Moderate High	Moderate High	Moderate High	Moderate High

Habitat modification via wetland destruction of mangroves and salt marshes is arguably the largest global impact of extensive and semi-intensive fish farming. Due to a lack of regulations, semi-intensive shrimp farming is a prime example of a formerly extensive fishery that has

destroyed mangrove forests in developing countries due to an increase in demand. Table 3 documents the amount of mangrove area lost to aquaculture in seven developing countries.

Table 3: Amount of mangrove loss per country due to shrimp aquaculture (Thornton 2003)				
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Country	Area Lost (ha)	Percent of Total Mangrove Habitat	Dates	
Bangladesh	6,527	87%	1976-1988	
Thailand	150,925	50-65%	1975-1997	
Philippines	139,500	~50%	1951-1988	
Indonesia	260,000		1960-1990	
Vietnam		80%	1952-2002	
Ecuador		50%	1982-2002	
Honduras	2,000-4,000 per year	33%		

The impacts of wetland loss are an exposure of coastal areas to erosion, flooding, increased storm damage, altered natural drainage patterns, increased salt intrusion, and removed critical habitats for aquatic and terrestrial species (Thornton 2003). These impacts were clearly illustrated during the 2004 tsunami that ravaged South East Asia:

"Early observations indicate that healthy mangroves seem to have been less affected than disturbed or degraded mangrove areas. Furthermore, many coastal communities have claimed that healthy mangroves have reduced the impacts of the tsunami and protected their lives or property."²

Moreover, the intensity of aquaculture ponds for shrimp or other species often leads to abandonment of the land after 5-10 years. The local community then suffers the loss of the land's economic value and the majority of their coastal ecosystem services – losses that easily exceed the benefits attributable to shrimp farming. For example, one study found that total economic value of an intact mangrove in Thailand exceeds that of shrimp farming by 70% (Blamford 2002).

The largest environmental impact of intensive aquaculture systems is the practice of feeding typically low-trophic level herbivore fish, fish meal and fish oil; thus increasing the trophic level of farmed fish. Currently, fish inputs can account for more than 40% of total fish feed inputs. The result is an increase in fish meal produced annually for aquaculture from less than 10% in 1980 to over 40% today. Thus, wild fisheries such as anchovies, sardines, herring, and menhaden continue to be exploited in order to sustain the growth of aquaculture.

Another environmental impact of aquaculture is the loss of wild seed stock. Many aquaculture operations do not reproduce their own stock; they must harvest juvenile fish, commonly referred to as seedstock, in order to maintain their farms from year to year. Some argue that the fish grow larger and faster in the farm environment (especially if they are fed a large percentage of fishfeed), yet that does not counter the problem of the loss of juveniles within the wild food web.

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² The World Conservation Union. 2005. Early Observations Of Tsunami Effects On Wetlands And Water Resources. *Statement From The Iucn Wetlands & Water Resources Programme*. Gland, Switzerland, 12 January. Web-Site Last Viewed On September 23, 2005: http://www.lucn.Org/Info_And_News/Press/Water-Wetlands-Statement.Pdf

All types of aquaculture allow producers to externalize costs to the surrounding environment by discharging untreated effluent water free of charge and without regulation. Any time fish are grown in a small area waste is released into the environment, and as fish ponds grow in size and become denser, the impacts compound. It is estimated that the Nordic salmon farming industry discharges quantities of nitrogen and phosphorous equivalent to the amounts in untreated sewage from a population of 3.9 and 1.7 million people, respectively (Folke 1994). Yet the industry claims that due to the nature of offshore fisheries, these huge releases of nutrients are dissipated into the surrounding environment, resulting in a reduced impact. Also, the fish meal that is not consumed by the fish in ponds and pens directly adds to the pollution of the surrounding areas. One way to offset these impacts is by installing on-site waste treatment facilities (Costa-Pierce 2003), which are being installed in areas where farms are making an effort to decrease environmental impacts.

The introduction of exotics into the environment is a huge impact for both terrestrial and ocean habitats. A prime example of the introduction of exotic species due to aquaculture is Atlantic salmon in the Pacific Ocean. Atlantic salmon has been documented in over 80 rivers in British Columbia alone (Volpe 2000), and currently, escaped farm salmon dominate the number of wild Atlantic salmon in many European rivers. By introducing exotic species to environments around the world, ecosystems and habitats have been and will continue to be altered and degraded. In fact, the United Nations has declared that the introduction of exotic - or alien - species is the greatest threat to global biodiversity after habitat loss.³

Outbreaks of pathogens are also a major risk factor in commercial aquaculture with millions of dollars lost annually (Ye 2002). Pathogens can not only wipe out a cultured fishery but they also can infect nearby wild species, which can result in a collapse of these wild fisheries. The best way to combat these two impacts would be to establish pen/cage structure regulations and to reduce the amount of pens/cages in open water. In some areas around the world, including Scottish Salmon farming, farms are installing double layered nets to combat this problem. Figure 1 captures most of the environmental impacts of aquaculture discussed in this section.

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³ David Suzuki Foundation. *Open Net Fish Farming*. Website viewed September 23, 2005: http://www.davidsuzuki.org/Oceans/Aquaculture/Salmon/

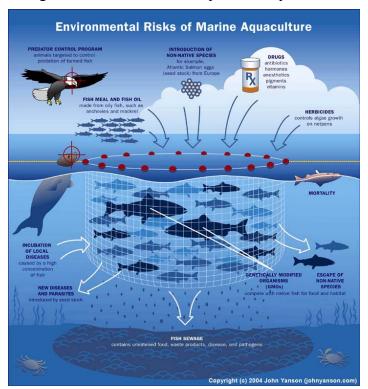


Figure 1: Environmental Impacts of Aquaculture

V. Aquaculture Fishprinting Methods

While the environmental impacts of various aquaculture systems have been relatively well documented, few studies have quantified the magnitude of such impacts. Fishprinting – a marine equivalent of the ecological footprint – is one way to generate such quantitative information.

An ecological footprint is a tool used to understand society's utilization of natural resources around the world. At the heart of footprinting is a systematic way to account for resources and the Earth's ecological limits, related as inputs/supply and outputs/demand. In order to compare these resources, each input and output is calibrated into comparable land areas equated to the amount of energy consumed for production.

The footprint is a holistic ecosystem-based indicator of sustainability. The goal of the footprint is to interpret the impact of human consumption and waste discharge on the Earth's natural resources. Fishprinting is a unique form of footprinting specifically designed for evaluating effects of fishery practices, such as aquaculture. There are three major fishprinting methods currently in use: (1) spatial ecosystem fishprinting, which estimates the spatial ecosystem support area that is needed for processing inputs and outputs in a given area; (2) spatial to weight fishprinting, which calculates the spatial ecosystem support area necessary to produce a quantity of fish by weight, and (3) weight to spatial area fishprinting, which converts the quantity of fish produced in a given area by weight into an area needed to assimilate waste and account for environmental service demands. The next three subsections detail each of the methodologies used, and the pros and cons of each methodology.

Spatial Ecosystem Fishprinting

The foundation of aquaculture fishprinting is rooted in quantifying the space needed to provide for and absorb the various resources needed to generate a given species in a given area. The best way to understand this methodology is to review the fishprint conducted by Larsson et al. In 1994, Larsson estimated the support area needed of six different systems in order to produce food inputs, nursery areas, and clean water to a semi-intensive shrimp farm in Colombia. Table 4 summarizes his results.

Table 4: Ecosystem appropriated for each square meter of semi-intensive shrimp farming in the				
Bay of Baracoas, Colombia (Larsson et al. 1994)				

Ecosystem Area	Aquaculture use	Area (m²/m²)
Mangrove Post larval Nursery Area	Area needed to produce sufficient amounts of shrimp fry via seed-reared hatchery raised or wild seed-stock.	9.6-160
CO ₂ -Sequestering Forest	Area needed to sequester fossil fuel burning on site.	0.8-2.5
Agricultural Ecosystems	Area required to produce crop based inputs to fish feed.	0.5
Marine Ecosystem Support Area	Sea surface area needed to produce the fish used in fish feed pellets. Area necessary to provide detritus for consumption	14.5
Mangrove Detritus	(assumed 30% of shrimp diet).	4.2
Mangrove Lagoon Area Needed for Clean Water	Area needed to provide clean water habit for shrimp production.	7.2 36.8 -
Total		188.9

Spatial methodology was also applied to fishprints conducted on two extensive systems, mussel rearing in Sweden and tilapia pond farming in Lake Kariba, Zimbabwe. The fishprint of mussels, conducted in the late 1980s, found that the bulk of energy invested was from three areas: harvesting and processing, the land area utilized, and the human labor inputs. While usually not considered significant in other culture systems, processing is the largest input for mollusks, crustaceans, and other bivalves that require cleaning. Seaweed also may require processing into sheets, noodles, or other various forms before it can be consumed, yet processing is also often overlooked or underestimated when quantifying fishprints. Other spatial to spatial fishprints include shrimp farming in Colombia, tilapia cage farming in Zimbabwe and salmon cage farming in Sweden.

Used mainly for extensive and semi-intensive systems, the benefit of this methodology is that it calculates the ecosystem area needed to provide oxygen and fixate waste, including the additional nitrogen and phosphorous released into the surrounding environment. Yet this method has been criticized for not effectively accounting for natural resources, neglecting other inputs, and questionable assumptions based on high conversion efficiencies.

Spatial to Weight Fishprinting

Used to calculate the area needed to produce a ton of fish, this methodology was most recently adopted in an in-depth study on salmon cage farming in British Columbia, Canada. It was specifically adopted in order to combat the assumptions made in spatial ecosystem fishprints, including assumptions made on the source of feed and the type of culture. The resulting fishprint captured a significant number of inputs including those listed in Table 5 below (Tyedmers 2000).

Table 5: Inputs for Salmon Area to Weight Fishprint					
Biological Inputs:	Prey or fish for fish meal and oil for formulated salmon feeds, based on trophic levels of processed fish.				
	Agriculture crop based inputs used for fish feed, based on the five-year average Canadian yield of grain corn.				
	Livestock by-products used for fish meal, based on the wet biomass of chicken raised on a diet of corn.				
Labor Inputs:	Ecosystem support area associated with labor inputs or person-days both for salmon farming and the harvesting of fish for fish feed. Based on the average Canadian's annual food consumption levels in 1993.				
Fossil Fuel Inputs:	Estimated forest area required to sequester the CO_2 equivalent to the amount of greenhouse gases produced when operating the salmon farms and when harvesting fish for fish feed.				
Electricity Inputs:	Includes the electricity necessary to run the salmon farms and to operate the fish meal boats. Specific to Canada, electricity is 90% hydroelectricity and 10% natural gas.				
	Inorganic and synthetic organic material inputs for materials necessary to produce one ton of farmed salmon, and materials necessary to harvest wild fish for fish feed, including aluminum, glass, steel, concrete, plastics, etc.				

Overall, this methodology has a serious advantage to the user because the FAO reports data in accordance to the quantity of fish sold per year. It allows a user to directly quantify the footprint of a species based on the amount recorded by the FAO. For example, Tyedmers report calculated the footprint of the four salmon species farmed in British Columbia (see Chart 1). When calculating the average impact of salmon species based upon Tyedmers numbers, the average impact on the environment of one ton of salmon is 12.25 hectares. If applied liberally, this means that in 2003 the 1.8 million tons of salmon cultured around the world roughly affected over 22 million hectares of land.

In addition, this methodology also clearly revealed that the majority of the ecosystem support and energy inputs into fish feed were due to inputs from the marine environment. This means that the fish supply used to create fish for fish meal alters the environment more than any other factor included in fishprinting; in fact, estimates were roughly 90% of the overall fish feed footprint. Best estimates for other forms of intensive finfish aquaculture provide similar results.

Table 6: Energy Inputs Necessary to Provide a Ton of Salmon Feed (Tye	edmers 2000)
Marine ecosystem necessary to produce fish-derived components Agricultural ecosystem necessary to produce livestock byproduct meal-derived	5.6 ha
components	0.456 ha
Agricultural ecosystem area necessary to produce crop-derived components	0.127 ha

Weight to Spatial Area Fishprinting

Used by S.W. Bunting to convert previously calculated area to area fishprints, this method is believed to be more appropriate in order to better understand individual consumption patterns. Bunting states that area to area fishprinting, "Fails to provide a comparative measure regarding the efficiency of natural resource use under different management strategies and between production systems," (Bunting 2001).

His methodology relates the amount of a given species produced each year in relation to the waste production and environmental services used for species with area to area fishprints. While Bunting's approach does reassess the spatial fishprinting, it still fails to do a comprehensive analysis of the resources used in providing fish meal and fish oil to semi-intensive and intensive systems.

Fishprinting in Practice

Irrespective of the methodology, it is important to note that all of these reports imply that the cultivation of higher trophic level species requires more resources in than out. Essentially this means that culture species that are omnivores or carnivores are a drain on the earth's ecosystems, or put more simply, they eat more protein than they produce.

Table 7 outlines the various fishprints that have been conducted on different species and systems.

	Table 7: Review of Current Aquaculture Fishprinting Estimates						
Type of Culture	Species	Type of System	Location	Resource Production Footprint	Unit	Waste Assimilation Footprint	Unit
Extensive	Mussel Rearing		Sweden	20	ha/ha		
Semi-	Tilapia Shrimp	Pond Farming Pond Farming	Zimbabwe Asia	0	ha/ha	0 2.0-22	ha/ha ha/ha
Intensive	Salmon Shrimp	Tank System Pond Farming	Chile Colombia	34-187	ha/ha	115-275	m ² /m ²
	Tilapia culture*	Cage Farming		0.7	kg/m² year	3.2402	g/m² year
	Shrimp Culture^	Pond Farming		0.1	kg/m² year	0.0843	g/m² year
Intensive	Salmon #	Cage Farming	Canada	12.25 40.000-	ha/ ton		
		Harvested, Ranched or		50,000	ha/ha		
	Salmon =	Farmed Cages	Norway	0.001	km²/kg		

Tila _l	oia Cage Farming	Zimbabwe	10,000	ha/ha	115-275	ha/ha
Tila _l cultu	-		198.7	kg/m²y ear	291.73825	g/m² year
Shri	•			kg/m²y	0.0040	g/m ²
Cult	ure^ Pond Farming		1.4	ear	0.2243	year

Sources: Kautsky et al. 1998 and #Tyedmers 2000. * Berg et al. 1996. ^Robertson and Phillips 1995.

This table along with the synopsis on methodologies above provides quantitative information about the true environmental impacts of aquaculture and can be used to understand the differences between sustainable and unsustainable aquaculture systems. This chart demonstrates that as the intensity increases so does a fish's footprint on the world. This provides scientific evidence that as the intensive nature of aquaculture continues to increase, the amount of protein available in the world either in the marketplace or in the marine ecosystem is decreasing rapidly.

The Limitations of Fishprinting

While fishprinting is the best tool available to evaluate the sustainability of aquaculture operations, it is important to note the environmental impacts that cannot be quantified within the fishprint framework. These impacts are indirect and hard to truly quantify. It is relatively safe to say that if these impacts were included, the fishprint would increase. These impacts are summarized by Table 8.

Table 8: Major Environmental	Table 8: Major Environmental Impacts that Aren't Included in Fishprinting					
Impacts	Causes					
Displacement of Wild Populations	via escaping of farmed salmon from net pens					
Genetic Impacts	via breeding with wild fish and introducing farm- adapted genetic make-up					
Parasites and Diseases	via pathogens in net pens that can transfer to the wild					
Effects on other Wildlife	via net entanglement and underwater acoustics					
Aquaculture Wastes	via uneaten fish feed resulting in dead zones under net pens					
Chemicals and Antibiotics	via the use of antibiotics due to sea lice and lack of governmental control. Use of pesticides could cause bacteria to grow to resist the antibiotics forcing genetic mutation					
An increase of omega-6 fatty acid, PCBs, dioxins, DDT, chlordane and mercury in fish markets	a result of the high fat levels of farmed fish, and the bioaccumulation of dioxins, PCBs and PAHs of high tropic level species in general					

In addition, no fishprinting standards have been set to date, nor has a commonly accepted methodology emerged. This is mainly due to the nascent nature of fishprinting.

It is also important to note that fishprinting numbers are often regionalized because fishprints often rely on numbers specific to a given area; for example, the cost and energy of labor often varies per county. Again, this is due to the limited number of fishprints that have been recorded.

If a common standard is accepted and more effort is put into understanding the fishprint of aquaculture, these limitations can be overcome.

VI. Future Refinements

Based on the data that is available, more research needs to be completed before the entire fishprint of aquaculture is calculated and understood. Currently, research is being done to estimate the trophic level of cultured species. This data would provide an essential piece of information if a fishprint of aquaculture is to be completed. For example, if the trophic level of cultured species were estimated, general fishprints on trophic level ranges could be conducted and applied to species within the same trophic level range. Essentially, if amberjack and snapper were estimated at a cultured trophic level of about four, then the fishprint of salmon, also estimated at a culture level of four, could be used to establish their fishprint. This application would create a very rudimentary fishprint of aquaculture, and would require fishprints to be conducted for all trophic levels.

This basic calculation also requires fishprinting to adopt a common quantifiable measurement. A common methodology and measurement would greatly increase the accountability and science of aquaculture. After reviewing the basic methodologies, the most applicable and inclusive fishprint method seems to be the spatial to weight fishprint employed in Tyedmers salmon study; it is the recommendation of this report to adopt spatial to weight methodology in order to best conceptualize the entire aquaculture fishprint.

More information is also needed on the industrial and non-biological inputs of aquaculture. Without this information a comprehensive fishprint can not be competed. Currently, no data are available that significantly map out the energy needed to process and distribute cultured species. For example, the processing required for some mollusks could be substantial, which could greatly alter the footprint of those fisheries.

Most significantly, a better understanding of the implications of fish meal and fish oil in a culture system needs to occur within the aquaculture community. Studies show fish meal and oil generate the greatest environmental impact due to the high consumption of protein and the nutrient waste to the environment, yet the sense of urgency to combat this problem within the industry has yet to occur. Some aquaculture scientists believe that soy protein could easily replace the majority of fish used in fish meal; studies show that Salmonids, one of the most sensitive species, could tolerate up to 30% of soybean meal in their diet, while other species such as bass could tolerate up to 50%. These changes will not result in sustainable fisheries, but they could help reduce the impact of aquaculture, especially for high trophic level species, as the popularity grows. Another benefit of soybean protein is the stability of the market; the price of fish for fish meal is known to fluctuate due to available supply. As seen in the last El Nino event in 1997-98, a dramatic increase in the market price occurred due to a massive decrease in anchovy supply. One last similar option would be to partially substitute plant and terrestrial animal proteins for fish proteins in fish meal.

Researchers also need to better address the impact of the cultivation of large pelagic species. Current footprint analysis of this group is limited to only the footprint of salmon, the result of which is a huge ecological footprint per ton of salmon harvested. Due to the tremendous growth in this area of aquaculture, it is essential that policy makers, farmers and scientists better understand that the growth of this industry, which is resulting in an overall loss of fish protein in the environment.

To further understand the policy implication of expanding carnivorous fisheries, Appendix A includes a case study that outlines the current state of one of the most detrimental and fastest growing cultured species- the bluefin tuna. While salmon fishprinting is the largest fishprint conducted to date, it is not the highest trophic level species cultured. Increasing demand for bluefin tuna has created a huge market of tuna farming, which literally is tuna fattening. A better understanding of this practice is included in Appendix A, and until a fishprint of tuna is conducted, the true impact of aquaculture will not be calculated.

VII. Policy Implications

In June of 2003, the Pew Ocean Commission recommended a moratorium on new marine farms until regulations and standards are set. Just over a year later, the United States Commission on Ocean Policy encouraged establishing only environmentally sustainable offshore aquaculture.

Despite these recommendations, the National Oceanic and Atmospheric Association (NOAA) legislation to allow the culturing of large pelagic fisheries is moving forward. The legislation would encourage farming of large pelagic species, including salmon farming and tuna fattening, in the U.S. The aquaculture legislation proposed by NOAA has been sponsored by Democratic Senator Daniel Inouye of Hawaii and Republican Senator Ted Stevens of Alaska. Ironically, Hawaii currently accommodates the majority of offshore aquaculture research projects, while Stevens has outlawed aquaculture in his own state's coastal waters to protect Alaska's coastal fisheries.

The goal of the legislation is to establish a 5 billion dollar per year aquaculture industry in the U.S. To meet this goal, the bill would subsidize high-value, fast-growing species, including the most intensive species cultured on the planet – cod, salmon, moi, tuna, snapper, halibut, and others. The bill would give preference to aquaculture projects that anchor net pens to decommissioned oil derricks, freeing oil companies from costly legal requirements to remove the derricks. Since June, the bill has been under review by the Senate committee on Commerce, Science and Transportation, of which Stevens is chair. Currently, it awaits hearing in subcommittee.

California is also in the process of requiring leases on marine finfish aquaculture, excluding salmon. The state currently has a state law prohibiting farming of salmon in marine net pens and prohibiting the use of genetically modified fish for commercial or research purposes. Proposed by state Senator Joe Smitian, this new state bill does a better job than the national bill at setting standards by establishing requirements for leases, monitoring, public involvement and environmental standards for mariculture. Yet it does not do enough; scientists around the country agree that the ecological risks of marine aquaculture are too large and rise with intensity and scale of production (Naylor 2005).

Although the U.S. has good reason to enter the aquaculture market due to the current seafood trade deficit of \$13 billion annually, this new plan for open ocean aquaculture set forth by Stevens goes against both the Pew Report and the USCOP report recommendations. More importantly, the economic challenges of off-shore aquaculture are barely understood. This bill is a misguided attempt to create a sustainable, environmentally friendly food source through the support of large high value fisheries. While most believe that this bill will not be reviewed in this session, it is essential that the committee members understand that mariculture of large pelagic species is energy inefficient and will result in an overall net loss of fish protein, while also negatively impacting the environment.

Without further research related to aquaculture footprinting, detrimental aquaculture practices will continue to grow, while sustainable aquaculture will decrease. The U.S. has the ability to promote the growth of sustainable aquaculture, yet they need a better understanding of the field in general for individuals and agencies to understand the differences between their choices.

VIII. Concluding Thoughts

Even though the science of aquaculture fishprinting is young and requires further research and development, early calculations prove that higher trophic level species are greatly impacting the environment. Fishprinting also shows that aquaculture does have a future. Through extensive sustainable practices it can help alleviate the pressure on fisheries, which will reduce the need for fisheries to go deeper and farther out it into the oceans to provide protein for a growing number of individuals.

Yet, due to political and economic reasons, current aquaculture trends favor unsustainable intensive practices. What this means is that the current aquaculture movement is reducing the amount of protein available for consumption and increasing the negative impact on the environment. As a result, those 950 million plus individuals who rely on fish protein are losing their protein source at a rapid rate.

In the end, fishprinting is one tool that will allow aquaculture farmers and policy-makers to make informed decisions on how and what species to culture. And until sustainable aquaculture is a world-wide goal, aquaculture practices will continue the depletion of protein. The result is a continued threat to one of the world's greatest protein sources. Yet all hope should not be lost: sustainable, extensive aquaculture could turn out to be the blue revolution the world is looking for.

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Appendix A§

The Rise and Consequences of Bluefin Tuna Aquaculture

Bluefin tuna is at the very top of the oceanic food web, and easily considered the least energy efficient fish. And even though fisheries researchers, including Barbara Block of Stanford and Daniel Pauly of the University of British Columbia, have reported that stocks of the Atlantic, Southern, and Pacific bluefin tuna are declining in both size and number, the amount of tuna on the market is increasing.

Just over ten years ago, traditional fishermen were going broke and demand had reached an all-time high. Driven primarily by the strong Japanese market, prices skyrocketed. Businesses in Japan, Southern Australia, and countries along the Mediterranean began to take bluefin tuna the route of Atlantic salmon. Entrepreneurial fisherman began towing their undersize tuna back to the Mediterranean and Southern Australian shores where they could be "farmed."

The reason that tuna fattening is growing so rapidly despite its inefficiencies is that tuna fattening is a huge money maker. The fatty belly of these giants of the sea are cut and sold as toro for prices upwards of \$100,000 at Tokyo's Tsukiji fish market, the world's largest, and regularly sell for \$30,000 for fish that routinely weigh 300 kilos (650 pounds). According to the World Wildlife Fund and John Volpe of the University of Victoria, the tuna farming hub of Southern Australia is reputedly home to the largest proportion of millionaires in the southern hemisphere along with notorious members of the Croatian mafia.

The Impact of Fattening

Tuna farming isn't truly farming at all, but "fattening." These large predators are caught by purse seine and towed (often hundreds of miles) to coastal areas where feeding facilities have been established for the explicit purpose of adding weight and value to undersized and immature tuna. This process is quickly stripping the ocean of these large predators by depleting the juvenile population.

Once captured and towed to shore, the fish are transferred to holding tanks the size of football fields where they are fed a diet of sardines, anchovies and herring for 3 to 8 months. Like marathon runners, bluefin are extremely inefficient at converting what they eat into fat and flesh. By comparison, farmed salmon, which gets a notoriously bad rap, is about 700% more efficient at converting feed to biomass. Feeding these fish is draining the seas of fish, and excess feed and feces are polluting the near shore waters.

Recent advances in formulated feeds show some promise in streamlining the fattening process, yet even the new process of formulating feed is extraordinarily energy consumptive. So, while some steps are being taken to reduce the fishprint of the forage fish, the fishprint may rise as a result of the fuel embodied in the processing of fish feed.

Fattened and ready to harvest, fish are flash frozen and shipped primarily to markets in Japan, while some make their way to the United States.

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[§] Information provided by Ty Brookhart

Traditionally, commercial tuna fishing has been regulated by the International Commission for the Conservation of Atlantic Tunas (ICCAT) and the Convention for the Conservation of Southern Bluefin Tuna (CCSBT) by mandating accurate reporting and setting catch quotas for its members. ICCAT has 27 member states including France, Spain, and Greece. CCSBT members include Japan, Australia, New Zealand and South Korea. Despite this regulatory framework, current processing plants have found a way to avoid inspection points for any illegally caught or unreported tuna (a substantial percentage under the present system) through passing tuna via lax ports. Southern bluefin usually make their way through China and Indonesia, and tuna from the Mediterranean farms pass through non-member countries in Europe. Cut and packaged, it is then relabeled as "ready-to-eat tuna sashimi," which can enter Japanese or U.S. markets without being reported. This practice substantially jeopardizes conservation and management efforts of bluefin tuna.

According to the Australian government, reported catch for Southern bluefin indicate it is being harvested at a rate 30 percent greater than the total allowable catch set by international treaties. Over-harvesting is a problem with forage fish, as well. Forage fish caught for feed often go unreported as they make their way from the nets directly to the tuna larders. This is all taking place while the European Union heavily subsidizes the industry and the cartel spreads from Australia, to Europe and beyond. Recently, Mexico has also followed suit with commercial fattening facilities on the shores of Baja.

For the first half of 2005, the National Oceanic and Atmospheric Association (NOAA) Fisheries reports the United States has imported over 2.5 million pounds of bluefin tuna, at a cost of \$17.6 million. These values have already exceeded 2004 import values (\$14.3 million) and will likely eclipse last year's import weights before fall.

The American and World market for sushi and bluefin is ballooning and the tuna farms are right there to feed it, for now. Yet since no one has truly quantified what the tuna fattening industry is doing to the future of bluefin tuna, the mighty bluefin tuna's days may be limited.

Fishprinting BlueFin Tuna

In order to better understand the detrimental impacts of bluefin aquaculture and to increase public awareness, a footprint of this industry is needed. Right now this largely unsustainable practice has flown under the radar screen because of huge economic demand. After carefully reviewing the available data on bluefin tuna research, the following data inputs would need to be collected in order to calculate a footprint:

- Amount of fuel spent on capturing juvenile wild tuna.
- Average weight of tuna upon capture.
- Average weight of tuna upon sale.
- Amount of time an average tuna spends in fattening bins.
- Amount of fish fed per tuna everyday, and the trophic level of those species.
- Industrial energy inputs, including facility operation, exportation of fish to the market, and fish processing.
- Amount of waste assimilated into the environment.

The inputs listed above are complicated numbers that have yet to be collected by anyone in the aquaculture field. These inputs do not include the impact of harvesting juvenile tuna on the greater environment, which could easily lead to the collapse of the wild bluefin tuna population, nor do they begin to address the impact of illegal or unreported tuna catches. Until a proper footprint on bluefin tuna has been calculated and people start to understand the impact of bluefin tuna fattening farms on wild fisheries and the environment, proper regulations will not be instituted and the practice of fattening bluefin tuna will continue to increase.