Evaluating the Functional Trophic Level of the Global Aquaculture Sector

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Abstract

Previous studies have characterized the average trophic level of aquatic animals in culture at national, regional or global scales. All of these prior analyses, however, have assumed that the trophic level of an animal in culture is identical to when feeding in the wild. While reasonable for filter feeding organisms, it may poorly represent the diets of farmed aquatic organisms. For these, an estimate of the animal's functional trophic level is necessary. Building on previously unpublished work, this study pieces together the functional trophic level of all animals in culture globally from 1970 to 2013. The model combines country- and species- specific production data as reported by the Food and Agriculture Organization of the United Nations, with published data on the fraction of a cultured species' growth that is feed-based, the composition of that feed, and estimates of the trophic level of marine inputs to aquafeeds throughout the period of analysis. Results not only provide insight into which species in culture deviate most from their natural or wild trophic levels but also allow the examination of the relative dependencies and trajectories of aggregate dependence on terrestrial primary production via crop-based inputs and marine primary production based on fishery-sourced inputs. Results show that as the global aquaculture sector continues to increase in production it is reducing its dependency on marine-derived aquafeed components, which is rapidly being replaced by plant-based alternatives. This leads to the conclusion that the global aquaculture sector has recently seen a decrease in its energy consumption and has the potential to sustainably expand and contribute to global food security.

Keywords**: Aquaculture, Functional Trophic Level, Trophic Level Analysis, Compound Aquafeeds, Marine Capture Fisheries, Fish Meal, Fish Oil, Trophic Level, Food Security, Sustainability**

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Chapter 1: Introduction

1.1 The Aquaculture Industry in Context

Aquaculture production contributes to nearly fifty percent of the global seafood supply dedicated to human consumption, which includes fish, crustaceans and molluscs (Bostock et al., 2010; FAO, 2012; Naylor et al., 2009; Subasinghe, Soto & Jia, 2009). The aquaculture industry is the fastest growing animal protein food sector in the world, with an average growth rate of 8.2% per year from 1970 to 2010 (Tacon & Metian, 2013). In comparison, capture fisheries have remained at a relatively steady pace over the last few decades, with an average growth rate of 1.5% per year (Tacon & Metian, 2013). The top five aquaculture producers in the world are: China (36.7 million tonnes), India (4.6 million tonnes), Viet Nam (2.7 million tonnes), Indonesia (2.3 million tonnes), and Bangladesh (1.3 million tonnes) (FAO, 2012). These five countries accounted for 87.6% of total world aquaculture production in 2012 (FAO, 2012).

In lieu of the world's burgeoning population and the associated need for increased food production, the aquaculture sector is considered to have substantial potential to expand globally and contribute to food security. It is projected that the aquaculture sector will overtake capture fisheries by the year 2031 as the world's main source of seafood production (Tacon & Metian, 2013). There are two opposing narratives regarding the expansion of the aquaculture sector and its role in global food security:

i. The aquaculture sector consumes nutrient-rich small pelagic fish that could be re-directed for immediate human consumption, degrades aquatic systems, poses a health risk to consumers, and diminishes food resources for low-income populations (Troell et al., 2014).

ii. The aquaculture sector has the potential to reduce pressure on wild fish stocks, as capture fishery landings remain relatively stagnant and largely exploited. The aquaculture sector has an opportunity to contribute to global food security and certain types of aquaculture production could also provide ecosystem services in the form of wastewater treatment (Troell et al., 2014).

To gauge the magnitude of resources needed to sustain the aquaculture sector, and hence its suitability to tackle food security, a trophic level analysis could be applied. A trophic level analysis uses trophic level as a tool to measure the amount of resources consumed by a species. A trophic level is defined as a species relative position in the aquatic food chain, ranging from a 1 in plants (i.e. seaweed) to a 5 in apex predators (i.e. orca whales) (Pauly, Tyedmers, Froese & Liu, 2001b). Each increasing trophic level consumes more energy, or primary productivity, than the previous, of which there is only a finite amount available annually to service the Earth's ecosystems.

Two prior studies have used a trophic level analysis to characterize the aquaculture industry. In 2009, Stergiou, Tsikliras & Pauly conducted a study to determine trends of the mean trophic level in the Mediterranean marine and brackish aquaculture industries from 1970 to 2004. Stergiou et al. concluded that the Mediterranean industry was unsustainably "farming up the food web" (2009). "Farming up the food web" is a concept that has a negative connotation and implies that cultured species with high trophic levels (i.e. carnivorous marine finfish) have a larger impact on their environment, as they require increased amounts of nutrient-rich feed inputs to produce a single market-ready fish, when compared to low trophic level cultured species (Pauly et al., 2001b). A similar study done by Tacon et al. in 2010 attempted to illustrate the trophic level implications and trends of farmed and fished species in a global context between

1950 and 2006. Tacon et al. showed that global mean trophic level has remained relatively stable (2010).

These studies both calculate the mean weighted trophic level of cultured species under the assumption that the trophic level of a wild species is equivalent to the trophic level of a cultured species. This logic is imperfect because, as Tacon et al. posits, the aquaculture sector is unique in that "the trophic level of a cultured species is directly proportional to the required input (feed) of such farming" (2010, p. 98). In modern aquaculture system feed inputs consist of compound aquafeeds, a mixture of plant and animal products derived from an industrial process that provide a complete source of nutrition orally (normally in pelleted form) (Fisheries Department, 2001).

No previous trophic level analysis has examined the magnitude of resources consumed by the aquaculture sector by evaluating the composition of a species' fed diet (i.e. compound aquafeeds) and the affect that their artificial feeding patterns may have on a cultured species' trophic level. Arguably, the consideration of the role that compound aquafeeds have on a cultured species' trophic level may provide a more accurate portrayal of the resource consumption of the global aquaculture sector.

1.2 Objective of Study

This research aims to provide a robust global-scale assessment of the *functional* trophic level (FTL) of cultured species in the aquaculture sector to examine the magnitude of resources that aquaculture draws upon and its potential to sustainably expand and contribute to global food security. This study proposes to fill a gap in the academic literature by completing a detailed global analysis of the aquaculture industry from 1970 to 2013 to determine the role that compound aquafeeds play in determining the trophic level of species in culture. The functional trophic level of a species will be determined by reviewing the academic literature to obtain specific or estimated values of: the fraction of compound aquafeed that is consumed, the marine-derived component found in the aquafeed formulation, and the estimated trophic level of the fish that comprises the marine-derived component in the feed, for all cultured species reported in the FAO FishStatJ database.

1.3 Significance of Study

Filling this knowledge gap could assist in establishing future regulations and policies in the aquaculture industry. This study will reflect the wide variation of fish meal (in the form of compound aquafeeds) used globally among aquaculture producing countries, and the affect that this has on a cultured species' respective trophic levels. The breadth of analysis in this study will enhance the ability of major aquaculture producing countries to make informed decisions that enable their aquaculture industries to reach their potential to meet global demand for human fish consumption, contribute positively to economic growth, and support sustainable livelihoods (Subasinghe, 2009).

Chapter 2: Review of the Literature

This literature review will provide an overview of the global seafood sector; specifically its contributions to food security and the changes in capture fisheries and culture fisheries (aquaculture) over time. It will explore aquaculture’s reliance on reduction fisheries, and an examination of trophic level analysis as it has been defined thus far in the literature. This study tracks changes in the functional trophic level of aquaculture production to evaluate temporal changes in the relative dependence of the aquaculture sector on capture fisheries (in the form of compound aquafeeds). The goal of this study is to assist in understanding the impacts that the aquaculture sector has on its ecosystem services and quantify the sustainability of its production systems using a trophic level analysis.

2.1 The Global Seafood Sector and Its Role in Food Security

The global seafood sector plays an important role in food security, as it provides 16.6% of animal-derived protein to the world’s population (Tacon & Metian, 2013). Seafood is a particularly important dietary element of developing countries in the Sub-Saharan region of Africa, as these populations rely on fish to provide 8.1% to 8.6% of their total caloric intake, the highest percentage of any continent in the world (Tacon & Metian, 2009). The fisheries sector is uniquely positioned to provide affordable and high quality nutrients to those who experience malnutrition and poverty (Tacon et al., 2010).

The two types of seafood production that contribute to the global seafood sector are: capture fisheries (wild fish) and culture fisheries, known synonymously as aquaculture (farmed fish). The growth of aquaculture production has been rapid, at an annual rate of 8.2% (2.57 to 59.9 million tonnes) from 1970 to 2010 (Tacon & Metian, 2013). In comparison, capture fisheries landings have remained at a relatively steady pace of 1.5% annually (38.2 to 68.4 million tonnes) over the same time period (Tacon & Metian, 2013). As aquaculture continues to grow it is expected that this sector will eventually contribute more than half of total seafood production globally (Bostock et al., 2010; Tacon & Metian, 2013). A critical analysis of the resources consumed by varying production systems in the aquaculture sector will be key to ensuring that the industry can sustain its rapid growth rates and make a substantial contribution to global food security.

2.2 Exploitation of Global Capture Fisheries

Overfishing is a recurrent trend in global capture fisheries, with 53% of the world’s fisheries fully exploited and populations nearing or having reached their maximum sustainable production limit (Sarker & Vandenburg, 2012). The first study to provide quantitative evidence of the depletion of wild fisheries was conducted by Pauly et al. in 1998, which used a trophic level analysis to measure the trends of capture fisheries landings. A trophic level (TL) is defined as the relative position of an organism within the aquatic food chain, and normally ranges from 1 (marine plants) to 5 (marine mammals), with each increasing level consuming more energy than the next, as shown in Figure 1 (Pauly et al., 2001a; Tacon et al., 2010).

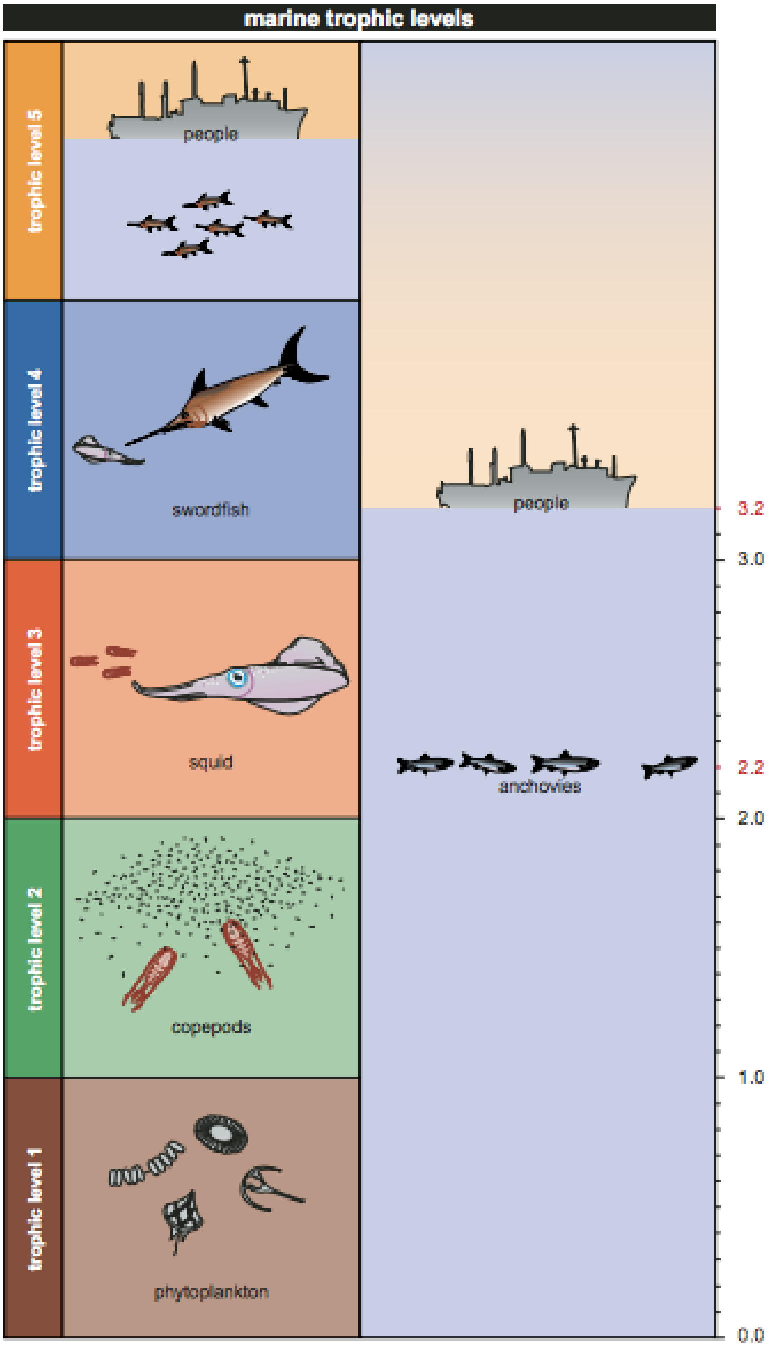


Figure 1. An overview of the assignment of marine trophic levels (Pauly et al., 2001b).

Pauly et al. argued that large enduring fish high in the food web were rapidly being depleted and replaced in landings by small ephemeral fish low in the food web (2001b). The trophic level analysis completed by Pauly et al. on capture fisheries revealed a decreasing trend of 0.1 TL per decade in the landings of marine fisheries and titled this concept “fishing down food webs”. This implied that, due to market demand, high trophic level capture fishery landings were being rapidly depleted and subsequently replaced by low trophic level landings, which could ultimately lead to a fisheries collapse (Pauly et al., 1998).

Since this work, there has been an additional publication on a similar concept of “fishing through food webs” by Essington, Beaudreau & Wiedenmann in 2006. This concept emphasizes that the reduction of high trophic level species in marine fisheries landings may also be linked to the addition of low-trophic level fisheries, which causes increasing and opposing demands on the finite ecosystem services of the ocean (Essington et al., 2006). Though capture fisheries remain largely exploited, an emphasis has been placed on sustainable management and use of fishery resources to prevent further damaging ecosystem effects (Essington et al., 2006; Sarker & Vandenburg, 2012; Tacon & Metian, 2009).

In 2012, the top five capture fisheries in the world were: China, Indonesia, India, the United States of America and Peru (FAO). The reported top five captured species globally were: Anchoveta, Alaskan Pollock, Skipjack Tuna, Atlantic Herring, and Chub Mackerel (FAO, 2012). The largest captured species globally, Anchoveta, is one of the major small pelagic fish species that the aquaculture sector relies on for nutrient inputs, in the form of fish meal and fish oil. This is an initial insight into the interconnectedness of capture and culture fisheries.

2.3 Aquaculture Sector: An Overview

The aquaculture industry contributes to nearly fifty percent of the global seafood supply (excluding mammals, reptiles and aquatic plants) (Bostock et al., 2010; FAO, 2012; Naylor et al., 2009; Tacon & Metian, 2009; Troell et al., 2014; Subasinghe et al., 2009). This number is expected to grow further to meet future animal protein demand as the global population increases (Bostock et al., 2010). The aquaculture sector is currently the fastest growing animal protein sector in the world, with an average growth rate of approximately 8% between 1961 and 2010 (Tacon et al., 2010; Troell et al., 2014; Subasinghe et al., 2009). The global leaders in aquaculture production are: China, India, Vietnam, Indonesia and Bangladesh (FAO, 2012).

2.4 Trends of the Aquaculture Industry

Historically, traditional aquaculture has consisted of small-scale operations based mainly in Asia, producing primarily herbivorous species fed by natural systems (no external inputs added), farm-made feeds, or with ‘low value fish’ (fish that are not considered fit for human consumption or are cheaply acquired) (Bostock et al., 2010; Edwards, 2015; Naylor et al., 2009; Tacon et al., 2010). The species farmed by these traditional systems are typically assigned a low trophic level value (2) and hence settle in the lower levels of the aquatic food web (Naylor et al., 2009). However, as the industry continues to grow there is a movement toward modern aquaculture systems (Edwards, 2015). Modern aquaculture can be described as any large-scale and intensive operation that produces species that are largely dependent on industrially manufactured aquafeeds, also known as compound aquafeeds (Edwards, 2015). In developing countries it is typical to observe small-scale operations that focus on producing low value, lower trophic level species (herbivorous species with a trophic level of ~2), while in developed countries there is a focus on modern aquaculture and the production of higher trophic level species that fetch a high market value (omnivorous or carnivorous species with a trophic level of ~3-4) (Tacon et al., 2010). Compared to low trophic level species, the culture of high trophic level species logically requires substantially more energy and feed inputs, and hence greater ecosystem demands.

With the growing expansion of the modern aquaculture industry from 1970 to the early 1990s the concept of “farming up the food web” was introduced by Pauly, Tyedmers, Froese, Rainer & Liu (2001a). Contrasting the previously discussed trend of “fishing down the food web” that occurred in capture fisheries, “farming up the food web” implies that there has been a substantial focus on culturing species with high trophic levels (i.e. carnivorous marine finfish) that have raised the mean trophic level of the aquaculture sector in most continents, with the exception of Asia and Africa (Pauly et al., 2001a). In the aquaculture sector, producing species at a higher trophic level is correlated with larger environmental and ecological implications, as these species require external nutrient inputs that are largely derived from marine capture fisheries (in the form of compound aquafeeds) (Tacon et al., 2010). The inefficiency of culturing higher trophic level species is emphasized by Tacon & Metian, who assert that the majority of these species consume more fishery resources than the quantity of farmed fish produced (2009).

The increased production of higher trophic level groups such as carnivorous finfish and crustaceans (salmon, catfish, shrimp, etc.), and omnivorous species has been motivated by the globalization of trade networks and the economic benefits of farming higher trophic level species. Higher trophic level species consequently fetch a greater market value than their lower trophic level counterparts (Edwards, 2015; Naylor et al., 2009; Tacon & Metian, 2009). Tacon et al. asserts that increased high trophic level aquaculture species production is incentivised by the large demand for high value species in developed countries, as developed countries imported nearly 80% of all internationally traded fisheries products in 2006 (2010). As the volume of high trophic level aquaculture increases, as exemplified by the tripling of farmed fish and shellfish production from 1995 to 2007, there is subsequently an increased demand for more compound aquafeed production (Naylor et al., 2009).

2.5 Aquaculture and Compound Aquafeeds

As the level of aquaculture production increases, there is concern that this will cause an increased dependence on marine capture fisheries, also known as ‘reduction fisheries’ (Tacon et al., 2010). Reduction fisheries are a portion of marine capture fisheries landings that are reduced into nutrient-dense fish meal and fish oil, which comprise of the main ingredients in pelleted compound aquafeeds, livestock feeds, and other products (Tacon, 2009).

Reduction fisheries consist of fish landings destined for non-food uses and in 2006 approximately 36.2% of total global capture fisheries landings were destined for reduction (Tacon & Metian, 2009). The main seafood groups destined for reduction include: small pelagic species (anchovies, herring, sardines, and menhaden); miscellaneous pelagic species (mackeral and capelin); and other species (squid, cuttlefish and octopi) (Tacon, 2009). The majority of reduction fishery landings occur off of the nutrient-rich waters of Peru and Chile, with 99.3% of the total anchovy catch in Peru reduced to fish meal and fish oil in 2006 (Tacon & Metian, 2009). There is growing concern that these fish destined for non-food uses could be instead re-directed for human consumption in the poorest regions of the world, as small-sized marine pelagic fish species are considered some of the most nutrient-rich aquatic animal foods, globally (Tacon & Metian, 2009; Tacon & Metian, 2013; Troell et al., 2014).

The increasing use of compound aquafeeds in the aquaculture sector competes for small pelagic fish resources that have the potential to be diverted for direct human consumption (Tacon & Metian, 2009; Troell et al., 2014). In 2009, the aquaculture sector consumed 68% of global fish meal and 88% of global fish oil (in the form of aquafeeds) produced by reduction fisheries (Naylor et al., 2010). The dependence of the aquaculture sector on external feed inputs is a key issue identified throughout the academic literature, and Tacon et al. states that the reduction of the amount of wild fish caught for compound aquafeeds in the form of fish meal and fish oil is key to the aquaculture sector's long-term economic viability and environmental sustainability (2010).

For the past two decades there has been a movement (largely driven by consumers and retailers) to improve the environmental sustainability of the aquaculture industry by reducing its dependency on marine capture fisheries, and hence its reliance on fish meal and fish oil in compound aquafeeds (Naylor et al., 2009; Tacon & Metian, 2008). This is exemplified by legislation enacted in California in 2006, as well as a bill introduced at the federal level of the United States in 2007, both aimed at reducing levels of fish meal and fish oil in aquafeeds (Naylor et al., 2009).

Tacon & Metian suggest that, although there has been a steady increase in the consumption of compound aquafeeds by the aquaculture sector, that this trend is due to the increase in production of fed systems versus the increased inclusion of fish meal and fish oil levels within aquafeeds (2008). These authors also predict that the inclusion of fish meal and fish oil within compound aquafeeds will decrease in the long term due to: increasing costs, diminishing supplies of wild forage fish, and the introduction of nutritionally sufficient feed alternatives (Tacon & Metian, 2008). This predicted outcome is illustrated in Figure 2.

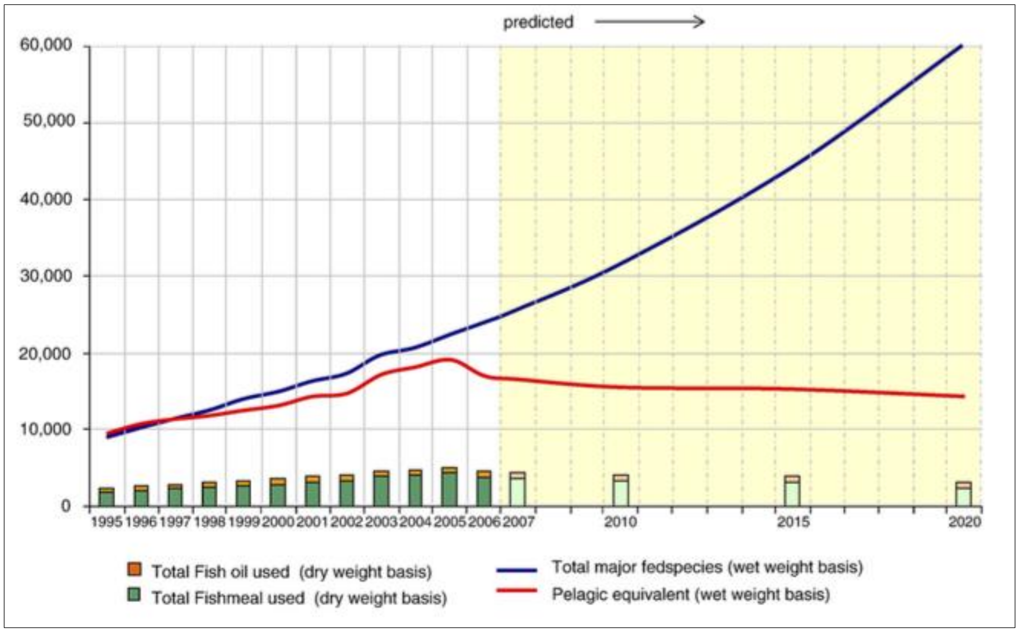


Figure 2. The predicted consumption levels of fish oil and fish meal by the aquaculture sector, and its pelagic fish consumption equivalent (Tacon & Metian, 2008).

The amount of fish harvested for reduction has remained relatively stable at 20-35 million tonnes (Mt) for the past 35 years, and species that notoriously consume large amount of aquafeeds (carnivorous marine finfish and marine crustaceans) have recorded dropping fish oil and fish meal inclusion rates (Tacon & Metian, 2008; Welch, et al. 2010). These studies suggest that the aquaculture sector may be moving towards productions systems that are less reliant on wild capture fisheries in the form of fish meal and fish oil feed components.

2.6 Applying a Trophic Level Analysis to Aquaculture

The use of trophic level analysis of the aquaculture sector in academic literature is sparse, as only two studies, the first conducted by Stergiou, Tsikliras & Pauly in 2009, and the other by Tacon et al. in 2010 implicitly use a trophic level calculation to reach a final assertion and recommendation. Both of these studies use an equation proposed by Pauly et al. in 1998 to calculate mean trophic level of cultured species, seen in Figure 3.

$$\overline{\mathrm{TL}}_i = \frac{\sum_{ij} \mathrm{TL}_{ij} \mathrm{Y}_{ij}}{\sum \mathrm{Y}_{ij}}$$

Figure 3. Mean trophic level formula (Tacon et al., 2010).

In this formula, the mean trophic level is calculated by using a weighted mean (Tacon et al., 2010). The trophic level of an individual species group, j, is multiplied by the recorded landings Y for a particular year, i (Tacon et al., 2010). In the aquaculture studies listed above, the trophic level values of calculated species are retrieved from the FishBase database and FAO production database and it was assumed that the trophic level of a species in culture is equivalent to its wild trophic level (Stergiou et al., 2009; Tacon et al., 2010).

The Stergiou et al. study focused solely on the Mediterranean mariculture industry (excluding brackish water aquaculture) from the period 1905 to 2004 to determine whether this sector was focused on producing high TL species and “farming up the food web” (2009). Using the formula in Figure 2, Stergiou et al. determined that the Mediterranean mariculture industry was indeed “farming up the food web” (See Figure 4).

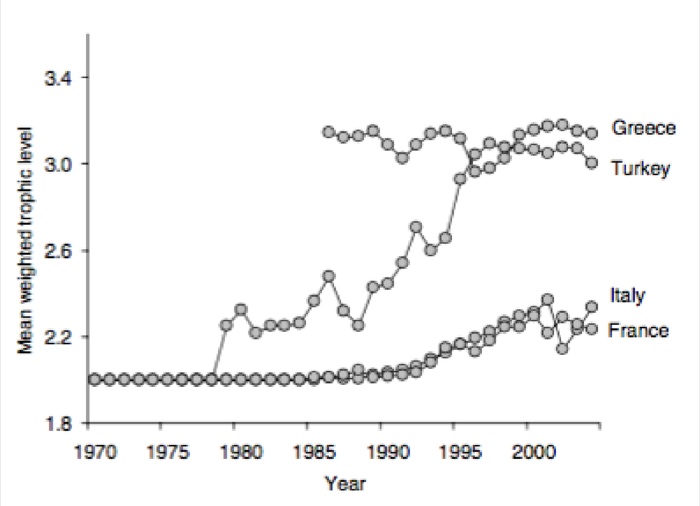
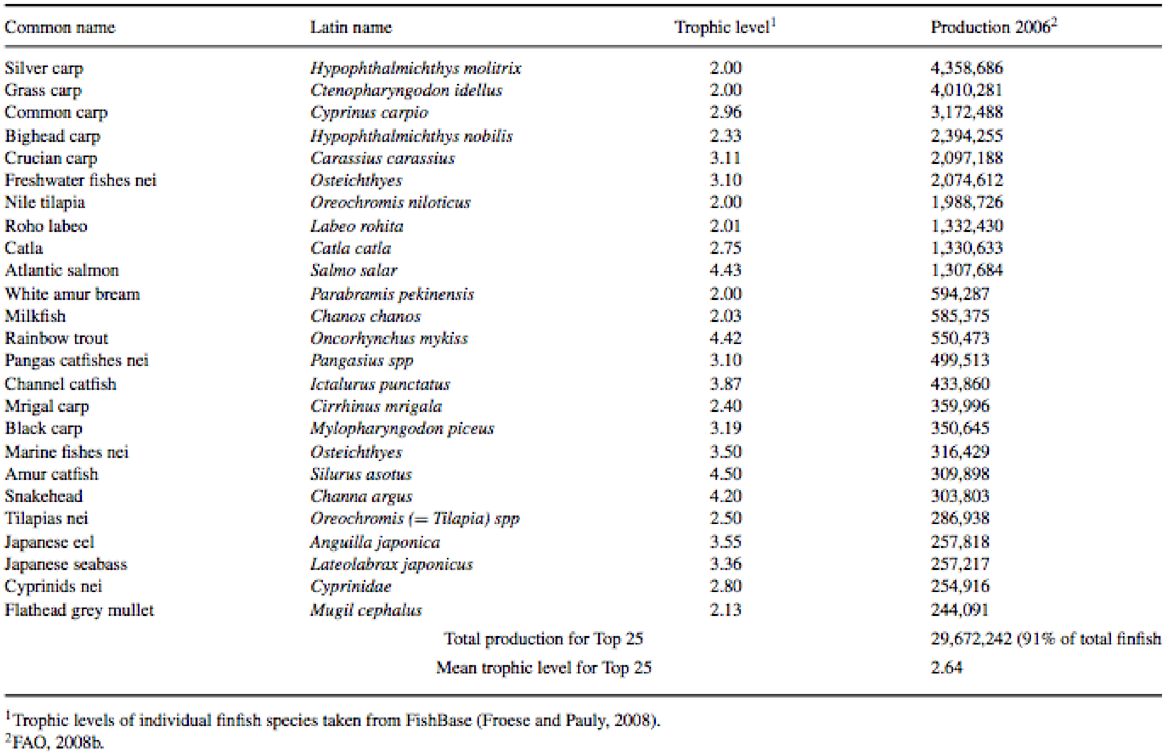


Figure 4. The mean weighted trophic level of marine farmed species in the 4 largest Mediterranean aquaculture-producing countries between the period 1970 and 2004 (Stergiou et al., 2009)

The authors concluded that the observed mean trophic level increase raises ecological, socioeconomic, and ethical concerns as feed inputs into these high TL species could potentially be redirected for direct human consumption (Stergiou et al., 2009).

The Tacon et al. study used the equation in Figure 2 to produce the mean TL of the top 25 produced aquaculture species in 2006, as well as the top 25 valued aquaculture species in thousands of US dollars (See Figures 5 and 6, respectively) (2010). Note in these figures that low trophic level species such as Silver Carp, Grass Carp, and Common Carp dominate production quantity levels, but high trophic level species, like Atlantic Salmon, are considered more economically valuable. This reinforces the discussion point that the consumer market is potentially providing an incentive for high trophic level species to be cultured.

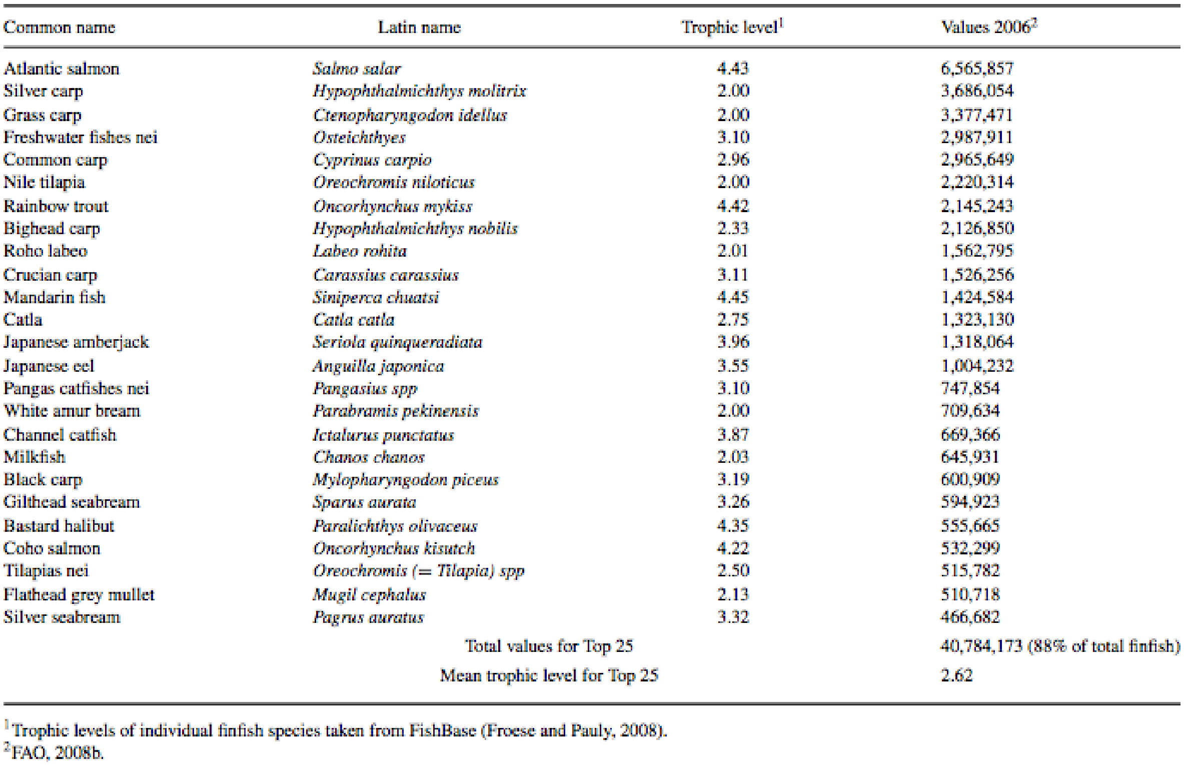


Common name	Latin name	Trophic level[1]	Production 2006[2]
Silver carp	*Hypophthalmichthys molitrix*	2.00	4,358,686
Grass carp	*Ctenopharyngodon idellus*	2.00	4,010,281
Common carp	*Cyprinus carpio*	2.96	3,172,488
Bighead carp	*Hypophthalmichthys nobilis*	2.33	2,394,255
Crucian carp	*Carassius carassius*	3.11	2,097,188
Freshwater fishes nei	*Osteichthyes*	3.10	2,074,612
Nile tilapia	*Oreochromis niloticus*	2.00	1,988,726
Roho labeo	*Labeo rohita*	2.01	1,332,430
Catla	*Catla catla*	2.75	1,330,633
Atlantic salmon	*Salmo salar*	4.43	1,307,684
White amur bream	*Parabramis pekinensis*	2.00	594,287
Milkfish	*Chanos chanos*	2.03	585,375
Rainbow trout	*Oncorhynchus mykiss*	4.42	550,473
Pangas catfishes nei	*Pangasius spp*	3.10	499,513
Channel catfish	*Ictalurus punctatus*	3.87	433,860
Mrigal carp	*Cirrhinus mrigala*	2.40	359,996
Black carp	*Mylopharyngodon piceus*	3.19	350,645
Marine fishes nei	*Osteichthyes*	3.50	316,429
Amur catfish	*Silurus asotus*	4.50	309,898
Snakehead	*Channa argus*	4.20	303,803
Tilapias nei	*Oreochromis (= Tilapia) spp*	2.50	286,938
Japanese eel	*Anguilla japonica*	3.55	257,818
Japanese seabass	*Lateolabrax japonicus*	3.36	257,217
Cyprinids nei	*Cyprinidae*	2.80	254,916
Flathead grey mullet	*Mugil cephalus*	2.13	244,091
	Total production for Top 25		29,672,242 (91% of total finfish
	Mean trophic level for Top 25		2.64

[1] Trophic levels of individual finfish species taken from FishBase (Froese and Pauly, 2008).

[2] FAO, 2008b.

Figure 5. Calculated mean trophic level values of the top 25 aquaculture species, production-wise in metric tonnes (Tacon et al., 2010).



Common name	Latin name	Trophic level[1]	Values 2006[2]
Atlantic salmon	*Salmo salar*	4.43	6,565,857
Silver carp	*Hypophthalmichthys molitrix*	2.00	3,686,054
Grass carp	*Ctenopharyngodon idellus*	2.00	3,377,471
Freshwater fishes nei	*Osteichthyes*	3.10	2,987,911
Common carp	*Cyprinus carpio*	2.96	2,965,649
Nile tilapia	*Oreochromis niloticus*	2.00	2,220,314
Rainbow trout	*Oncorhynchus mykiss*	4.42	2,145,243
Bighead carp	*Hypophthalmichthys nobilis*	2.33	2,126,850
Roho labeo	*Labeo rohita*	2.01	1,562,795
Crucian carp	*Carassius carassius*	3.11	1,526,256
Mandarin fish	*Siniperca chuatsi*	4.45	1,424,584
Catla	*Catla catla*	2.75	1,323,130
Japanese amberjack	*Seriola quinqueradiata*	3.96	1,318,064
Japanese eel	*Anguilla japonica*	3.55	1,004,232
Pangas catfishes nei	*Pangasius spp*	3.10	747,854
White amur bream	*Parabramis pekinensis*	2.00	709,634
Channel catfish	*Ictalurus punctatus*	3.87	669,366
Milkfish	*Chanos chanos*	2.03	645,931
Black carp	*Mylopharyngodon piceus*	3.19	600,909
Gilthead seabream	*Sparus aurata*	3.26	594,923
Bastard halibut	*Paralichthys olivaceus*	4.35	555,665
Coho salmon	*Oncorhynchus kisutch*	4.22	532,299
Tilapias nei	*Oreochromis (= Tilapia) spp*	2.50	515,782
Flathead grey mullet	*Mugil cephalus*	2.13	510,718
Silver seabream	*Pagrus auratus*	3.32	466,682
	Total values for Top 25		40,784,173 (88% of total finfish)
	Mean trophic level for Top 25		2.62

[1] Trophic levels of individual finfish species taken from FishBase (Froese and Pauly, 2008).
[2] FAO, 2008b.

Figure 6. Calculated mean trophic level values of the top 25 aquaculture species, value-wise in thousands of $US dollars (Tacon et al., 2010).

Tacon et al. found that over the last 56 years (1950 to 2006) no significant increase or decrease of mean weighted trophic level had occurred (2010). The researchers lament that although there was no significant increase or decrease of mean weighted trophic level in the aquaculture sector, there are marked trends of increasing the culture of high trophic level species in developed countries (and to a lesser extent, China) (Tacon et al., 2010). Reversing these trends toward "farming down the food web", or focusing on the culture of very low trophic level species could potentially reduce the environmental impacts of aquaculture as they require little to no external input and in some cases improve water quality (Tacon et al., 2010).

2.7 Literature Review Summary and Its Relation to This Study

In summary, the aquaculture sector will play an increasingly important role in food security, as 53% of the world's global capture fisheries are fully exploited with populations nearing or having reached their maximum sustainable production limit (Sarker & Vandenburg, 2012). It is projected that the aquaculture sector will overtake capture fisheries to become the sole provider of global seafood production by 2031 (Tacon & Metian, 2013). Though the majority of aquaculture production is focused on the cultivation of low-trophic level species, there has been an increase in the amount of "modern aquaculture" production, which focuses on the cultivation of high-trophic level species that rely heavily on a fed diet (Edwards, 2015). The high consumption levels of fish meal and fish oil by the aquaculture sectors are considered problematic because they rely on wild fish stocks, and in some cases these stocks could be re-directed for immediate human consumption (Tacon & Metian, 2009; Troell et al., 2014). Recent analysis has shown, however, that the amount of fish meal and fish oil in compound aquafeeds is projected to decrease as the costs of these commodities increase and cost-efficient feed alternatives are introduced (Tacon & Metian, 2008; Welch et al., 2010).

The two studies that have used a trophic level analysis to measure the impacts of aquaculture systems have equated the trophic level of a cultured species to that of its wild counterpart, which assumes that a cultured species feeds as it would in the wild. This assumption does not take into consideration that the recent increase of modern aquaculture production promotes the use of intensive systems that rely heavily on compound aquafeeds. The results of one study showed an increasing trend of culturing high trophic level species in the Mediterranean (farming up the food web), while the other employed a global-level analysis that showed no significant increase or decrease of mean weighted trophic level in the aquaculture sector (Stergiou et al., 2009; Tacon et al., 2010).

This study will take into consideration that a cultured species does not feed as it would in the wild, and calculate the trophic level of a species based upon the amount of compound aquafeeds a species consumes, what percentage of that aquafeed comes from fish meal and fish oil (i.e. reduction fisheries) and the trophic level of those reduction fisheries. This analysis will be similar to Tacon et al. in that it will provide a global evaluation of the aquaculture sector. Global level analysis is key to implementing any global aquaculture strategy to improve the sustainability of the aquaculture sector, as these strategies will need to be introduced at a national level (Troell et al., 2014).

Chapter 3: Methods

This study builds upon the work of Pauly, Tyedmers, Froese, and Liu, which proposed that the trophic level of a cultured species should not be considered as equivalent to a wild species (2001b). Tacon et al. reiterated this concept in 2010 by stating that the aquaculture sector is unique in that "the trophic level of a cultured species is directly proportional to the required input (feed) of such farming" (p. 98). The research completed by Pauly et al. resulted in a conference paper presented in San Francisco in 2001 titled "Down with fisheries, up with aquaculture? Implications of global trends in the mean trophic levels of fish" (2001b). There has been no formal publication of this work and it has remained untouched since 2001 (when it was last updated by Dr. Peter Tyedmers). The original work to be expanded upon consisted of: a master Excel file (comprised of 6 spreadsheets) which calculated the functional trophic level of 1800 species/country combinations in culture from 1970 to 2001, a worksheet of the references utilized in the master spreadsheet up to 2001, and an additional spreadsheet consisting of the calculated trophic levels of the world's reduction fisheries from 1970 to 1998.

3.1 Overview of the Previous Model

To account for the factors involved in calculating the trophic level of a species in culture, the following functional trophic level (FTL) formula was procured:

$$FTL = 1 + (A\times((F\times TLr) + (1-F))) + ((1-A)\times(TLw-1))$$

Where:

- A is the percentage of commercial aquafeed relative to the total food ingested by the organism in culture;

- F is the percentage, by weight, of the commercial aquafeed that is derived from reduction fisheries, specifically fish meal and fish oil;
- TLr is the estimated average TL of the commercially harvested fish destined for reduction to fish meal and fish oil; and
- TLw is the estimated TL that a cultured organism would have in the wild (Pauly et al., 2001b).

This equation is unique in that it takes into account the effects that the marine-derived components of compound aquafeeds have on the trophic level of cultured species. This equation also offers an opportunity to produce a global analysis that will provide more accurate trophic levels of species in culture and hence provide a better understanding of the implications of fish meal and fish oil use.

Each spreadsheet from the master Excel file was carefully examined and dissected to ensure a solid understanding of the processes that ultimately determined the FTL of cultured species. See Table 1 for an explanation of each of the five spreadsheets from the master Excel file.

Table 1. A detailed description of the spreadsheets contained in the previous model.

Title of Spreadsheet	**Content of Spreadsheet**	**Function of Spreadsheet**
Global Aquaculture Production	The quantity of species (in tonnes) produced per country, per year. Additionally, a column was added to this spreadsheet for the wild trophic level of each species.	To determine the number of total subjects to be used in the study. Additionally, to determine the TLw value in the FTL formula.
Fraction of Growth Based Upon Commercially Prepared Aquafeeds	The percentage of growth, per species, per country, and per year based upon compound aquafeeds.	To determine A in the FTL formula, the percentage of commercial aquafeed ingested by the organism.
Proportion of Aquafeed Diet Derived From Marine Resources	The percentage of inclusion of fish meal and fish oil, by weight, in the compound aquafeed formulation.	To ensure that the F encompasses the proportion of compound aquafeed that is marine-derived (in the form of fish meal or fish oil) in the FTL formula. Additionally, 1-F=A,
Trophic Level of Reduction Fisheries	The trophic level of reduction fisheries, with country-specific values bolded.	To determine the TLr value calculated in the FTL formula.
Default Master Table[1]	Global assumption values for A, F, and TLr.	To ensure that a FTL could be calculated for each species/country combination in lieu of specific data.

[1]This spreadsheet was not manipulated in any way

The model explained above was replicated precisely in this study, and expanded to include over 2800 species/country combinations. The model provided a guideline for the input of new data sets and allowed for manipulation (i.e. the update of wild trophic levels as listed currently).

3.2 Global Aquaculture Production

To obtain production data for each species per country per year:

1. The “Global Aquaculture Production- Quantity (1950-2013)” dataset was extracted under the “Global Workspace” heading from the database FishStatJ.
2. In FishStatJ the data was then sorted into a hierarchy of continent, species, and then country to align with the sorting of the 2001 spreadsheet.

3. The data from 1970 to 2013 was then transferred onto a new Excel sheet, adding more than 1000 species/country combination rows to the original 1800. To ensure that all of the sheets were uniform, every new row was systematically added by hand to all of the existing sheets in the master Excel model.

Global aquaculture production data is an important factor in calculating the weighted FTL of the globe and its continents, as the magnitude of production associated with a species/country combination will determine how it will influence the weighted average FTL in a global, continent, or species-specific calculation.

3.3 Wild Trophic Levels

To obtain the wild trophic level of each species:

1. The common name of each aquaculture species produced from 1970 to 2013 was typed into the search bar of the database FishBase.ca.
2. If more than one option appeared in the search result list, the country-specific row was chosen. If no country-specific trophic level was available then the global FAO value was selected.
3. After the appropriate item was chosen from the search list, the “Economy” item was selected under the heading “More Information”.
4. The trophic level of the species was then found under the header “Feeding”. One trophic level was selected from the following options (from primary choice to last choice, based upon availability):
    a. Original sample from diet composition.
    b. Original sample from individual food items.
    c. Unfished population from diet composition.

Obtaining a wild trophic level value was essential to the FTL calculation, as it provided a baseline for each species. In a situation where a species was produced in an extensive (i.e. un-fed) system, the wild trophic level of a species is equivalent to its FTL, as a species consumes as it does in the wild.

3.4 Aquafeed Fractions & Marine Component of Aquafeeds

Both the aquafeed fraction of a species' diet and the marine component of the compound aquafeed were expressed as a percentage per species, per country, per year. These values were found by extensive examination of the literature. Where global mean and species/country/year-specific data were both available, the latter values were used. When more than one species/country/year-specific reference was available, the one that indicated the lowest value was used.

These two values are important factors in the FTL calculation of a species. If a species is produced in an intensive aquaculture system, they are completely fed, and hence their trophic level is completely dependent on the percentage of marine components included in that compound aquafeed and the trophic level of the associated reduction fishery species. For more information on the published literature that was used in this study see Appendix A.

3.5 Trophic Level of Reduction Fisheries

The trophic level of reduction fisheries was derived from two core databases: FishStatJ and FishBase.com. In this calculation fish meal was used to determine the trophic level of reduction fisheries for two reasons: to ensure that recorded tonnage per species was not overestimated, hence skewing the trophic level value, and because fish meal yields have a more consistent conversion ratio from wet weight to meal, while fish oil yields vary more heavily and are more sensitive to environmental changes (Parker & Tyedmers, 2012).

To calculate the trophic level of reduction fisheries:

1. The “Commodities” dataset from FishStatJ, found under the folder “Miscellaneous”, was extracted and transferred into an Excel sheet. This data set contained the reported amount of fishmeal produced in tonnes per country, per year, from 1976 to 2011.
2. The fishmeal listed under each country was either a) species specific or b) species general:
    a. If the fishmeal was species specific then it was assumed that the fish meal was indeed made up purely of one species.
        i. The wild trophic level of that species was obtained from FishBase.ca using the procedures listed in section 3.3.
        ii. The trophic level obtained from FishBase.ca will then be representative of the trophic level of that fishmeal type.
    b. If the fishmeal was species general then the species makeup of the fishmeal was estimated, based upon knowledge from the literature of the reduction fisheries in that country and the general species name.
        i. The wild trophic level of those species was obtained from FishBase.ca using the procedures listed in section 3.3
        ii. The average of the trophic levels obtained from FishBase.ca will then be representative of the trophic level of that fishmeal type.
3. The trophic level of each fish meal type and its tonnage was then used to calculate a weighted average of the trophic level of each reduction fishery, per country, per year. This value was bolded when inputted in the Excel spreadsheet to represent a visual differentiation from the general approximation explained below.

4. If a country did not have a recorded fish meal tonnage, and hence no reduction fishery, a best weighted average of all animals destined for reduction globally was calculated, per year.

Ten country-specific reduction fisheries (Chile, Denmark, Ecuador, Iceland, Japan, Norway, Peru, USA, UK, Former USSR) were calculated, with the intention of producing a more accurate FTL calculation, as species dedicated to reduction vary greatly depending on geographic location and fishery practices.

3.6 Weighted Functional Trophic Level

Once the model was completely updated and refined, the FTL of each species/country combination was calculated each year from 1970 to 2013, using the equation from Section 3.1. For any comparison that included numerous FTL values (i.e. continent, globe, species-specific) a weighted FTL calculation was required, as the weight of each unique value cannot be equivalent, as the production levels (and hence mathematical importance) of each species/country combination varied greatly.

To obtain a weighted FTL of a dataset, the FTL was multiplied by the global aquaculture production data as obtained in Section 3.2, and then divided by the identical global aquaculture production: Weighted FTL = (FTL × Production) / (Production).

Chapter 4: Results

This study included 2870 species/country combinations in a global analysis. In terms of production diversity (i.e. the number of species/country combinations per continent), Asia had the greatest amount of diversity, with 945 species/country combinations. Europe followed closely with 931, then Africa with 359, North America with 275, South America with 196, Oceania with 145, and lastly the Former USSR with 14.

Chapter 4 will present the results for: global aquaculture production tonnages, top country tonnages, top species tonnages, and illuminate the aquafeed fraction and marine component of aquafeeds for five aquatic species. It will further explore the weighted trophic level of reduction fisheries, and most importantly present the functional trophic level (FTL) values calculated by using the formula explained in Section 3.1.

4.1 Production Tonnages

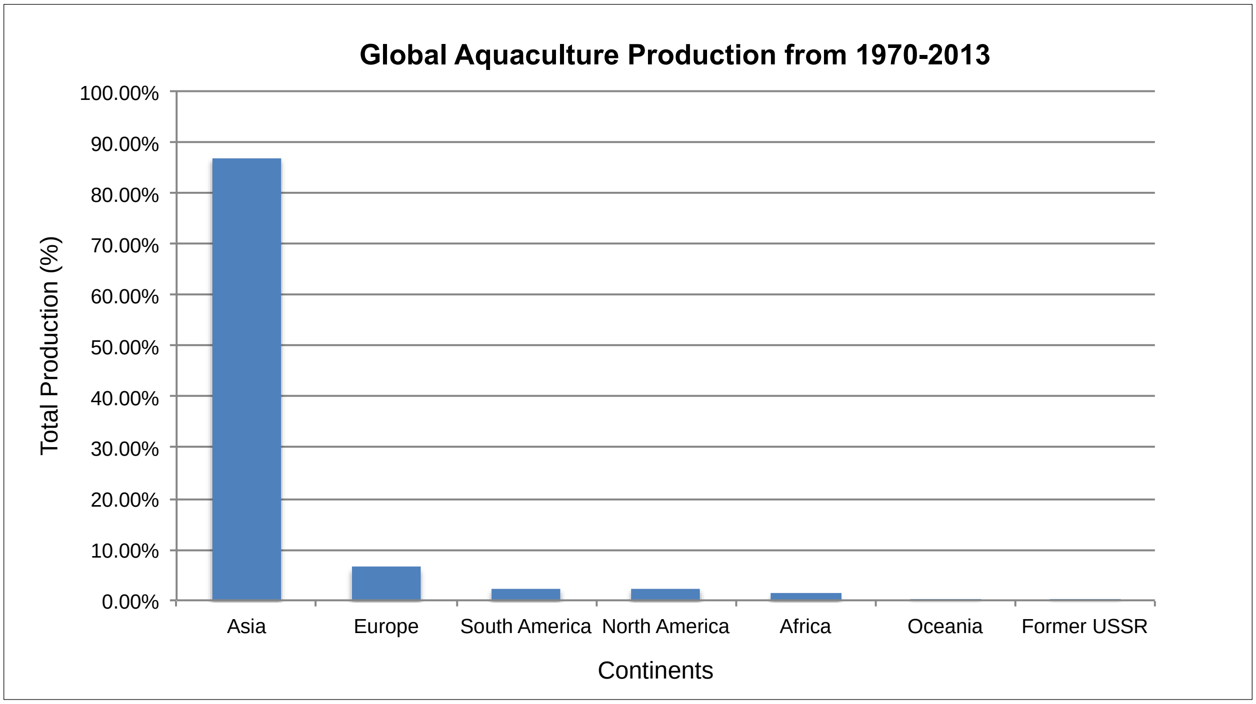


Figure 7. Total global aquaculture production (%) by continent from 1970 to 2013. Data obtained from FishStatJ (FAO, 2015).

As seen in Figure 7, Asia is the continent with the largest aquaculture production from 1970-2013 at 86.88%. This aligns with the literature, as Asia has historically been the ‘giant’ of aquaculture production. Europe produced 6.45% of global aquaculture production, South America 2.33%, North America 2.30%, Africa 1.39%, Oceania 0.34% and the Former USSR 0.31%. The domination of Asia indicates that any calculation of the weighted trophic level of the global aquaculture sector will be heavily influenced by the trophic level of the species production that occurs in Asia. Hence, separate calculations of continent-specific trophic level production were needed to obtain a more comprehensive picture of the global aquaculture sector when implementing a trophic level analysis.

Table 2 breaks down global aquaculture production data further by presenting the top aquaculture producing countries in the seven continents from 1970 to 2010. In the majority of continents, one country tends to dominate aquaculture, producing over 50% of the total continent production. Over the indicated timespan, Asian aquaculture operations occur most heavily in China, Japan, and India; North American aquaculture production is dominated by operations in the United States of America, Canada, and Mexico; South American aquaculture production is dominated by operations in Chile, Ecuador, and Brazil; African aquaculture production is dominated by operations in Egypt and Nigeria; and Oceanic aquaculture production is dominated by operations in Australia and New Zealand. In 2010, however, we see that the distribution of aquaculture is becoming more widespread, as more countries introduce aquaculture operations, or add the cultivation of new species into current facilities. Conversely, European aquaculture is an anomaly in this analysis, as production has been more evenly distributed between countries from 1970, and the top countries vary between decades. In the past two decades, however, Norway, Spain, and France have remained as the top three aquaculture-producing countries, respectively.

Table 2. Top five aquaculture-producing countries (%) by continent in 1970, 1980, 1990, 2000, and 2010. Data obtained from FishStatJ (FAO, 2015).

ASIA

Country	1970 (%)	Country	1980 (%)	Country	1990 (%)	Country	2000 (%)	Country	2010 (%)
China	42.49	China	38.09	China	60.03	China	69.82	China	69.82
Japan	16.08	Japan	16.57	India	9.42	Japan	7.24	Japan	7.24
India	6.76	India	10.57	Japan	7.44	Indonesia	5.13	Korea, Repub	5.13
Indonesia	5.94	Korea, Republ	8.3	Thailand	4.63	India	4.54	India	4.54
Philippines	5.49	Philippines	5.78	Philippines	3.52	Taiwan Provin	2.51	Thailand	2.51

EUROPE

Country	1970 (%)	Country	1980 (%)	Country	1990 (%)	Country	2000 (%)	Country	2010 (%)
Spain	31.37	France	27.28	France	16.02	Norway	23.94	Norway	40.09
France	21.38	Spain	27.1	Russian Fede	15.88	Spain	15.08	Spain	9.92
Netherlands	17.27	Netherlands	10.15	Spain	12.72	France	13.01	France	8.82
Italy	5.75	Italy	9.84	Norway	9.4	Italy	10.41	United Kingdo	7.9
Germany	4.72	Germany	5.11	Italy	9.29	United Kingdo	7.44	Italy	6.03

NORTH AMERICA

Country	1970 (%)	Country	1980 (%)	Country	1990 (%)	Country	2000 (%)	Country	2010 (%)
United States	97.41	United States	91.91	United States	78.87	United States	64.1	United States	53.15
Canada	2.07	Mexico	4.71	Canada	10.23	Canada	17.91	Canada	17.35
Mexico	0.31	Canada	1.95	Mexico	5.56	Mexico	7.55	Mexico	13.5
Cuba	0.2	Cuba	1.26	Cuba	2.04	Cuba	4.6	Cuba	3.36
Honduras	0	Panama	0.1	Panama	0.86	Honduras	1.41	Honduras	2.94

SOUTH AMERICA

Country	1970 (%)	Country	1980 (%)	Country	1990 (%)	Country	2000 (%)	Country	2010 (%)
Chile	55.02	Ecuador	61.04	Ecuador	52.58	Chile	55.34	Chile	42.92
Ecuador	15.2	Brazil	23.85	Chile	21.95	Brazil	23.96	Brazil	28.52
Peru	12.16	Peru	7.34	Brazil	13.82	Colombia	8.73	Ecuador	16.68
Venezuela	6.08	Chile	4.04	Colombia	7.07	Ecuador	8.66	Peru	5.44
Argentina	5.78	Venezuela	1.74	Peru	3.53	Venezuela	1.9	Colombia	4.88

AFRICA

Country	1970 (%)	Country	1980 (%)	Country	1990 (%)	Country	2000 (%)	Country	2010 (%)
Egypt	58.42	Egypt	77.34	Egypt	72.51	Egypt	85.76	Egypt	71.76
Nigeria	37.08	Nigeria	9.18	Nigeria	23	Nigeria	6.48	Nigeria	15.65
Kenya	2.34	South Africa	4.51	Ghana	1.1	Madagascar	1.84	Uganda	7.41
Senegal	0.97	Zambia	1.82	Kenya	0.61	Ghana	1.26	Kenya	0.95
Ghana	0.92	Kenya	1.54	Senegal	0.57	Zambia	1.07	Zambia	0.8

OCEANIA

Country	1970 (%)	Country	1980 (%)	Country	1990 (%)	Country	2000 (%)	Country	2010 (%)
Australia	83.37	Australia	73.58	New Zealand	68.04	New Zealand	70.04	New Zealand	58.89
New Zealand	16.62	New Zealand	26.34	Australia	29.5	Australia	25.96	Australia	38.16
American Sam	0	French Polyne	0.05	New Caledoni	1.5	Fiji Islands	1.46	French Polyne	1.16
Cook Islands	0	Guam	0.03	Guam	0.5	New Caledoni	1.443	Papua New G	0.84
Fiji Islands	0	American Sam	0	French Polyne	0.21	French Polyne	0.66	New Caledoni	0.65

FORMER USSR

Country	1970 (%)	Country	1980 (%)
Un. Sov. Soc.	87.9	Un. Sov. Soc.	75.45
Un. Sov. Soc.	6.05	Un. Sov. Soc.	20.2
Un. Sov. Soc.	5.66	Un. Sov. Soc.	3.68
Un. Sov. Soc.	0.39	Un. Sov. Soc.	0.65
Un. Sov. Soc.	0	Un. Sov. Soc.	0.01

In Table 3, top species production by continent, we see several trends mirrored from Table 2. In 1970 and 1980, a single species tends to dominate in production (>25%, excluding Asia). Notice that the top species are being produced in a very small number of countries per continent. Generally, we also observe a more even distribution of species production in the last decade.

Looking specifically at Asia, we see that throughout this selected time period, Chinese bivalve and carp varieties dominate species production. These are low wild trophic level species (ex. Silver Carp has a 2.40 wild trophic level) and typically do not require external feed inputs as they are produced in extensive aquaculture systems. In terms of species distribution, Asia is the most evenly distributed, with the top five cultured species cultured in quantities relatively similar to each other. This may indicate the initial and increasing diversity of Asian aquaculture, as they were shown in this analysis to have the highest diversity in terms of species/country combinations (945).

European aquaculture displays an initial focus on cultivating mussel and oyster varieties (Sea mussel, Blue mussel, Pacific cupped oyster) and then in 1990 we see the introduction of Norwegian Atlantic Salmon production, followed by Atlantic Salmon production in the United Kingdom in 2000. Atlantic Salmon is a high wild trophic level species (4.50), and it continues to rise until it becomes the top species produced in the continent. As we see Atlantic Salmon production increase we also see that the proportion of this species is increasing in relation to other species cultivation, until there is a domination of Norwegian Atlantic Salmon (36.93%) in 2010. Based solely on trophic level values, this suggests that European aquaculture may see an increasing trend in FTL from 1990 onwards. Europe recorded the second highest amount of diversity in this analysis (931), but with the domination of Atlantic Salmon this diversification of species/country combinations may be contributing minimal tonnages to continental production.

South American aquaculture shows a focus in the cultivation of Whiteleg Shrimp in Ecuador during 1970 (35.26%), 1980 (48.51%), and 1990 (46.42%). It is one of the few continents that cultivate higher wild trophic level species such as crustaceans (ex. Whiteleg Shrimp has a 2.70 wild trophic level) and freshwater finfish (ex. Rainbow trout has a wild trophic level of 4.10). In 2000 there appears to be a sharp increase in Salmon production as Atlantic Salmon, Coho (=Silver) Salmon, and Rainbow trout were the top three species cultivated in the continent. In 2010, however, there is return to Ecuadorian Whiteleg Shrimp production (13.67%), along with a diversification of continental species production.

North American aquaculture is a story of the rise and continuous authority of American Channel Catfish production. The Channel Catfish has a high wild trophic level of 4.20 and is cultured in production systems that are typically 100% fed. In 2010 there was a dynamic change in species production, as Canadian Atlantic Salmon became the second most cultivated species (10.17%). Based solely on trophic level values, the North American aquaculture system may see a relatively high FTL, reflecting the domination of American Channel Catfish production.

African aquaculture is dominated by Egypt and Nigeria, respectively. This continent has focused on the cultivation of carp and tilapia varieties, with Nile Tilapia being the most cultivated species in every decade except 1990, which focused on Common Carp production. Nile Tilapia has a low wild trophic level of 2.00, and in 2010 there was an increase of Nile Tilapia production (40.97%) when compared to the other top-produced species (8.97%; 7.77%; 7.13%; 6.92%). The prominence of low trophic level species production suggests that Africa will remain at a relatively low trophic level throughout the analysis.

Similarly, two countries dominate Oceanic aquaculture: Australia and New Zealand. Bivalve production is the most popular species for cultivation, more specifically the Sydney cupped oyster, New Zealand mussel, and Pacific cupper oyster. These species all share a low wild trophic level of 2.10. In 1990 we see the introduction of Chinook(=Spring=King) Salmon and Atlantic Salmon, with production levels remaining quite high and recording in 2010 production proportions of 16.94% (2nd highest) and 6.54% (4th highest). New Zealand mussel production, however, remained dominant in 2010 at 50.68%. Based on the low trophic level of bivalve production, but an introduction of high trophic level salmonids, it is predicted that the FTL of Oceanic aquaculture will see an increasing trend.

Lastly, when it was still in existence, the Former USSR focused on culturing carp species, specifically Common Carp. Common Carp has a wild trophic level of 3.10, and based on this it is expected that the FTL will mirror that value.

Table 3. Top five species produced (%) by continent in 1970, 1980, 1990, 2000, and 2010. Data obtained from FishStatJ (FAO, 2016).

ASIA

Country	Species	1970 (%)	Country	Species	1980 (%)	Country	Species	1990 (%)	Country	Species	2000 (%)	Country	Species	2010 (%)
China	Silver carp	14.56	China	Silver carp	11.42	China	Silver carp	12.95	China	Cupped oysters nei	10.25	China	Grass carp(=White amur)	8.1
Japan	Pacific cupped oyster	10.6	Japan	Pacific cupped oyster	7.36	China	Grass carp(=White amur)	9.47	China	Silver carp	9.93	China	Cupped oysters nei	6.99
China	Cupped oysters nei	6.83	China	Cupped oysters nei	6.18	China	Bighead carp	6.09	China	Grass carp(=White amur)	9.73	China	Silver carp	6.92
China	Bighead carp	6.47	China	Bighead carp	5.08	China	Common carp	4.84	China	Common carp	6.52	China	Japanese carpet shell	6.79
China	Grass carp(=White amur)	4.85	Korea, Repub	Pacific cupped oyster	4.87	China	Cupped oysters nei	4.66	China	Japanese carpet shell	5.03	India	Catla	5.19

EUROPE

Country	Species	1970 (%)	Country	Species	1980 (%)	Country	Species	1990 (%)	Country	Species	2000 (%)	Country	Species	2010 (%)
Spain	Sea mussels nei	30.13	Spain	Sea mussels nei	25.3	Russian Federation	Common carp	12.37	Norway	Atlantic salmon	21.46	Norway	Atlantic salmon	36.93
Netherlands	Blue mussel	17.27	France	Pacific cupped oyster	13.75	Spain	Sea mussels nei	10.82	Spain	Sea mussels nei	12.08	Spain	Sea mussels nei	7.39
France	Pacific cupped oyster	8.14	Netherlands	Blue mussel	10.14	Norway	Atlantic salmon	9.12	France	Pacific cupped oyster	6.51	UK	Atlantic salmon	6.08
France	Blue mussel	6.53	France	Blue mussel	8.85	France	Pacific cupped oyster	8.87	UK	Atlantic salmon	6.29	France	Pacific cupped oyster	3.73
France	European flat oyster	3.84	Italy	Mediterranean mussel	3.09	Netherlands	Blue mussel	6.17	Netherlands	Blue mussel	3.26	Italy	Mediterranean mussel	2.52

NORTH AMERICA

Country	Species	1970 (%)	Country	Species	1980 (%)	Country	Species	1990 (%)	Country	Species	2000 (%)	Country	Species	2010 (%)
USA	American cupped oyster	59.08	USA	American cupped oyste	35.92	USA	Channel catfish	40.82	USA	Channel catfish	37.77	USA	Channel catfish	23.24
USA	Pacific cupped oyster	16	USA	Channel catfish	19.03	USA	Pacific cupped oyster	8.65	Canada	Atlantic salmon	10.17	USA	American cupped oyster	11.58
USA	Channel catfish	10.48	USA	Pacific cupped oyster	12.97	USA	Red swamp crawfish	8.04	USA	Pacific cupped oyster	5.39	Canada	Atlantic salmon	10.86
USA	Rainbow trout	5.72	USA	Rainbow trout	11.88	USA	American cupped oyster	7.95	USA	American cupped oyster	5.37	Mexico	Whiteleg shrimp	10.62
USA	Cyprinids nei	3.29	USA	Red swamp crawfish	5.92	USA	Rainbow trout	6.43	Mexico	Whiteleg shrimp	4.41	USA	Red swamp crawfish	5.66

SOUTH AMERICA

Country	Species	1970 (%)	Country	Species	1980 (%)	Country	Species	1990 (%)	Country	Species	2000 (%)	Country	Species	2010 (%)
Chile	Chilean mussel	35.26	Ecuador	Whiteleg shrimp	48.51	Ecuador	Whiteleg shrimp	46.42	Chile	Atlantic salmon	23.59	Ecuador	Whiteleg shrimp	13.67
Ecuador	Whiteleg shrimp	15.2	Brazil	Freshwater fishes nei	21	Brazil	Freshwater fishes nei	12.17	Chile	Coho(=Silver)salmon	13.2	Chile	Chilean mussel	13.56
Chile	Chilean flat oyster	15.2	Ecuador	Blue shrimp	10.07	Chile	Coho(=Silver)salmon	8.99	Chile	Rainbow trout	11.15	Chile	Rainbow trout	12.24
Peru	Rainbow trout	12.16	Peru	Whiteleg shrimp	3	Chile	Atlantic salmon	6.41	Brazil	Common carp	7.71	Brazil	Tilapias nei	9.52
Venezuela	Rainbow trout	6.08	Ecuador	Giant river prawn	2.46	Ecuador	Blue shrimp	5.26	Ecuador	Whiteleg shrimp	7.08	Chile	Atlantic salmon	7.35

AFRICA

Country	Species	1970 (%)	Country	Species	1980 (%)	Country	Species	1990 (%)	Country	Species	2000 (%)	Country	Species	2010 (%)
Egypt	Common carp	25.31	Egypt	Nile tilapia	30.91	Egypt	Common carp	30.87	Egypt	Nile tilapia	34.51	Egypt	Nile tilapia	40.97
Egypt	Nile tilapia	21.91	Egypt	Common carp	28.62	Egypt	Nile tilapia	24.7	Egypt	Mullets nei	20.15	Nigeria	North African catfish	8.97
Nigeria	Tilapias nei	20.73	Nigeria	Tilapias nei	10.94	Egypt	Mullets nei	7.41	Egypt	Grass carp(=White amur)	16.57	Egypt	Cyprinids nei	7.77
Nigeria	Torpedo-shaped catfishes	14.52	Egypt	Grass carp(=White amu	9.54	Egypt	Grass carp(=White amur)	7.41	Egypt	Nile tilapia	4.88	Egypt	Common carp	7.13
Egypt	Grass carp(=White amur)	8.76	Nigeria	Torpedo-shaped catfish	8.73	Egypt	Nile tilapia	6.07	Egypt	Common carp	4.09	Egypt	Mullets nei	6.92

OCEANIA

Country	Species	1970 (%)	Country	Species	1980 (%)	Country	Species	1990 (%)	Country	Species	2000 (%)	Country	Species	2010 (%)
Australia	Sydney cupped oyster	83.37	Australia	Sydney cupped oyster	67.5	New Zealand	New Zealand mussel	57.1	New Zealand	New Zealand mussel	62.16	New Zealand	New Zealand mussel	50.68
New Zealand	New Zealand mussel	11.88	New Zealand	Pacific cupped oyster	13.5	Australia	Sydney cupped oyster	12.95	Australia	Atlantic salmon	8.92	Australia	Atlantic salmon	16.94
New Zealand	Pacific cupped oyster	4.75	New Zealand	New Zealand mussel	12.84	New Zealand	Chinook(=Spring=King)salmon	5.47	New Zealand	Chinook(=Spring=King)salmon	4.65	Australia	Flat and cupped oysters nei	7.95
Australia	Rainbow trout	0	Australia	Rainbow trout	5.26	New Zealand	Pacific cupped oyster	5	Australia	Sydney cupped oyster	4.06	New Zealand	Chinook(=Spring=King)salmon	6.54
Australia	Pacific cupped oyster	0	Australia	Pacific cupped oyster	0.82	Australia	Atlantic salmon	4.16	Australia	Pacific cupped oyster	3.84	Australia	Penaeus shrimps nei	2.81

FORMER USSR

Country	Species	1970 (%)	Country	Species	1980 (%)
USSR	Common carp	87.9	USSR	Common carp	75.45
USSR	Silver carp	6.05	USSR	Silver carp	20.2
USSR	Whitefishes nei	5.66	USSR	Whitefishes nei	3.68
USSR	Common carp	0.39	USSR	Grass carp(=White amu	0.65
USSR	Grass carp(=White amur)	0	USSR	Common carp	0.01

4.2 Aquafeed Fraction & Marine Component of Aquafeeds

In this Section, the results will focus on five country-specific cultured species, based on our findings from Section 4.1. These species will be: Norwegian Atlantic Salmon, Egyptian Nile Tilapia, American Channel Catfish, Ecuadorian Whiteleg Shrimp, and Chinese Silver Carp. The data points associated with aquafeed fraction and marine component of aquafeed data are derived from an extensive review of academic literature (See Appendix A). A blank space indicates that there was no data point available for a species during that time span.

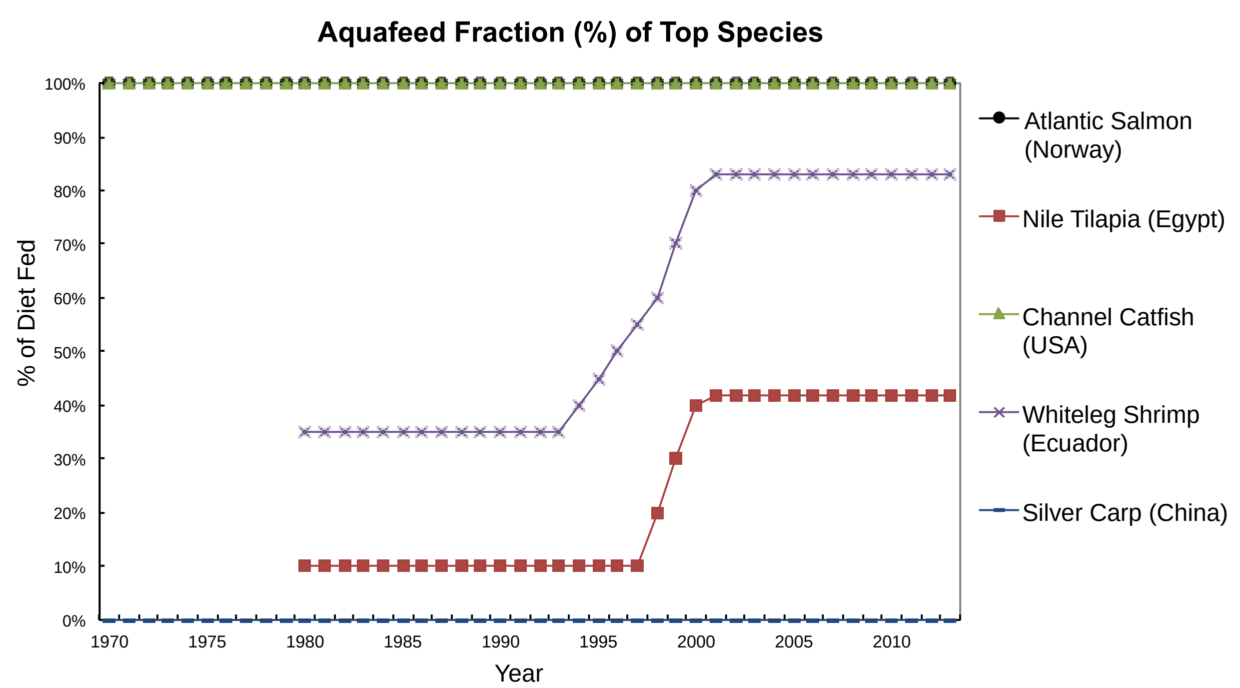


Figure 8. The aquafeed fraction (%) of a species' diet from 1970-2013.

Figure 8 reflects the percentage of a species diet that is composed of compound aquafeeds, or commercial aquafeeds. In this analysis, we make the assumption that the other portion of a species' diet consists of what they would naturally feed on in the wild. Silver Carp, as expected, does not rely on any compound aquafeed in their diet, as they are produced in extensive systems. Atlantic Salmon and Channel Catfish, however, are completely reliant on compound aquafeeds for their source of nutrition, as they are raised in intensive (artificial) systems. This means that their FTL calculation will be completely dependent upon the components found in their specific compound aquafeed formulation. Both the diets of Nile Tilapia and Whiteleg Shrimp are partially dependent upon compound aquafeeds. Whiteleg Shrimp has experienced an increased dependence from 35% in 1993 to 83% in 2001, and has remained stable since. Nile Tilapia also experienced a similar, though not as dramatic, increased dependence on compound aquafeeds from 10% in 1997 to 42% in 2001.

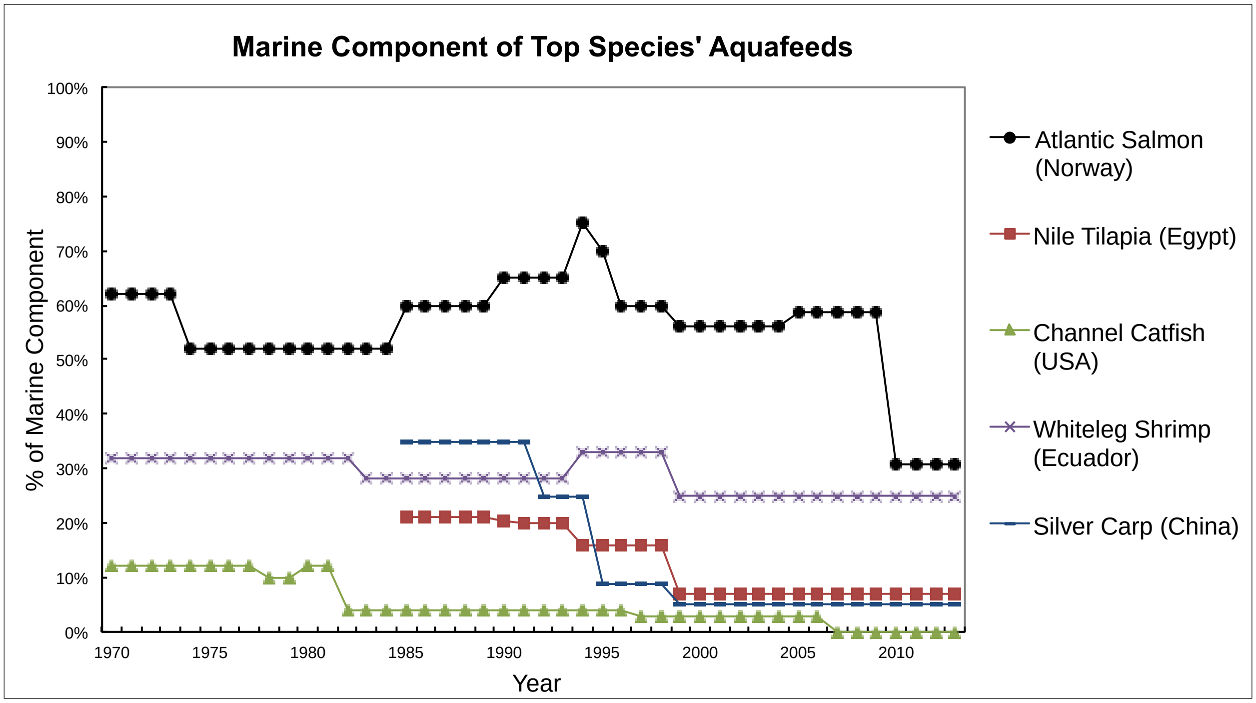


Figure 9. The marine component (%) of a species' fed diet from 1970 to 2013.

Figure 9 reflects the percentage of marine-derived components included in the formulation of a species-specific compound aquafeed. In this analysis it is assumed that a compound aquafeed is composed of both plants and animals (Fisheries Department, 2001). The portion of a compound aquafeed that is marine-derived will receive a trophic level assignment that is representative of a country's reduction fishery (if applicable) or a global-level estimation, while the remaining plant-based component will receive a trophic level assignment of 1.

Looking at Figure 9, we see that Norwegian Atlantic Salmon consumes compound aquafeeds that are largely marine-derived. It is interesting to note that from 1970 to 2009 Atlantic Salmon required compound aquafeeds with at least a 50% marine-based inclusion, until 2010 when we see a dramatic drop in feed formulation to only 31% marine-derived inclusion. Contrary to this, American Channel Catfish consumes compound aquafeeds that are largely plant-based. Generally, all species in this analysis see a reduction in the proportion of marine-derived components in their compounds aquafeeds.

4.4 Trophic Levels of Reduction Fisheries

The trophic level of a country's reduction fishery represents the trophic level of its marine-derived compound aquafeed components, in the form of fish meal and fish oil. The trophic level values vary between countries based upon geographical location and the small pelagic fish species available in that region that are dedicated to reduction fisheries. For this analysis, when a country did not have a calculated reduction fishery, a global estimation of the trophic level of reduction fisheries was used as the default.

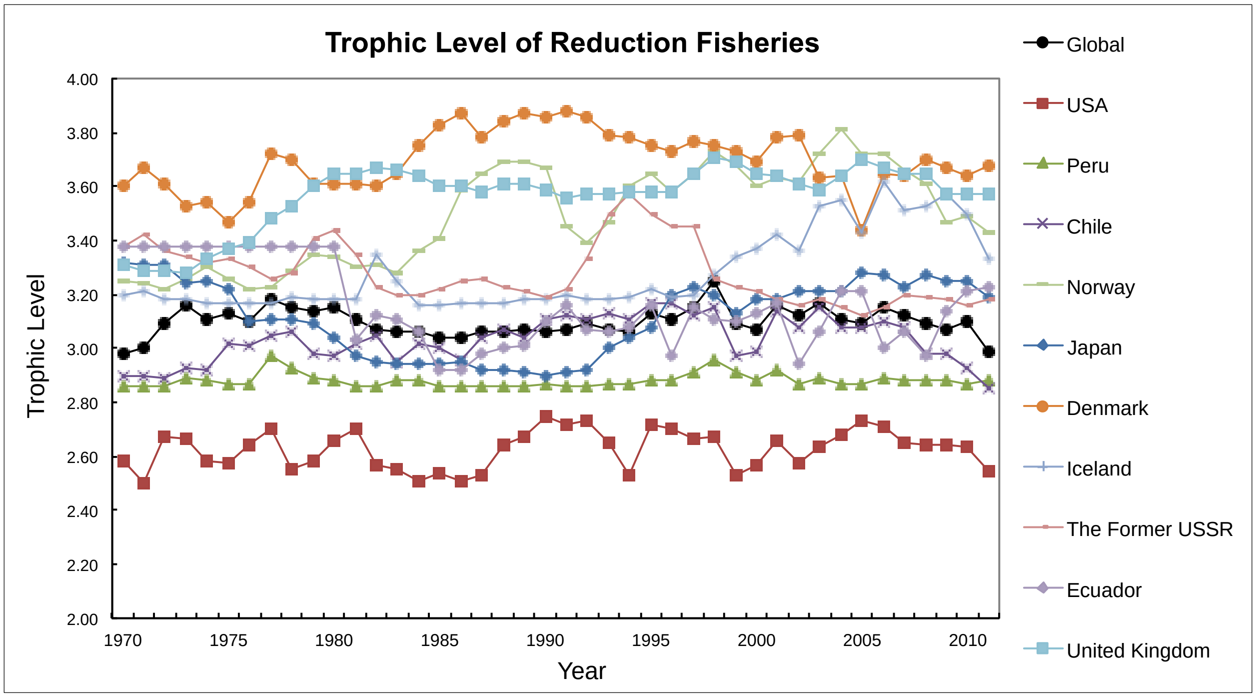


Figure 10. The weighted trophic level of global and country-specific reduction fisheries from 1970 to 2011.

In Figure 10, we see that the trophic level of reduction fisheries vary greatly, from 2.50 in the United States of America in 1984 to a 3.88 in Denmark in 1991. Though each country generally records a trophic level change each year based upon its fishery landings, the maximum change for each country is +/- 0.40 from 1970 to 2011. This indicates that there is a fairly consistent value for the weighted trophic level of global and country-specific reduction fisheries.

4.5 Functional Trophic Level

As already mentioned, the functional trophic level values represented in Figure 11, Figure 12, and Figure 13 were calculated using the formula described in Section 3.1. Additionally, they are *weighted* calculations, meaning that the production tonnages from Section 4.1 determine the magnitude of impact each species' FTL has on the final FTL value.

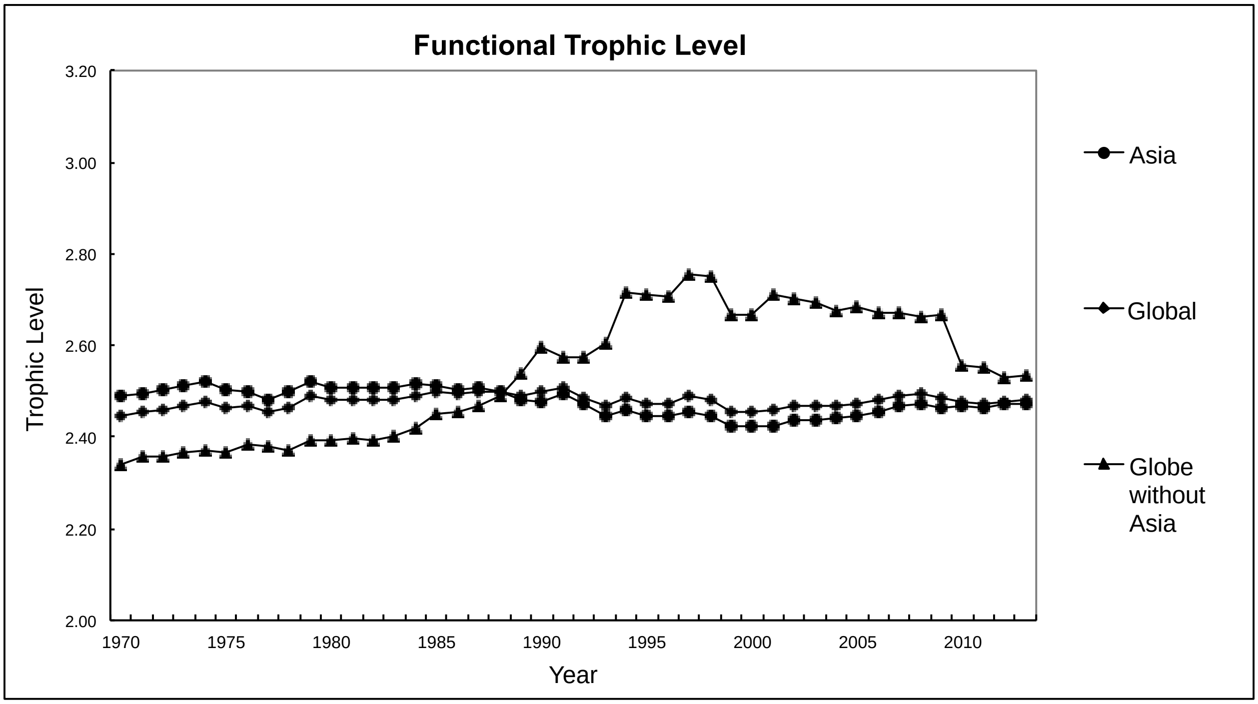


Figure 11. The weighted functional trophic level of the Globe, Asia, and the Globe without Asia from 1970 to 2013.

Figure 11 shows that the FTL of the Globe and Asia are closely mirrored, as the majority of aquaculture production (86.88%) occurs in China with mainly low trophic level species such as carp, tilapia, and bivalves. Both FTL values remain stable at around 2.50 from 1970 to 2013. When we look at the Globe without Asia there is a distinctly different trend, with FTL increasing consistently from 1970 to 1990 and then reaching a peak of 2.76 in 1997. From 1997 onwards there is a slight decrease, and eventually a large drop between 2009 and 2010, leaving the FTL of the Global without Asia at a 2.54 in 2013.

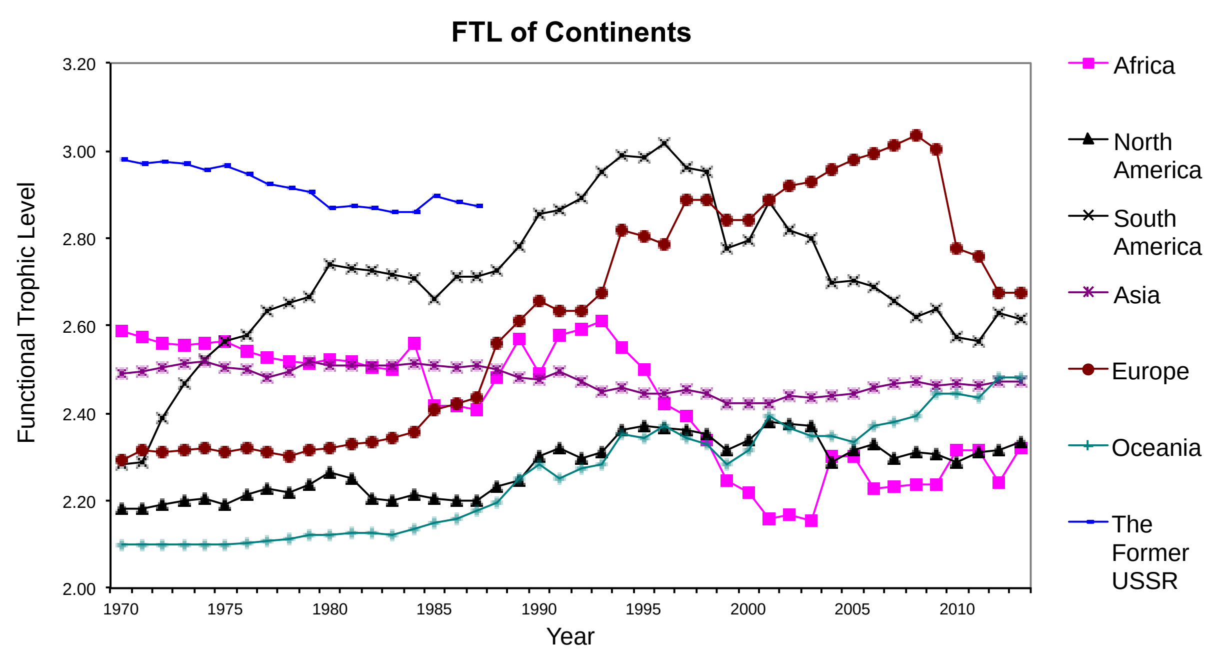


Figure 12. The weighted functional trophic level of the continents of the globe from 1970 to 2013.

When we further deconstruct global FTL to expose each continent’s respective FTL, we see some dramatic value fluctuations. Europe clearly plays a large role in the FTL of the ‘Globe without Asia’ line in Figure 11, as the increasing trend we see from 1970 to 1990 and the decreasing trend from 2009 to 2013 are reflected. This makes sense, as Europe is the second largest aquaculture-producing continent (6.45%). Below is an explanation of the trends that occur in each continent and associated reasoning:

Table 4. An explanation of the continental trends seen in Figure 12.

Continent	**Trends**	**Reasoning**
Asia	Stable FTL ranging from 2.42 to 2.51 between 1970 and 2013.	As we discovered in Section 4.1, Asia produces species that are un-fed, so this is mainly a reflection of low wild trophic level values.
Europe	Increasing FTL from 2.29 in 1970 to 2.66 1990. Sharp decrease in FTL from 3 in 2009 to 2.67 in 2013. Relatively high FTL.	The increasing trend reflects the rapid expansion of Atlantic Salmon production, which has one of the highest FTLs. The decreasing trend reflects the reduction of marine components in the compound aquafeed formulation for an Atlantic Salmon.
South America	General increase in FTL from 2.28 in 1970 to 3.02 in 1996, then a roughly decreasing FTL until reaching 2.62 in 2013. Relatively high FTL.	South America has an initially high FTL because of its crustacean and finfish production. The rise of FTL was accompanied by an expansion of salmonid production and the decline occurred after transitioning their production levels back to Whiteleg Shrimp and Chilean mussels.
North America	Gradual increase in FTL from 2.18 in 1970 to 2.37 in 1996. Overall a relatively stable, low FTL.	This trend reflects the mainly plant-based diet of Channel Catfish, which dominates North American production. Though they have a high wild trophic level, they are a completely fed species that consumes mostly plant-based compound aquafeeds (in 2013, USA Channel Catfish consumed 100% plant-derived aquafeeds). The slight increase represents the growth of Canadian Atlantic Salmon production.
Africa	FTL of 2.59 in 1970. Dramatic drop in FTL from 2.61 in 1993 to 2.15 in 2003. Lowest FTL in the past decade and a half.	This drop in FTL is a direct result of the decreasing inclusion rates of marine components in the aquafeed formulations of the top cultured species in Africa: Nile Tilapia (20% → 7%) and Common Carp (30% → 5%) between 1993 and 2003.
Oceania	Increasing FTL from 2.10 in 1970 to 2.48 in 2013. Initially the lowest FTL, now the 3rd highest.	This increasing FTL trend is due to the introduction of salmonids in the mid 1980's into what had typically been a continent dominated by bivalve production, which have a low FTL of 2.1 (equivalent to their wild trophic level).
Former USSR	Highest FTL from 1970 to 1987, ranging from 2.86 to 2.98.	This high FTL reflects the dominance of Common Carp and Silver Carp production. During this time period these species were mainly un-fed, so they reflect their wild trophic levels of 3.1 and 2.4, respectively.

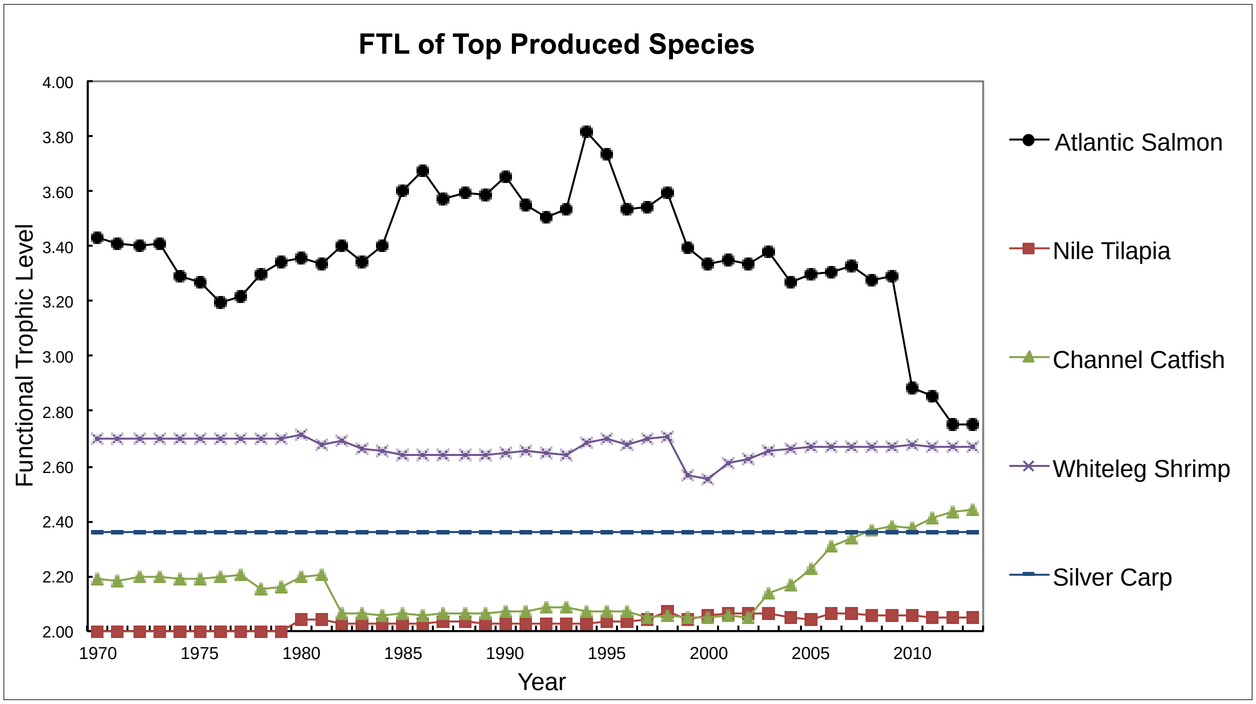


Figure 13. The weighted functional trophic level of top-produced species from 1970 to 2013.

As was alluded to, a species' functional trophic level is heavily dependent upon the proportion of marine-derived components that a species consumes from aquafeeds, in the form of fish meal and fish oil. In Figure 13, this is especially important for Channel Catfish and Atlantic Salmon, as their diet is 100% reliant on compound aquafeeds. Because of this reliance, the value of their FTL is derived directly from the formulation of their compound aquafeeds (some percentage fish-based and the remaining plant-based) and the trophic level of that fish-based component (i.e. reduction fisheries) per year. Atlantic Salmon has seen the widest variation and highest FTL values of the species examined in Figure 13. The highest weighted FTL of Atlantic Salmon was recorded in 1994 at 3.82 and the lowest at 2.75 in 2012 and 2013. For Channel Catfish, the highest weighted FTL occurred at 2.44 in 2013 and the lowest at 2.05 from 1997 to 2002. To the contrary, Silver Carp have no reliance on compound aquafeeds, and hence their FTL consistently reflects the value of their wild trophic level, which is a 2.40. Whiteleg Shrimp is becoming increasingly more dependent upon compound aquafeeds, but the marine component in those aquafeeds has remained fairly stable over the period of analysis. This has resulted in a fairly stable weighted FTL, with the highest occurring in 1980 at 2.72, and the lowest at 2.55 in 2000. Similarly, Nile Tilapia has seen an increased dependence upon compound aquafeeds, but the marine component in those aquafeeds is minimal, resulting in a weighted FTL that reflects their wild trophic level of 2.00. The highest weighted FTL for Nile Tilapia occurred in 1998 at 2.07, the lowest at 2.00 from 1970 to 1979.

Chapter 5: Discussion

5.1 Outcome of the Study and Its Relation to the Literature

5.1.1 The Rise of Atlantic Salmon and the FTL of the Global Aquaculture Sector

This study has identified the importance of the rise of Atlantic Salmon production, especially in the European, North American, and Oceanic continents. This reinforces the literature in Section 2.4 that emphasized that there is an increasing consumer demand in developed countries for high value seafood (Edwards, 2015; Tacon et al., 2010). Chapter 4 also illuminated the impact that increased Atlantic Salmon production has had on FTL values, as traditionally Atlantic Salmon (and other carnivorous marine finfish species) require a large amount of fish-derived inclusion rates (50-60%) in their aquafeed formulation, which results in an elevated FTL value, when compared to other species. This study has discovered, however, that from the years of 2010 to 2013 the fish-derived inclusion rates have dropped significantly to approximately 33%. This signals that there has been a successful substitution of plant-based feed alternatives, which has had a decreasing effect on the FTL of Atlantic Salmon, as this species is now consuming a diet that is more than 50% plant-based. Hence, their energy consumption (i.e. primary productivity required) is decreasing dramatically, as projected by Tacon et al. and Welch et al. (2008; 2010).

The calculation of the global aquaculture sector revealed a low weighted FTL of approximately 2.50 over this study's time period. This FTL reflects the weighted trophic level value obtained by Tacon et al. between the years 1950 and 2006, which was approximately 2.6 (2009). Tacon et al.'s analysis assumed that the consumption patterns of a species in the wild and a species in culture were identical, hence equating their trophic levels (2009). Based upon this study's results in Chapter 4, this logically follows, as the Globe is dominated by Asian production, which is largely comprised of extensive (i.e. un-fed) production systems. Therefore, in the majority of species that heavily impacted the weighted Global FTL calculation, the trophic level of a cultured species was indeed equivalent to its wild trophic level.

5.1.2 The Results and Their Sustainability Implications

On a larger scale, the findings in Section 5.1.1 indicate that a fundamental change is occurring in the aquaculture industry. As production levels continue to grow, this study shows that the majority of cultured species are becoming more dependent on compound aquafeeds (possibly due to the introduction of highly productive intensive (i.e. fed) aquaculture systems). The composition of these aquafeeds, however, is in the process of overcoming traditional fish-based dependence towards a formulation that is dominated by plant-based inclusions. This opposes the Mediterranean mariculture study conducted by Stergiou et al., which argued that the aquaculture sector is "farming up the food web" (2009).

Though this study does reinforce Stergiou et al.'s (2009) conclusion that there has been an increased production of more high value, high trophic level species, the feeding consumption patterns of those same species transforms their wild trophic levels to the FTL values listed in Table 5.

Table 5. Top five species' wild trophic levels versus their weighted FTLs in 1998 and 2013.

Species (Common Name)	**Wild FTL[1]**	**1998 FTL**	**2013 FTL**
Atlantic Salmon	4.5	3.39	2.75
Nile Tilapia	2.00	2.07	2.05
Channel Catfish	4.20	2.05	2.44
Whiteleg Shrimp	2.70	2.71	2.67
Silver Carp	2.40	2.36	2.36

[1] Wild trophic levels obtained from FishBase.com

It is important to consider the implications of these results in terms of the sustainability of the aquaculture industry. Firstly, the majority of global aquaculture production consistently occurs in Asia at a low trophic level (bivalves and carp varieties). Hence, overall, the characterization of the sector could be considered sustainable in terms of energy consumption in a trophic level analysis.

For high trophic level species, which are the species that are often marked as the most problematic in terms of sustainability, because they require increased amounts of nutrient-rich inputs to produce a single market-ready fish (Pauly et al., 2001b), this narrative is shifting. Though the above statement was true from the 1970s to the 2000s, it appears that the aquaculture sector has addressed this concern in countries with high levels of production by reducing the amount of ‘nutrient-rich’ inputs into the feed formation of many high trophic level species. Table 5 exemplifies this change.

Hence this evaluation results in the conclusion that the sustainability of the aquaculture sector has increased over the indicated study period, as the sector has shown a decreasing dependence on fish meal and fish oil in compound aquafeeds. It is important to note, however, that a study conducted by Ardura et al. revealed, using DNA analysis, the presence of high trophic level marine fish in three different types of commercial fish meal in Spain (2012). This is contrary to the understanding that fish meal is largely produced using small pelagic species that are dedicated to reduction fisheries. This revelation, if confirmed elsewhere, would change the results of this study drastically, as high trophic level species destined for reduction would result in a higher trophic level calculation of reduction fisheries and influence the FTL calculations towards a higher value, resulting in a different conclusion on the topic of the global aquaculture sector’s sustainability.

5.1.3 The Results and Their Global Food Security Implications

In terms of food security, based purely on energy consumption represented by this trophic level analysis, this study aligns with the narrative that aquaculture production could sustainably expand and contribute to global food security. This conclusion is largely due to the changing formulation of compound aquafeeds, which suggests that the dependence of the aquaculture sector on fish-based feed derivatives, in the form of fish meal and fish oil, is decreasing. This suggests that there would be potential for these nutrient-rich small pelagic fish resources to be re-directed for immediate human consumption. This could further increase food availability for low-income populations, as the fisheries sector is uniquely positioned to provide affordable and high quality nutrients to vulnerable populations (Tacon et al., 2010).

This study indicates, that in terms of energy consumption, there is additional potential for the sustainable expansion of the global aquaculture sector. This is due to the reduction of the aquaculture sector's dependence on marine capture fisheries coupled with the projected growth of the aquaculture sector, which are consequences of capture fisheries productivity reaching their maximum sustainability production limit, as well as the projected increasing demand for seafood products (Sarker & Vandenburg, 2012; Welch et al., 2010).

5.2 Limitations and Delimitations of Study

This study, being the first of its kind, attempted to produce an accurate depiction of the global aquaculture sector. It is acknowledged, however, that this analysis is a coarse reflection of the world, due in part to the delimitations and limitations listed below.

The delimitations of the study are as follows:

- Only countries listed in the Food and Agricultural Organization (FAO) aquaculture production database (FAO, 2015) were included in the trophic level analysis, unless mentioned otherwise in the academic literature.
- Based on the trend of more accurate data reporting and the beginning of aquaculture production in many countries, the time span of this study covered the years 1970 to 2013, inclusively.
- Due to time constraints, the implications of terrestrial-based animal derivatives (found in small amounts in some compound aquafeeds) were not considered when calculating functional trophic levels (i.e. blood, feather and meat meals).
- Additionally, due to time constraints, the trophic level of reduction fisheries was over-simplified. These trophic levels do not take into account the trade that occurs between countries, does not encompass all of the countries that currently have a reduction fishery, and does not consider that there is often the inclusion of many by-product meals in any singular type of fish meal that is created.
- It was also brought to the author's attention that Japan's reduction fishery is unique in the fact that it does not dedicate purely small pelagic fish toward reduction, but also a wide array of high trophic level pelagic species (personal communication, W. Swartz, February 2, 2016). The current representation of Japan's reduction fishery does not consider the inclusion of any species other than small pelagic species, and hence is limited in its accuracy.

The limitations of the study are as follows:

- All information provided by the FAO databases is acknowledged as being imperfect, as the information compiled for the databases is mainly self-reported by country.

- The length of the study will not exceed the date of 18 April, 2016.

5.3 Future Work

Moving forward, future work would first address the limitations of this study. This would encompass the inclusion of terrestrial-based animal derivatives found in compound aquafeeds, the expansion of the trophic level of reduction fisheries to include additional countries, and an exploration into the species comprising Japanese reduction fisheries to ensure that the reduction fishery calculations in this model are an accurate reflection of current Japanese reduction fishery practices.

Future work would also tackle the development of an algorithm that will smooth the data points that are currently represented as step functions in Figure 8 to Figure 13. The smoothing of data points will result in a more accurate representation of the data, as it is unlikely that such large fluctuations were seen within a single year. This statement is especially relevant to Figure 8 and Figure 9 (‘Aquafeed Fraction of Diet’ and ’Marine Component of Aquafeed’).

Lastly, the development of a trophic level model was purposeful, in that it can be easily transformed to indicate primary productivity required to sustain the global aquaculture sector and the total carbon appropriated by the global aquaculture sector. These avenues will be pursued, along with the continued research and input of new data points for the model. Additional data is critical for future work, as it will strengthen the model, especially the strength of observations that can be made when referring to any specific country and species combination.

Ultimately, the goal of future work pertaining to this study is to build a platform from which to examine the magnitude of resources that the aquaculture sector draws upon globally in comparison to other food production sectors.

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Appendix A

Group/species	Country	Year	Fish meal %	Fish oil %	Plant %	Marine Component of Diet %	Reference
Fish	USA	1940	24	0	52	24	Halver, 1972
Catfish (warm-water fish)	USA	1947	16.6	0	66.6	16.6	Shell, 1966
Catfish (warm-water fish)	USA	1957	15	0	85	15	Shell, 1966
Trout	USA	1964	730	0	1045	36.5	Halver, 1972
Catfish (warm-water fish)	USA	1966	5	0	80	4.5	Shell, 1966
Eels (Anguilla japonica)	Taiwan	1969	60	0	40	60	Swingle, 1969 and Chen, 1976
Trout	Japan	1969	38	0	62	38	Swingle, 1969
Catfish	USA	1970	240	0	1560	12	Hastings, 1970
Japanese Eel	Japan	1973	66	0	34	66	Swingle, 1969 and Schmittou, 1972
Penaeid Japonicus	Japan	1974	620	0	380	62	Cuzon, 1994
Milkfish	Indonesia	1975	10	0	90	10	New, 1987
Freshwater Prawns	Indonesia	1976	20	0	80	20	New, 1987
Freshwater Prawns	Indonesia	1976	30	0	70	30	New, 1987
Catfish (warm-water fish)	USA	1978	10	0	88	10	Lovell, 1980
Tilapia	South America	1978	33	0	67	33	Cruz, 1978
Sparus aurata	South Africa	1979	15.6	0	71.4	15.6	Marais, 1979
Marine Shrimp	Indonesia	1980	54	0	46	54	New, 1987
Catfish	Thailand	1981	56	4	40	60	New, 1987
Channel Catfish	USA	1981	12	0	78	12	New, 1987
Atlantic Salmon	U.K	1982	90	0	10	90	New, 1987
Catfish	Hungary	1982	60	0	40	60	New, 1987
Common Carp	Israel	1982	15	0	85	15	New, 1987
Common Carp and Tilipia	Israel	1982	30	0	70	30	New, 1987
Common Carp, Channel Catfish &Tilipia	Mexico	1982	0	0	100	0	New, 1987
Freshwater Prawns	Thailand	1982	24.5	3	72.5	27.5	New, 1987
Indian Carps	India	1982	0	0	100	0	New, 1987
Pacific Salmon	USA	1982	68	10	22	78	New, 1987
Raibow Trout	Denmark	1982	71.2	3	25.8	74.2	New, 1987
Tilipia	Central African Republic	1982	0	0	92	0	New, 1987
Tilipia	Philippines	1982	0	0	70	0	New, 1987
Tilipia	Philippines	1982	23	0	77	23	New, 1987
Tilipia	Sri Lanka	1982	0	0	95.34	0	New, 1987

Group/species	Country	Year	Fish meal %	Fish oil %	Plant %	Marine Component of Diet %	Reference
Catfish (warm-water fish)	USA	1983	4	0	88.5	4	Anov. 1983
Channel Catfish	USA	1983	4	0	88.5	4	New, 1987
Chinook Salmon	B.C, Canada	1983	356	120.8	484.6	47.7	March, 1987
Common Carp	USA	1983	15	0	85	15	Anov. 1983
Marine Shrimp	USA	1983	25	0	50	33.3	New, 1987
Rainbow Trout	B.C, Canada	1983	400	50	450	45	March, 1988
Shrimp	USA	1983	25	0	75	25	Anov. 1983
Tilapia	USA	1983	5	0	95	5	Anov. 1983
Trout/Salmon	B.C, Canada	1983	250	80	550	33	March, 1989
Freshwater Prawns	Malaysia	1984	10.5	0	89.5	10.5	New, 1987
Grouper/Seabass	Southeast Asia	1984	34	3	53	37	Boonyaratpalin, 1997
Marine Shrimp	Malaysia	1984	33	0	67	33	New, 1987
Marine Shrimp	Malaysia	1984	27	0	63	27	New, 1987
Rabbitfish	Malaysia	1984	15	0	85	15	New, 1987
Rabbitfish	Southeast Asia	1984	15	0	85	15	Boonyaratpalin, 1997
Sea Bass and Gropers	Malaysia	1984	67.5	0	32.5	67.5	New, 1987
African Catfish	Central African Republic	1985	0	0	94	0	New, 1987
Indian Carps	Indian Sub-Continent	1985	0	0	100	0	New, 1987
Freshwater Prawns	Hawaii	1986	1.5	0	90.5	1.5	New, 1987
Marine Shrimp	Bangladesh	1986	20	0	50	20	New, 1987
Colossoma macropomum	Brazil	1987	35	0	60	35	Merola, and Cantelmo, 1987
Sea Bass and Gropers	Indonesia	1987	71	3	20	74	New, 1987
Asian Seabass	Southeast Asia	1988	70	1.5	28.5	71.5	Boonyaratpalin, 1997
Milkfish	Southeast Asia	1988	46	3	51	49	Boonyaratpalin, 1997
Salmon	USA	1988	60	10	27	70	Laird, 1988
Trout	USA	1988	30	10	37	40	Laird, 1988
Grouper	Southeast Asia	1989	75.5	4	20.5	79.5	Boonyaratpalin, 1997
Marine Fish	Japan	1989	56.4	0	43.6	56.4	Honma, 1993
Penaaeid Monodon	South East Asia	1990	500	0	500	50	Cuzon, 1994
Rabbitfish	Southeast Asia	1990	22	2	76	24	Boonyaratpalin, 1997
Black Carp	China	1991	35	0	65	35	Lin, 1991
Eel	China	1991	80	0	20	80	Lin, 1991
Finfish	Philippines	1991	12.5	0	86.5	12.5	Cruz, 1997
Grass Carp	China	1991	10	0	90	10	Lin, 1991

Group/species	Country	Year	Fish meal %	Fish oil %	Plant %	Marine Component of Diet %	Reference
Milkfish	Philippines	1991	4	0	96	4	Pascual, 1995
Milkfish	Southeast Asia	1991	8	0	92	8	Boonyaratpalin, 1997
Shrimp	Philippines	1991	45	0	54	45	Cruz, 1997
Tilapia	China	1991	15	0	85	15	Lin, 1991
Tilapia	Philippines	1991	21	0	79	21	Pascual, 1995
Black Carp	China	1992	5	0	84.83	5	Li, 1994
Blunt Snout	China	1992	2.67	0	94	2.7	Li, 1994
Catfishes	Global	1992	5	2	93	7	New, 1994
Common Carp	China	1992	23.75	0	64.63	23.8	Li, 1994
Common Carp	Global	1992	20	10	70	30	New, 1994
Eels	Global	1992	40	10	50	50	New, 1994
Freshwater Prawns	Global	1992	20	1	79	21	New, 1994
Grass Carp	China	1992	10.15	0	88.6	10.2	Li, 1994
Marine Shrimps	Global	1992	25	3	72	28	New, 1994
Milkfish	Global	1992	15	7	78	22	New, 1994
Other Carnivorous Fish	Global	1992	60	12	28	72	New, 1994
Other Crustacea	Global	1992	20	1	79	21	New, 1994
Salmons	Global	1992	50	15	35	65	New, 1994
Seabreams/Seabasses	Global	1992	60	12	28	72	New, 1994
Tilapia	China	1992	6.5	0	47.25	6.5	Li, 1994
Tilapias	Global	1992	20	0	80	20	New, 1994
Trouts	Global	1992	30	10	60	40	New, 1994
Yellowtails	Global	1992	60	12	28	72	New, 1994
Snakehead	Thailand	1994			15	85	Webster & Lim 2002
Fish (freshwater)	Nepal	1995	7.5	0	88.5	7.5	Pantha, 1995
Arctic Char, *Salvelinus alpinus*	Norway	1995	60.8	12.5	26.7	73.3	Hatlen, 1995
Brood Char	Quebec, Canada	1995	464	110	426	57.4	Guillou, 1995
Carp	Global	1995	8	1	91	9	Tacon, 1997
Carp	Bangladesh	1995	0	0	100	0	Zaher, 1995
Carp	Vietnam	1995	15	0	65	15	Luu, 1995
Catfish	Global	1995	5	2	93	7	Tacon, 1997
Catfish	Bangladesh	1995	40	0	60	40	Zaher, 1995
Catfish	Thailand	1995	15	2	83	17	Jantrarotai; and Somsueb, 1995
Catfish	Thailand	1995	75	0	25	75	Somsueb, 1995
Channel Catfish	USA	1995	4	0	92	4	Kim, 1995
Channel Catfish	USA	1995	100	30	870	13	Lumlertdacha, 1995
Common Carp	Nepal	1995	13.6	0	86.4	13.6	Pantha, 1995
Eel	Global	1995	50	10	40	60	Tacon, 1997
Freshwater Prawn	Thailand	1995	35	0	65	35	Somsueb, 1995
Gilthead Seabream	Spain	1995	76.61	5.99	17.4	82.6	Robaina, 1995

Group/species	Country	Year	Fish meal %	Fish oil %	Plant %	Marine Component of Diet %	Reference
Herbivorous Fish	Thailand	1995	16	0	84	16	Somsueb, 1995
Hybrid Striped Bass	USA	1995	392.8	53.9	553.3	44.7	Sullivan, 1995
Marine Fish	Global	1995	50	15	35	65	Tacon, 1997
Marine Shrimps	Global	1995	30	3	67	33	Tacon, 1997
Marine Shrimps	Thailand	1995	47	0.5	51.5	47.5	Boonyarapalin, 1995
Marine Shrimps	Thailand	1995	64.5	0.5	35	65	Boonyarapalin; and Souueb, 1995
Milkfish	Global	1995	15	5	80	20	Tacon, 1997
Milkfish	Philippines	1995	13.5	2.1	84.4	15.6	Sumagaysay, 1995
Nile Tilapia, *Oreochromis niloticus*	Mexico	1995	59.46	1.15	39.39	60.6	Reyes-Sosa, 1995
Rainbow Trout, *oncorhynchus mykiss*	Portugal	1995	40	6	47	46	Gomes, 1995
Salmon	Global	1995	45	25	30	70	Tacon, 1997
Shrimp	Bangladesh	1995	20	0	50	20	Zaher, 1995
Shrimp	India	1995	35	0	62	35	Nandeesha, 1995
Shrimp	Vietnam	1995	74.58	0	25.42	74.6	Luu, 1995
Snakehead	Thailand	1995	70	0	20	70	Jantrarotai; and Somsueb, 1995
Snakehead	Thailand	1995	90	0	10	90	Somsueb, 1995
Tiger Shrimp	Malaysia	1995	55.5	1	45.5	55.4	Utama, 1995
Tilapia	Global	1995	15	1	84	16	Tacon, 1997
Tilapia	Malaysia	1995	20	0	80	20	Utama, 1995
***Tor* spp., *acrossocheilus* and Trout**	Nepal	1995	20	0	80	20	Pantha, 1995
Trout	Global	1995	35	20	45	55	Tacon, 1997
Red Drum/Channel Catfish	USA	1996	280	38.6	681.4	31.86	McGoogan, 1996
Red drum, *Sciaenops ocellatus*	USA	1996	50.3	2.7	47	53	Gaylord, 1996
Rainbow trout	Germany	1997	15	8	37	23	Schuhmacher, 1997
Striped Bass and Hybrids	USA	1997	33.1	5	61.9	38.1	Gatlin, 1997
Freshwater Prawn	USA	1998	7.5	0.5	84.5	8	Tidwell, 1998
Rainbow trout	Canada	1998	28	8	50	36	Vandenberg, 1998
Rainbow trout	Europe	1998	580	170	220	77.3	Rouhonen, 2000
Coho Salmon	USA	1999	574	130	301	70	Arndt, 1999
Japanese Flounder	Japan	1999	75	6	19	81	Kikuchi, 1999

Group/species	Country	Year	Fish meal %	Fish oil %	Plant %	Marine Component of Diet %	Reference
Rainbow Trout	Canada	2000	39	11.5	37.5	50.5	Bureau, 2000 and Vandenberg, 1998
Atlantic Salmon	Norway	2000	61.31	20.6	18.09	81.9	Oparvest, 2000
Atlantic Salmon	Norway	2000	354	245	401	59.9	Nordrum, 2000
Catfish	USA	2000	0	32.5	568.5	3.2	Lim, 2000
Salmon	Canada	2000	380	180	320	56	Peter, 2000
Seabass/Seabream	Europe	2000	31.1	8.8	60.1	39.9	Coutteau, 2000
Seabass/Seabream	Europe	2000	25.4	6	63.3	31.4	Coutteau, 2000
Silver Perch	Australia	2000	27.1	0	70.86	27.1	Booth, 2000
Pangasius Catfish	Thailand	2002	15		84	15	Booth, 2000
Red Drum	USA	2002	32.3	5	52	37.3	Booth, 2000
Snakehead	Thailand	2002	17.5		31.5	67.5	Booth, 2000
Coho Salmon	USA	2003	516.6	86.1	231.2	60.3	Murray et al 2003
Coho Salmon	USA	2003	51.66	8.61	22.25	60.3	Murray et al, 2003
Grouper	Indonesia	2005	13	4	26	72	Nur 2007
Salmon	Scotland	2005	391.7	276.5	316.1	66.8	Young et al 2005
Tilapia	Nigeria	2005	15	4	76	19	Fagbenro & Adebayo, 2005
Major Indian Carp, Rohu, Mrigal Carp	India	2006	5		94	5	Biswas et al, 2006
Silver Barb	India	2006	15	2.5	77.5	17.5	Mohanta et al, 2006
Atlantic Cod	Norway	2007	69.4	11.2	19	80.6	Olsen et al, 2007
Black Tiger Shrimp	Thailand	2007	33	0.5	46.4	47.5	Olsen et al, 2007
Chinese River Crab	China	2007	24.5		68.05	24.5	Olsen et al, 2007
Clariid Catfish	Thailand	2007	20	3	74	23	Throngood 2007
Common Carp	China	2007	3	0	-1930	3	Throngood 2007
Common Carp	Malawi	2007			100	0	Hecht 2007
Crucian Carp	China	2007	3	0	-1907	3	Hecht 2007
Eel	China	2007	62	0	32.2	62	Hecht 2007
Fleshy Prawn	China	2007	25	2	50	40.5	Hecht 2007
Flounder	China	2007	42	0	43	42	Hecht 2007
Giant Freshwater Prawn	China	2007	23.5		71.45	23.5	Hecht 2007
Grass Carp	China	2007	0	0	97.75	0	Weimin & Mengquing, 2007

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Mozambique Tilapia	Malawi	2007			100	0	Hecht 2007
Nile Tilapia	Cameroon	2007	11		75	11	Hecht 2007
Nile Tilapria	China	2007	4	0	86.6	4	Weimin & Mengquing, 2007
Oriental River Prawn	China	2007	15.5		71.25	15.5	Weimin & Mengquing, 2007
Pacific White Shrimp	China	2007	23	1	64.6	27	Weimin & Mengquing, 2007
Red Sea Bream	China	2007	30	4	56	34	Weimin & Mengquing, 2007
Salmon	Canada	2007	285	90	515	37.5	Pelletier & Tyedmers 2007
Salmon	Norway	2007	33.1	25.5	41.4	58.6	Pelletier et al 2009
Salmon	UK	2007	40.5	26.1	33.4	66.6	Pelletier et al 2009
Salmon	Canada	2007	20.9	10.7	48.5	31.6	Pelletier et al 2009
Salmon	Chile	2007	25.1	17.1	42.7	42.2	Pelletier et al 2009
Seabass	Thailand	2007	70	1.5	24.4	71.5	Pelletier et al 2009
Sharptooth Catfish	Kenya	2007	50		49	50	Hecht 2007
Sharptooth Catfish	Nigeria	2007	25	6	54	31	Hecht 2007
Sharptooth Catfish	Uganda	2007	2		50	2	Hecht 2007
Sharptooth Catfish	Cameroon	2007	11		75	11	Hecht 2007
Shrimp	India	2007	15	1-2%	33-51	Range	Ayyappan & Ali, 2007
Tilapia	Indonesia	2007	3	2	92	5	Pelletier & Tyedmers 2010
Tilapia	Thailand	2007	20		77	20	Pelletier & Tyedmers 2010
Tilapia	Kenya	2007	16		84	16	Nyandat 2007
Trout	Chile	2007	25.1	17.2	42.7	42.3	Pelletier et al 2009
Turbot	China	2007	45	1	40.5	46	Pelletier et al 2009
Wuchang Bream	China	2007	0	0	97.75	0	Pelletier et al 2009
Malabar Grouper	China	2008	50	3.4	36.9	53.4	Wang et al 2008
Black & Red Pacu	USA	2009	10		89	10	Lochmann & Chen, 2009
European Seabass	Greece	2009	42	8	45	50	Aubin et al 2009
Rainbow Trout	France	2009	69		30.1	69	Aubin et al 2009

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Turbot	France	2009	63.5	5	27.5	68.5	Aubin et al 2009
Black Carp	China	2011	150	34	630	18.4	Sun et al, 2011
Rice Field Eel	China	2011	500	0	440	500	Yuan et al, 2011
Black Pacu	Peru (Artisanal)	2012	6		94	6	Avadi et al 2015
Black Pacu	Peru (Commercial)	2012			88	0	Avadi et al 2015
Salmon	Canada	2012	18.4	9.8	46.3	28.2	McGrath et al 2015
Salmon	Norway	2012	19.5	11.2	69.3	30.7	Ytrestoyl et al 2015
Tilapia	Peru (Generic)	2012	10	0.3	89.7	10.3	Avadi et al 2015
Tilapia	Peru (Commercial)	2012	4	1	90	5	Avadi et al 2015
Channel Catfish	USA	2013			92.22	0	Menghe & Robinson, 2013
Signal Crayfish	Spain	2013	61.5	3	17.13	64.5	Fuertes et al, 2013
Yellowtail	Japan	2014	60	16	20	76	Khaoian et al, 2014
Black Carp	China	2015	20	1.5	74.86	21.5	Hu et al, 2015
Trout	Peru (Artisanal)	2015	40	5	55	45	Avadi et al 2015
Trout	Peru (Commercial)	2015	20	6	52.5	26	Avadi et al 2015
Salmonids	Chile	1980s	73	5	22	78	Hardy, 1994.
Salmonids	Chile	1990s	60	12	28	72	Hardy, 1994.