TRENDS IN AQUACULTURE PRODUCTION AND ITS ROLE IN MEETING HUMAN PROTEIN NEEDS

by

Zhi Ying Lin

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ABSTRACT

Regional and global trends in aquaculture production, value and price are assessed for the last 30 years relative to trends in wild caught species. Based on data from the Fisheries and Aquaculture Department of the Food and Agriculture Organization of the United Nations for aquaculture production, data is extracted for the first time to address regional (Europe, North America, South America, Africa, Oceania and Asia) trends in production focused on the top five aquaculture produced species. Previous uses of the database have largely focused on global production. Of the top five species (whiteleg shrimp *Penaeus vannamei*, Atlantic salmon *Salmo salar*, silver carp *Hypophthalmichthys molitrix*, common carp *Cyprinus carpio*, and giant tiger prawn *Penaeus monodon*), Asia accounts for most of the global production (with the exception of Atlantic salmon *Salmo salar*). The central issue considered in this thesis concerns the likelihood and capacity of aquaculture production of fish and shellfish protein for human consumption relative to that of exploited wild stocks. Over the last 30 years or so, aquaculture production has risen exponentially and captures of wild caught fish have now plateaued. The relative status, rearing practices, production and basic economic perspectives of the principle aquaculture produced species globally are compared with wild caught production. The principle finding is that total global aquaculture production will exceed that of commercial wild caught species by about 2015. The significance of this is discussed in terms of current views of environmental (e.g. pollution, disease and habitat degradation) and economic (e.g. production level, farm price, marketing economics, fixed costs (facility and equipment depreciation, loan interest, land lease, fixed wages), variable costs (cost of seed stock, feed, energy)) impacts of aquaculture. Similarly, these issues are considered for the fishing industry (e.g. fishing down the food web, likelihood of expansion of bottom fisheries into deeper waters, reduction of biodiversity, declining global catches). It is concluded that aquaculture is a necessity and that if current trends continue aquaculture production can more than supplement human fish protein needs even in the given context of the rapid growing population, but that in the long term aquaculture production will itself be substantially supplemented by "rebounding" wild fishery production.

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ACKNOWLEDGEMENTS

I would like to thank Dr. Robert Blake and James Brander, for their support, encouragement and patience during the time of my project. They were very helpful every step of the way. I would also like to thank the members of the Blake lab for their support and encouragement throughout the process. I enjoyed the weekly lab meetings which helped me with my research and my time doing this interdisciplinary project. I have learned a lot during the process. I am grateful to my family and friends for their continual support and encouragement.

1. INTRODUCTION

The total human protein supply includes vegetable proteins, animal proteins, milk and dairy products, eggs, in addition to fish. Currently, vegetable proteins constitute the most common source of protein for the world with the exception of North and Central America. On a global scale, fish constitute roughly fifteen percent of total protein consumed on a weight per capital per day basis. (Data was obtained from the Fisheries and Aquaculture Department of the Food and Agriculture Organization of the United Nations for Aquaculture production from 2006). The contribution of fish relative to other protein sources in the human diet of the future depends on the total contribution wild caught fish and that produced by aquaculture.

With few exceptions (e.g. Southeast Atlantic, Southwest Pacific and West Central Pacific Oceans), all of the world's major fishing areas have shown minor changes or declines in landings such that yields are now at their maximum sustainable level (FAO 2000) and global landings of marine caught fish are leveling off. Sustainable aquaculture (fish and shellfish farming) is needed to supplement the world's food protein needs. Future increases of wild capture from these areas are not expected. Currently, the wild capture fisheries production on a global basis is estimated to be between 89.5 to 93.8 million metric tonnes (FAO 2000). This figure includes that for the production of fish meal and oil. There is concern that these levels of production will not be indefinitely sustainable. Indeed, of the eighty-two fish species that are at risk of extinction, a number are currently fished (e.g. several species of shark, skate, sturgeon, smelt, cod, rockfish, grouper, Atlantic salmon *Salmo salar*, Atlantic halibut *Hippoglossus hippoglossus*) (Martin, 2002). In addition, the main regions where total captures may still be following an increasing trend are those where the state of exploitation is largely unknown or uncertain (Martin, 2002).

With this as a backdrop, the role of aquaculture is increasingly viewed as one that may provide for the world's future protein needs. Indeed, aquaculture may have the potential to supplement and/or replace wild captured species for human consumption. Aquaculture involves activities and processes that are not associated with capture of wild stocks (e.g. stocking, feeding, health maintenance, predator protection; FAO 2000). In addition, farming also implies ownership of the stock under cultivation. In 2000 the value of global aquaculture was assessed at 52 billion U.S. dollars (FAO 2000).

Whilst reasons for the decline and the negative environmental impacts of global wild caught fisheries are now known (e.g. loss of biodiversity, fishing down the food web; Pauly et al., 2003), it is evident that the aquaculture sector is also associated with negative impacts. These include the accidental or deliberate introduction of exotic or genetically manipulated species ("biological pollution") into marine ecosystems, susceptibility to disease associated with confining animals, the environmental factors or organic wastes from fish farming in the vicinity of the farm, elevated phosphorous levels in the environment stemming from aquaculture feeds, abuse and misuse of therapeutic drugs and chemicals and introduction and spread of parasites among them (Pauly et al., 2002). Clearly, solving these problems and setting standards and practices for sustainable aquaculture production would be a growing importance as reliance on aquaculture produced protein continues.

This study considers regional and global trends in aquaculture production, value and price. Trends in aquaculture production are compared with those for wild caught fisheries and both are discussed in the context of their current and possible future contributions to human protein needs. Specifically, my objective is 1. to address the current status and future sustainability of fish and shellfish production from wild stocks relative to that of aquaculture production and 2. to explore the economic and environmental consequences of continuing increases in aquaculture production.

2. MATERIAL AND METHODS

Data was obtained from the Fisheries and Aquaculture Department of the Food and Agriculture Organization of the United Nations for Aquaculture production (quantity from 1954 - 2004 and value from 1984 - 2004) and capture production (quantity from 1954 - 2004). Raw data was sorted by region to identify the status of aquaculture production by species for 2004. In addition, information provided prior to 2004 is summarized to provide a history of global aquaculture production trends. The data was extracted using FishStat Plus version 2.31 from which analysis was performed.

To account for change in currency value (U. S. dollar) with time, the aquaculture value in the dataset was corrected using the consumer price index from the Federal Reserve Bank of Minneapolis (Minneapolis, United States of America). The value of aquaculture is referenced to the value of the dollar in 2004, the last year available in the dataset. The aquaculture value referenced to the year 2004 is calculated by first multiplying the value in the given year by the consumer price index of 2004 and subsequently dividing that value by the consumer price index of the given year. In this thesis, the term aquaculture when unqualified refers to the farming of fish and shellfish.

3. RESULTS

Production over time is plotted for six geographical regions; Europe, North America, South America, Africa, Oceania and Asia from 1954 to 2004 (Fig. 1). In Europe, a marked increase in production that is largely attributable to salmonid aquaculture (Atlantic salmon *Salmo salar* and rainbow trout *Oncorhynchus mykiss*) occurring from 1984 to 2004. The only other significant production is that of common carp (*Cyprinus carpio*) which though significant on a scale of total production has increased slowly from 1964 to 1994 and fell between 1994 and 2004. Total aquaculture production in North America also shows a large increase from the mid-eighties to 2004. This is partly attributable to farmed Atlantic salmon *S. salar* but largely due to the continued rise in channel catfish *Ictalurus punctatus* that began in the mid-seventies. The increase in production of South American aquaculture is marked by a rapid increase in the farming of salmonids (*S. salar* and *O. mykiss*), Whiteleg shrimp *Penaeus vannamei* and tilapia *Oreochromis* spp. in the mid-nineties. This pattern is paralleled in Africa where total production is also dominated by a rapid increase in tilapia *Oreochromis* spp. aquaculture since the mid-nineties. Aquaculture production of silver carp *Hypophthalminchthys molitrix* began in the mid-eighties in Oceania and has dominated total production since the mid-nineties. Similar to the other principal geographic regions considered, Asia's total production is marked by a rapid rise from 1984 to 2004. However, a number of species (e.g. silver carp *H. molitrix*, bighead carp *H. nobilis*, Grass carp *Ctenopharyngodon idellus*, common carp *C. carpio*, Japanese eel *Anguilla japonica* and Yesso scallop *Patinopecten yessoensis*) contribute significantly to the increase.

Fig. 1 shows the global production of aquaculture produced fish and shellfish (ocean plus freshwater) from 1954 to 2004. Three principle results are clear: 1. There has been an exponential growth in world production over the course of the last 50 years or so. 2. This growth has been dominated by Asian production. 3. The overall global production of aquaculture fish and shellfish is likely to continue to increase for the foreseeable future.

The aquaculture production and value (inflation adjusted) of ocean and freshwater fish and shellfish species United States dollars for the six geographical regions are shown for 2004 in Figs. 2 to 13. In Europe, the dominant production of salmonids is directly reflected in value with Atlantic salmon and rainbow trout together accounting for about 60 % of the total (Fig. 2). While in North America the largest component of production (channel catfish *Ictalurus punctatus*) accounts for the largest “value component” of total production, both Atlantic salmon *S. salar* and whiteleg shrimp *P. vannamei* are high value components relative to their production levels (Fig. 3 and 9). Similar to Europe, South American value components largely mirror production with Atlantic salmon *S. salar*, rainbow trout *O. mykiss* and whiteleg shrimp *P. vannamei* representing the highest value species (Fig. 4 and 10). For Africa, the second ranked species with regard to production (flathead grey mullet *Mugil cephalus*) has value comparable to the dominant species produced (Nile tilapia *O. niloticus*) (Fig. 5 and 11). In Oceania, the highest production levels (New Zealand mussel *Perna canaliculus* and Atlantic salmon *S. salar*) are also reflected in the figures for highest value (Fig. 6 and 12). This is also the case for Asia although there are some notable exceptions with Yesso scallop *P. yessoensis* and Pacific cupped oyster *Crassostrea gigas* showing values that are high and low respectively relative to their production levels (Fig. 7 and 13). World values for aquacultural production based on the six geographic regions (Fig. 1) show a rapid rise in value for Asia from 1984 to 2004 relative to the rest of the world.

Trends in production and value can be further understood by considering their ratio (value divided by production) which is a price. Value is plotted for all species produced in each of the six regions in Figs. 8 to 13 and price is shown for the principle species (top 20 species measured by production) in Figs. 14 to 19 for 2004. Trends in value and price versus time (1984 to 2004) are shown in Fig. 20 and 21. The most striking regional trend is that for Asia where production and value have risen exponentially since the late 1980's (Fig. 1 and 20 respectively) with a commensurate steady drop in price over the same period (Fig. 21). Globally, prices rose between 1984 and 1989 and fell steadily thereafter to 2004 levels (Fig. 21).

World production and value for the twenty highest ranked aquaculture species in 2004 are shown in Fig. 22. The highest production for the fish species is for Atlantic salmon *S. salar*. However, the collective production and value of the five carp species (bighead carp *H. nobilis*, common carp *Cyprinus carpio*, Crucian carp *Carassius carassius*, grass carp *Ctenopharyngodon idella*, silver carp *Hypophthalmichthys molitrix*) far exceeds that of for salmon. Fig. 22 shows that when fish alone are considered, the greatest production in value is for freshwater reared forms (largely carp species). Most ocean reared aquaculture production and value is attributable to invertebrates (shellfish).

Fig. 23 shows the weight of wild caught fish and invertebrates based on the sum of ocean and freshwater fish for the six regions considered and their total over the period from 1954 to 2004. Since the mid 1980's, the following regional trends are apparent:

values for Europe show a steady decrease, those for North America have changed little, the mean trend for South America shows an overall increase and capture rates for Oceania and Africa have increased slightly. In contrast, production of captured fish and invertebrates over this period has increased rapidly in Asia. The rapid rise in the global total production of commercially caught fish and invertebrates is largely attributable to the Asian fishing effort.

Values of the total global commercial catch have increased logarithmically between 1954 and 2004 with the curve “flattening off” since about 1990 (Fig. 24). In contrast, global aquaculture production has increased exponentially since 1954. As of 2004, the proportion of capture and aquaculture production relative to their sum is 66 % and 34 % respectively (Fig. 25).

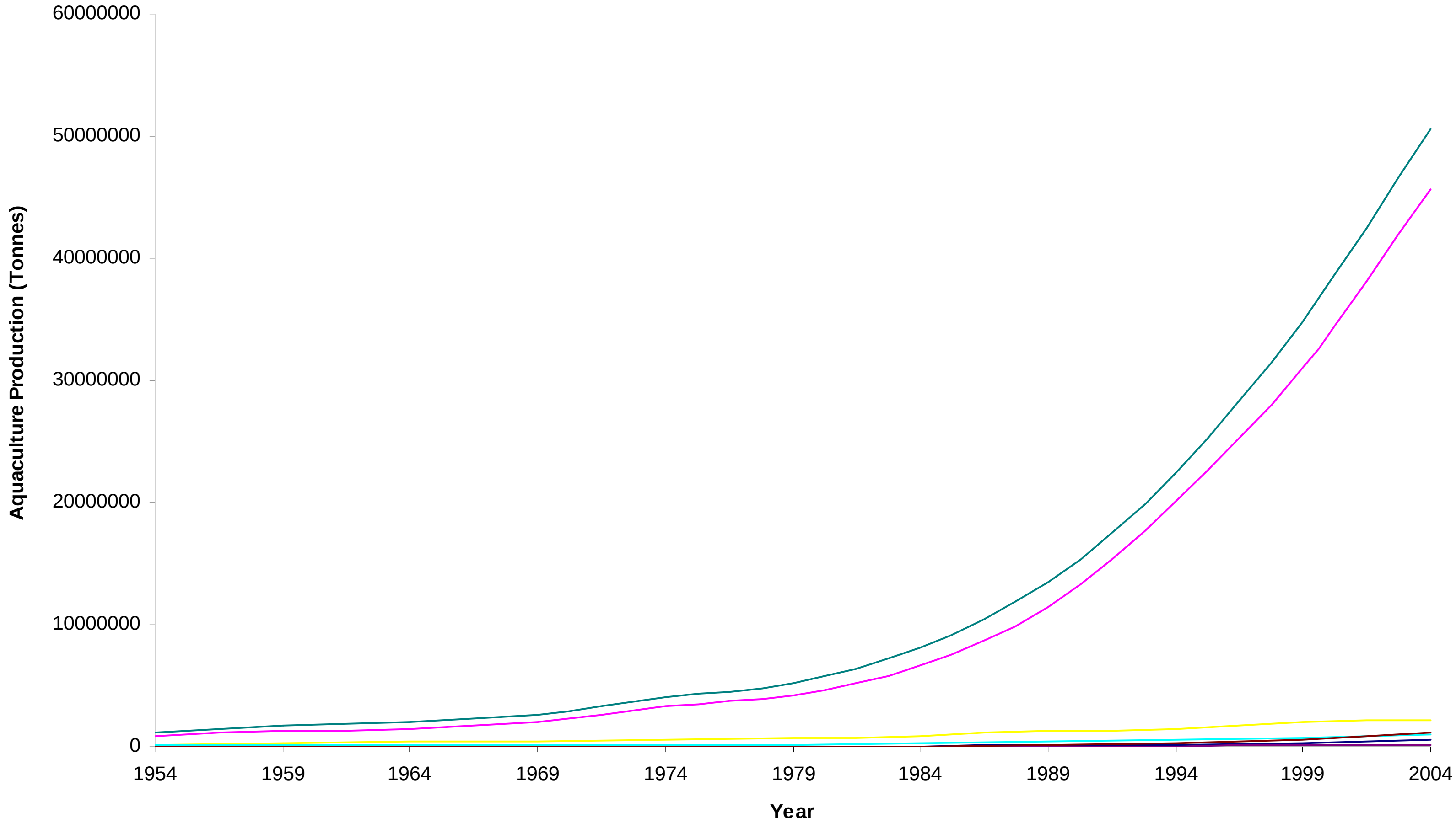

Fig. 1. Aquaculture production versus year for Europe (yellow), North America (light blue), South America (brown), Africa (dark blue), Oceania (purple) and Asia (pink). Total production is shown by the green line.

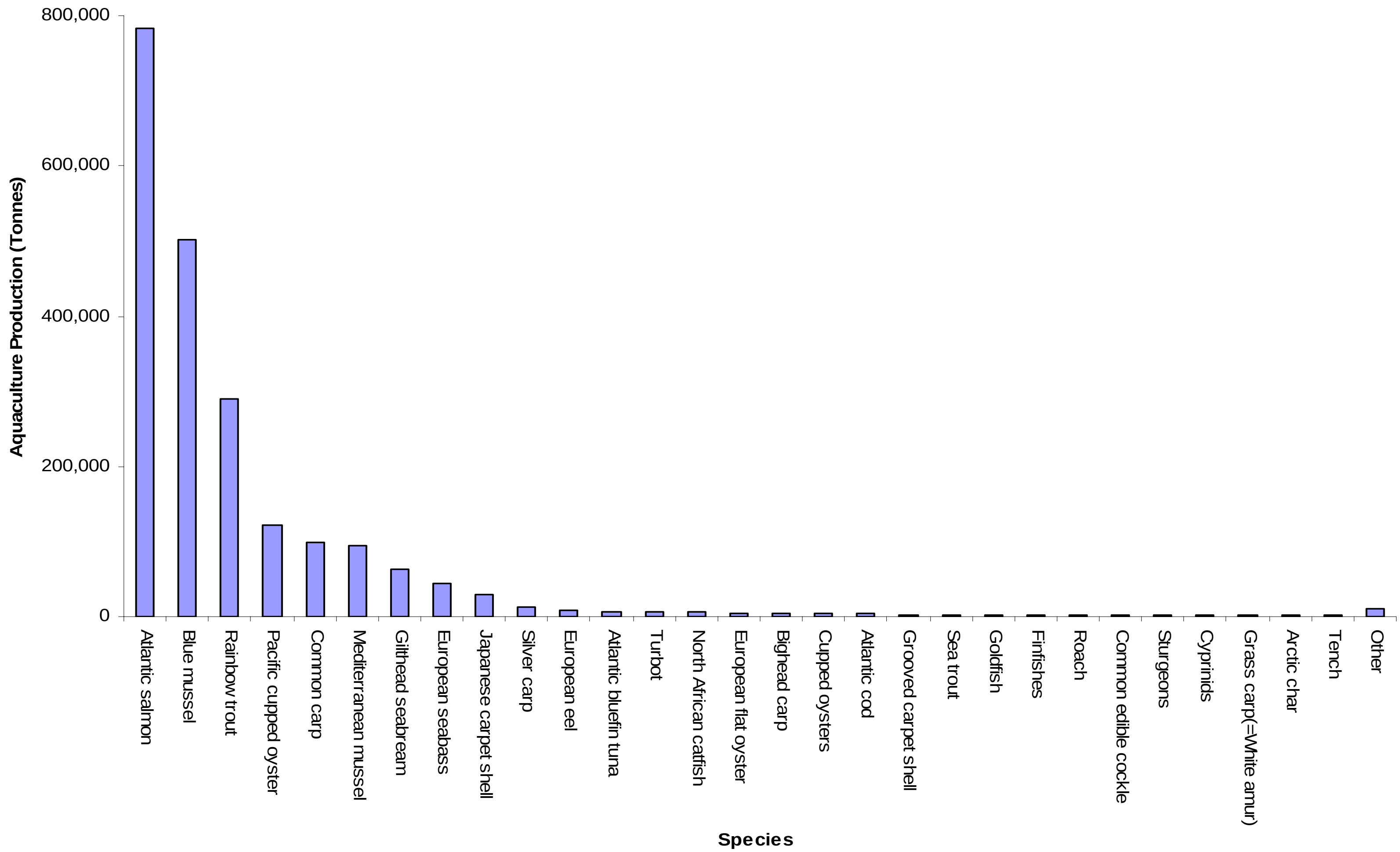

Fig. 2. Aquaculture production for Europe in 2004. Other includes brook trout, meagre, Crucian carps, trouts, wels catfish, chars, clams, flathead grey mullet, European whitefish, striped bass, Nile tilapia, pullet carpet shell, torpedo-shaped catfish, Northern pike, pike perch, So-iuy mullet, freshwater bream, sea mussels, Atlantic halibut, black bullhead, common Pandora, Siberian sturgeon, tilapias, porgies, white seabream, great Atlantic scallop, kuruma prawn, European perch, haddock, palaemonid shrimp, common sole, blackspot seabream, scallops, Euro-American crayfishes, wakame, silversides, mullets, gobies, harpoon seaweeds, venus clams and rudds.

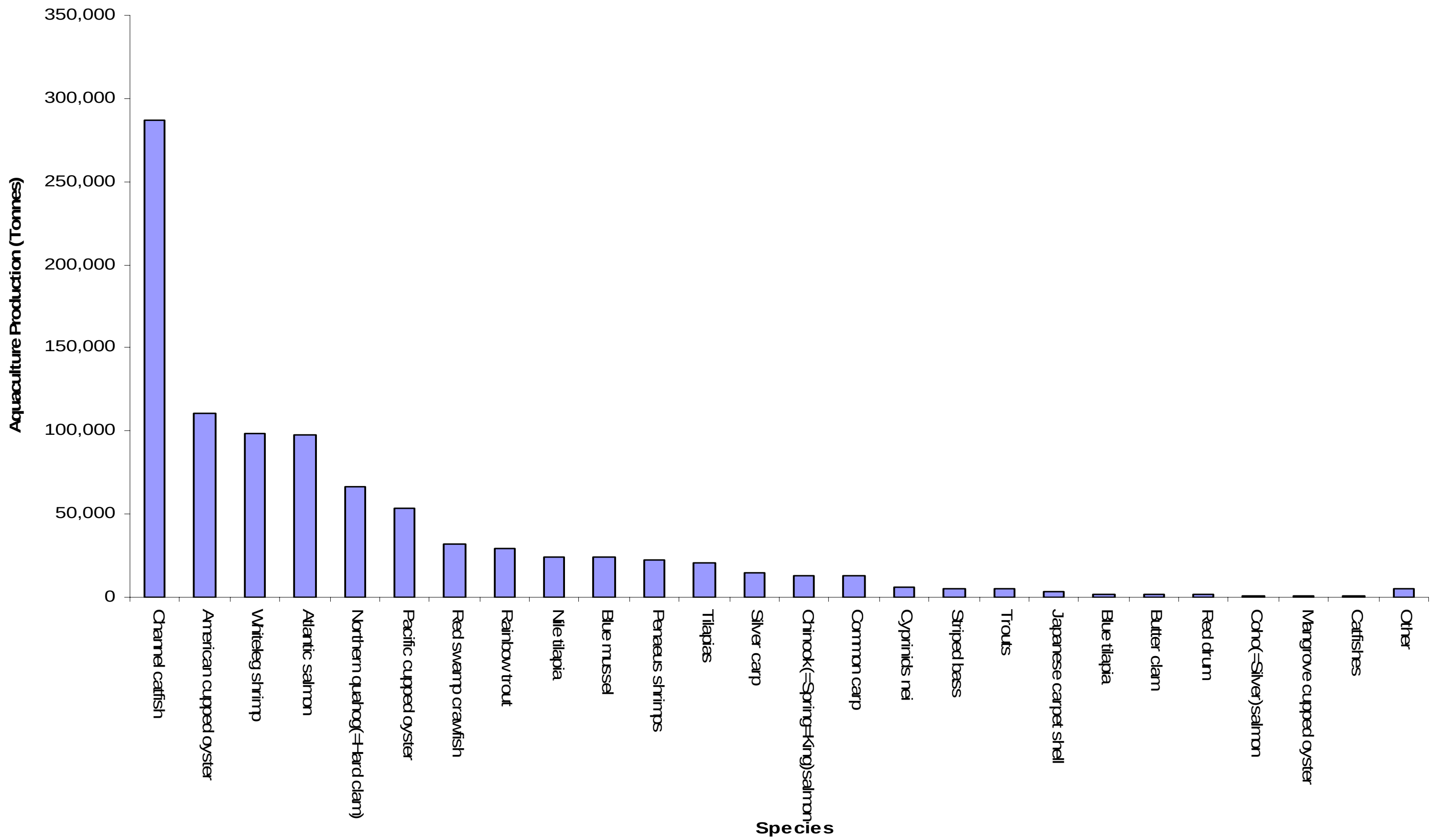

Fig. 3. Aquaculture production for North America in 2004. Other includes Marine mollusks, Pacific bluefin tuna, Blue shrimp, Cupped oysters, Southern white shrimp, Pacific geoduck, Giant river prawn, Abalones, Sand gaper, Mozambique tilapia, Largemouth black bass, Cachama, Scallops, Pacific littleneck clam, Frogs, Gilthead seabream, White crappie, Blue crab, European flat oyster, Arctic char, Sea mussels, Olympia flat oyster, Black seabass, Brine shrimps, European seabass and Florida pompano.

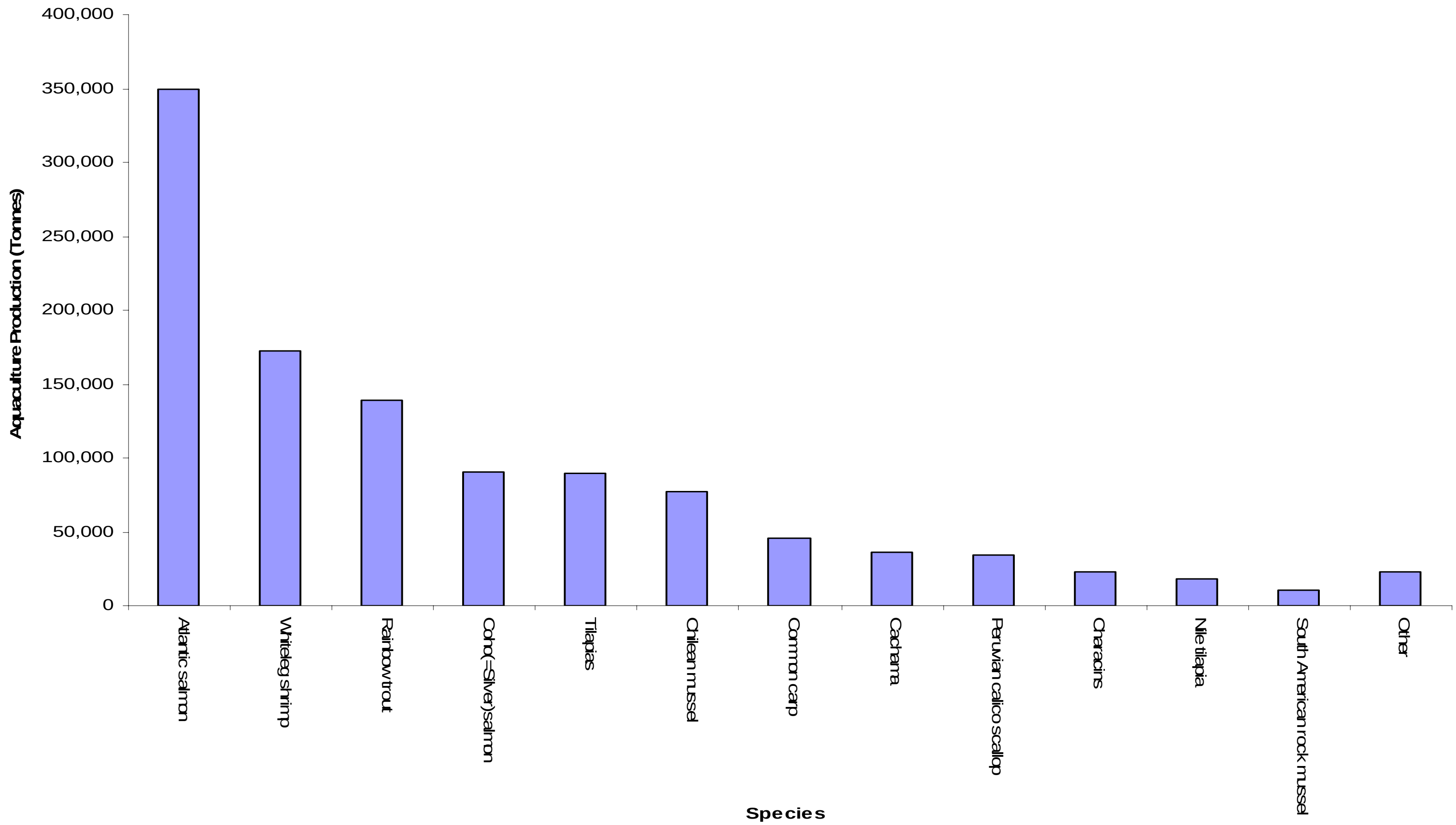

Fig. 4. Aquaculture Production for South America in 2004. Other includes Chinook salmon, cupped oyster, netted prochilod, Pacific cupped oyster, prochilods, freshwater siluroids, channel catfish, cholga mussel, pirapatinga, frog, giant river prawn, choro mussel, pacu, flatfishes, abalones, North African catfish, Chilean flat oyster, Mozambique tilapia, Argentinian silverside, Penaeus shrimp, Brycon cephalus, Atipa, Blue mussel, River plata mussel and cyprinids.

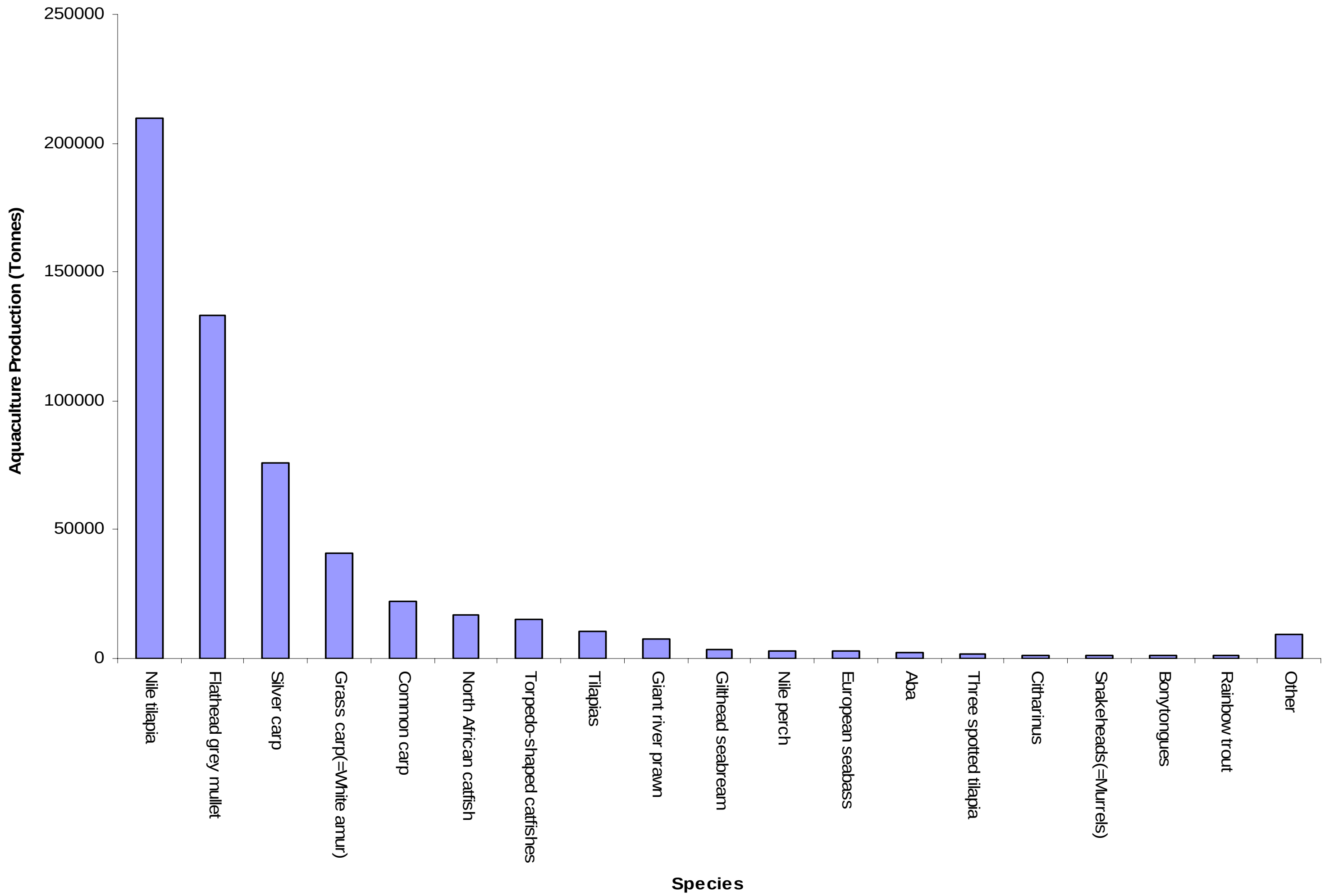

Fig. 5. Aquaculture production for Africa in 2004. Other includes Kafue pike, Grass-eaters, Upsidedown catfishes, Characins, Mediterranean mussel, Perlemoen abalone, Reticulate knifefish, Red drum, Mudfish, Pacific cupped oyster, Bayad, Atlantic bluefin tuna, Indian white prawn, Blue tilapia, Redbreast tilapia, Algerian barb, European eel, Freshwater siluroids, Mozambique tilapia, Longfin tilapia, Jacks, Wels(=Som)catfish, Bagrid catfish, Pike-perch, Black catfishes, Cyprinids, Largemouth black bass, Gasar cupped oyster, Rudd, Drums and Roaches.

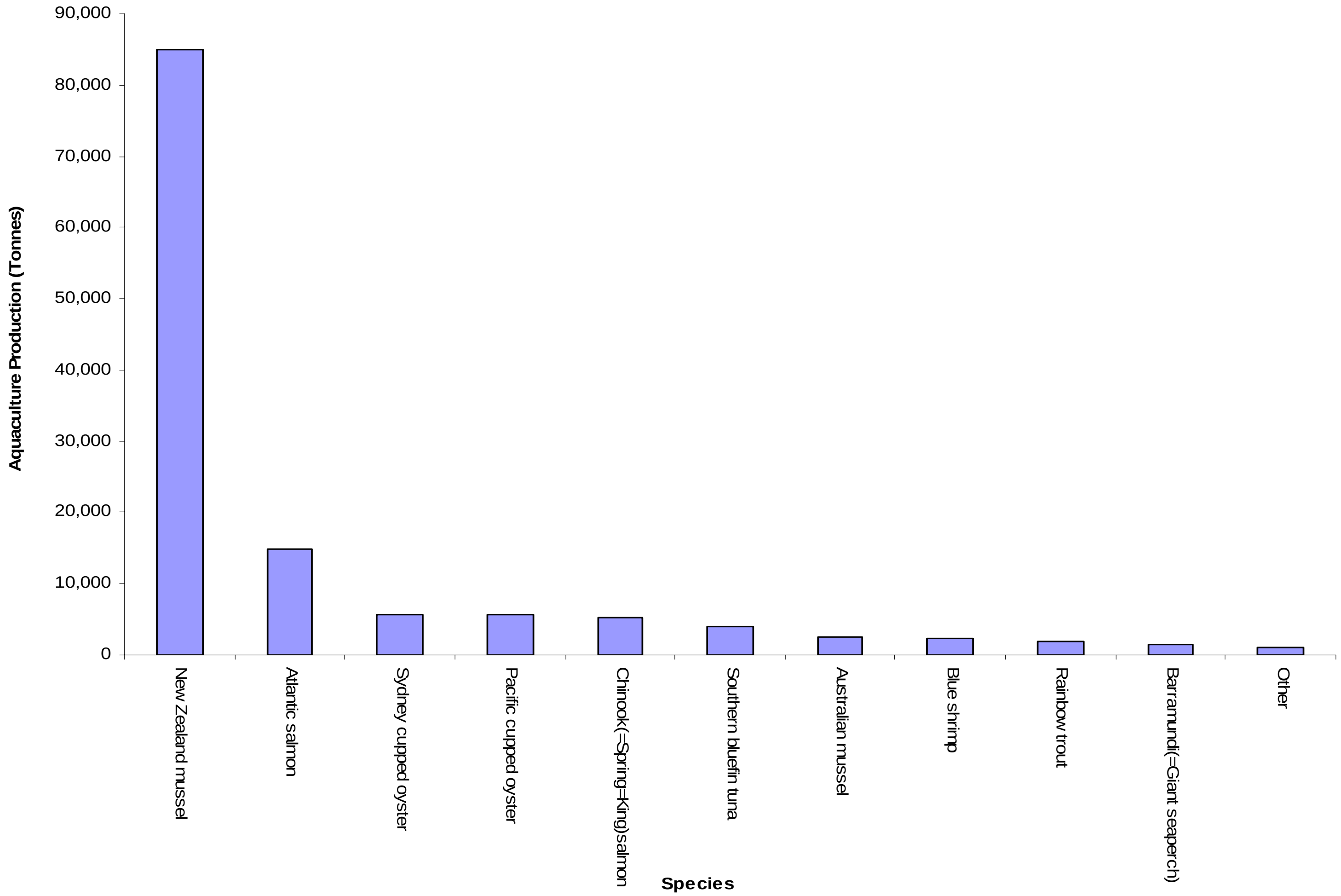

Fig. 6. Aquaculture production for Oceania in 2004. Other includes Kuruma prawn, Silver perch, Blacklip abalone, Red claw crayfish, Yabby crayfish, Marron crayfish, Murray cod, Giant river prawn.

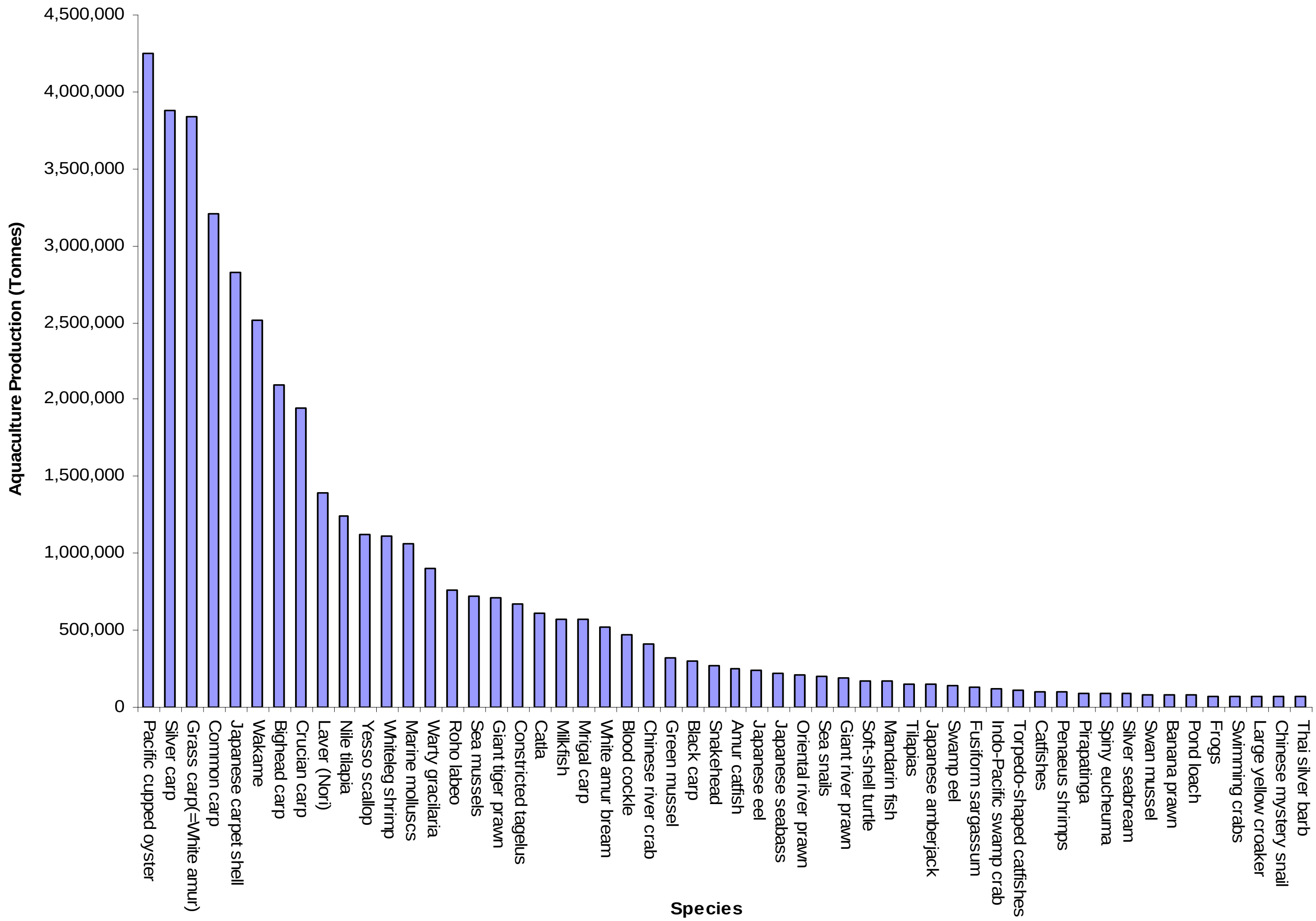

Fig. 7A. Aquaculture production for Asia in 2004.

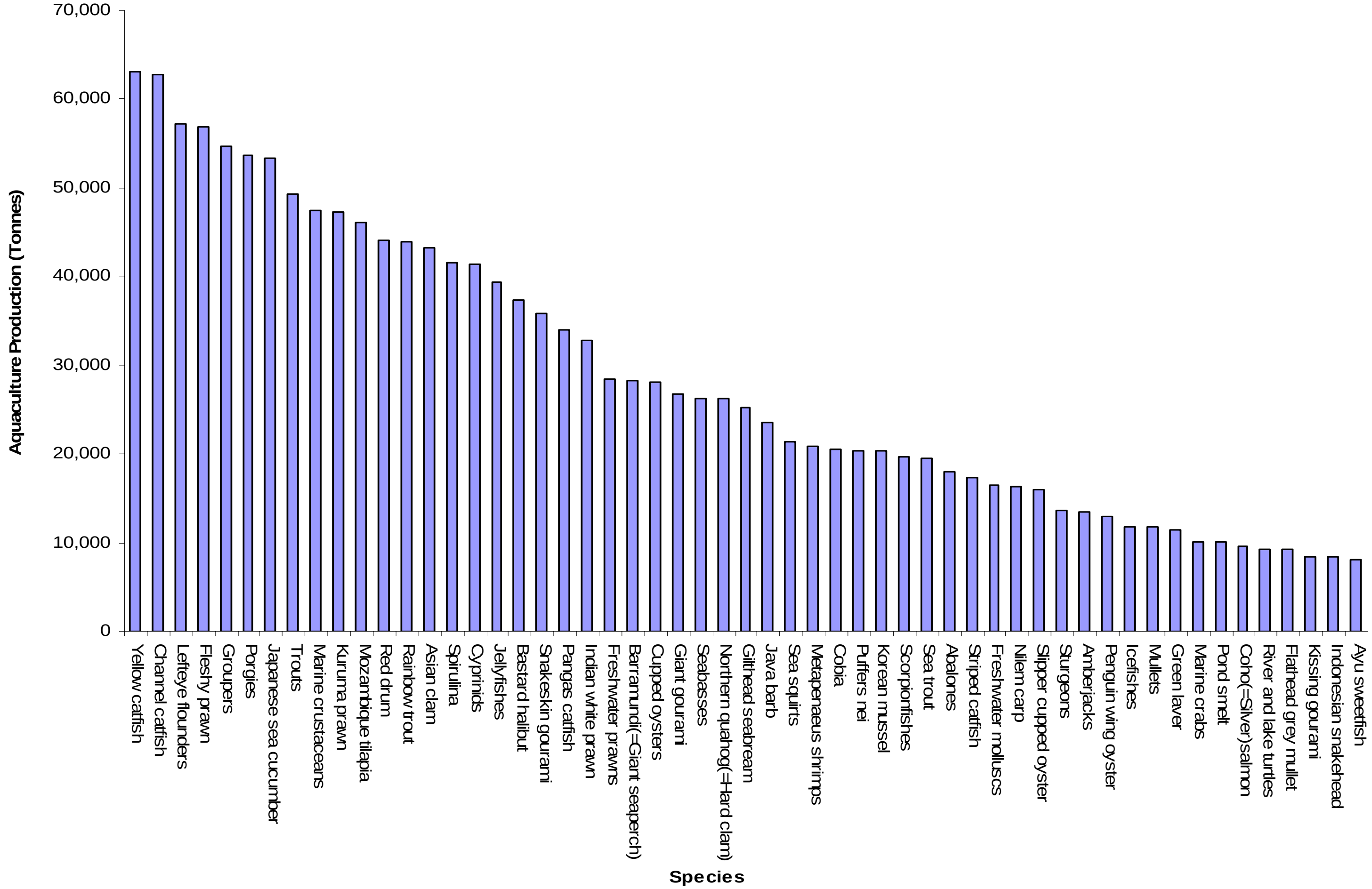

Fig. 7B. Aquaculture production for Asia in 2004.

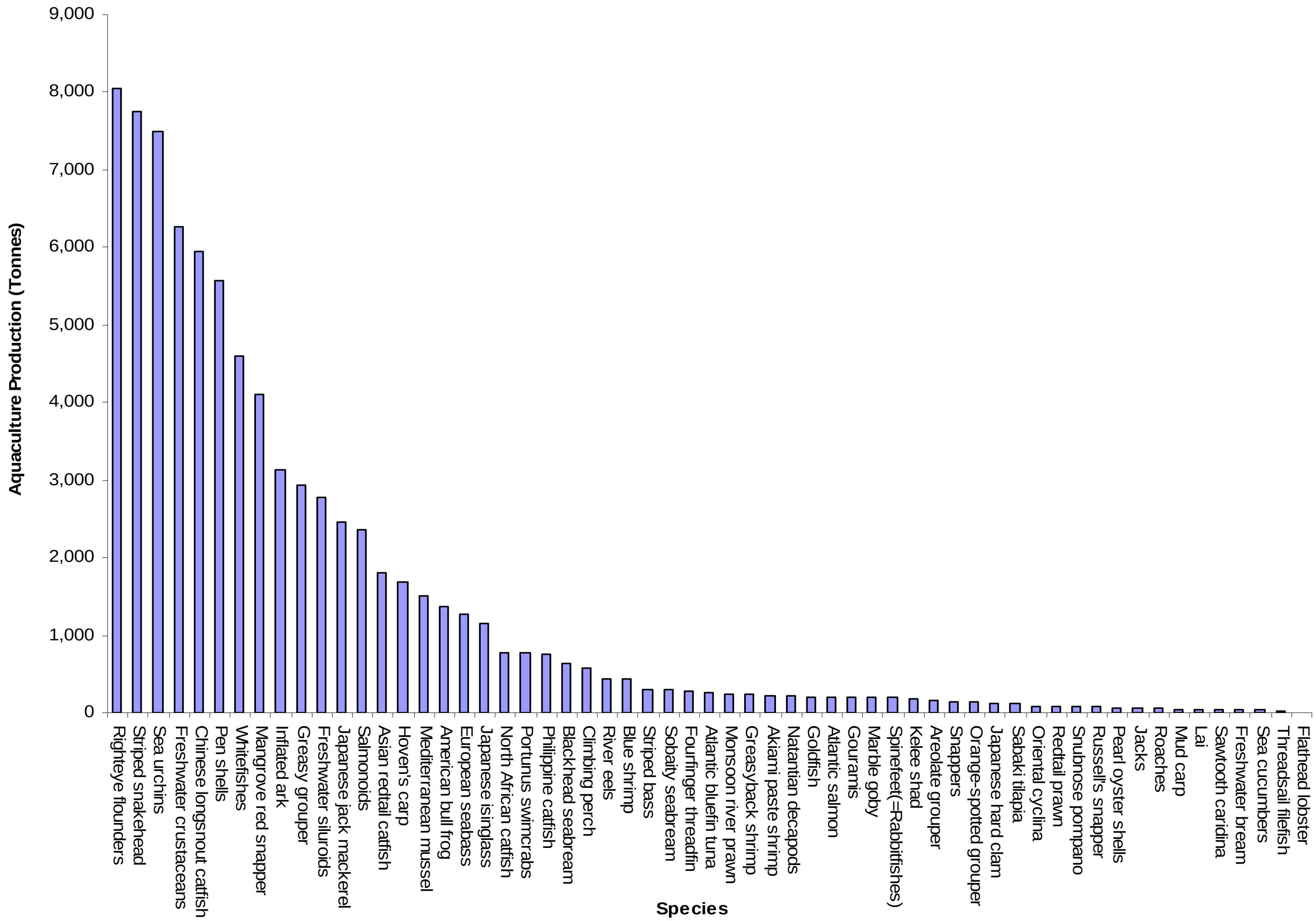

Fig. 7C. Aquaculture production for Asia in 2004.

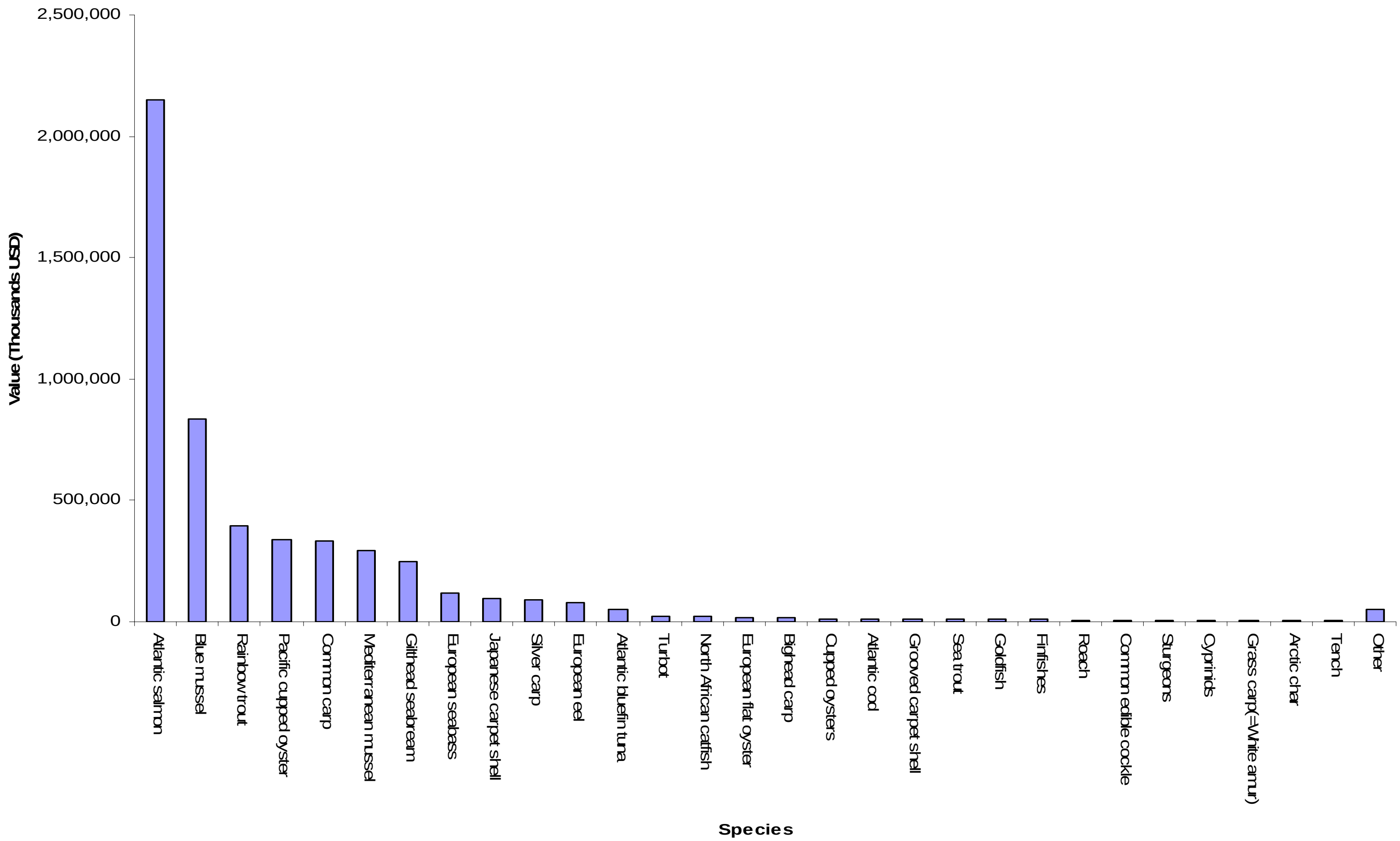

Fig. 8. Value of aquaculture for Europe in 2004. Other includes Trouts, Tench, Grass carp(=White amur), European whitefish, Wels(=Som)catfish, Cyprinids, Salmonoids, Flathead grey mullet, Kuruma prawn, Clams, Striped bass, Crucian carp, Atlantic halibut, Pullet carpet shell, Common Pandora, Porgies, White seabream, Siberian sturgeon, Nile tilapia, Pike-perch, Northern pike, Tilapias, Black bullhead, Torpedo-shaped catfishes, Great Atlantic scallop, So-iuy mullet, Euro-American crayfishes, Common sole, Freshwater bream, Scallops, Haddock Blackspot(=red) seabream, Palaemonid shrimps, European perch, Sea mussels, Silversides(=Sand smelts), Venus clams, Gobies, Mullets, Rudd and Wakame.

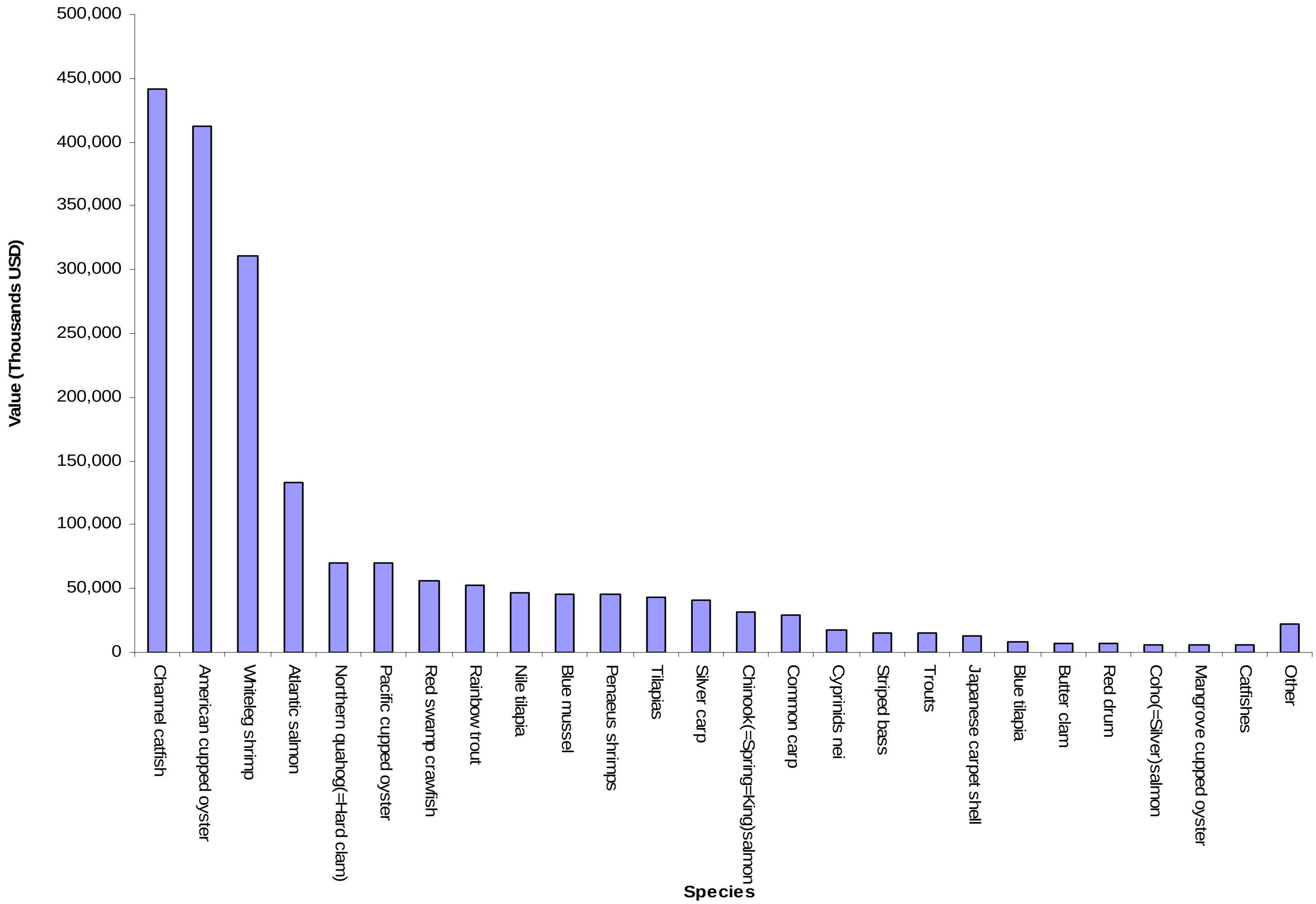

Fig. 9. Value of aquaculture for North America in 2004. Other includes Coho(=Silver)salmon, Blue tilapia, Giant river prawn, Cupped oysters nei, Catfishes nei, Southern white shrimp, Mangrove cupped oyster, Blue shrimp, Mozambique tilapia, Scallops, Frogs, Blue crab, Largemouth black bass, Arctic char, Cachama, Pacific littleneck clam, European flat oyster, Sand gaper, Gilthead seabream, Olympia flat oyster, Black seabass, White crappie, Sea mussels nei, European seabass, Florida pompano and Brine shrimps nei.

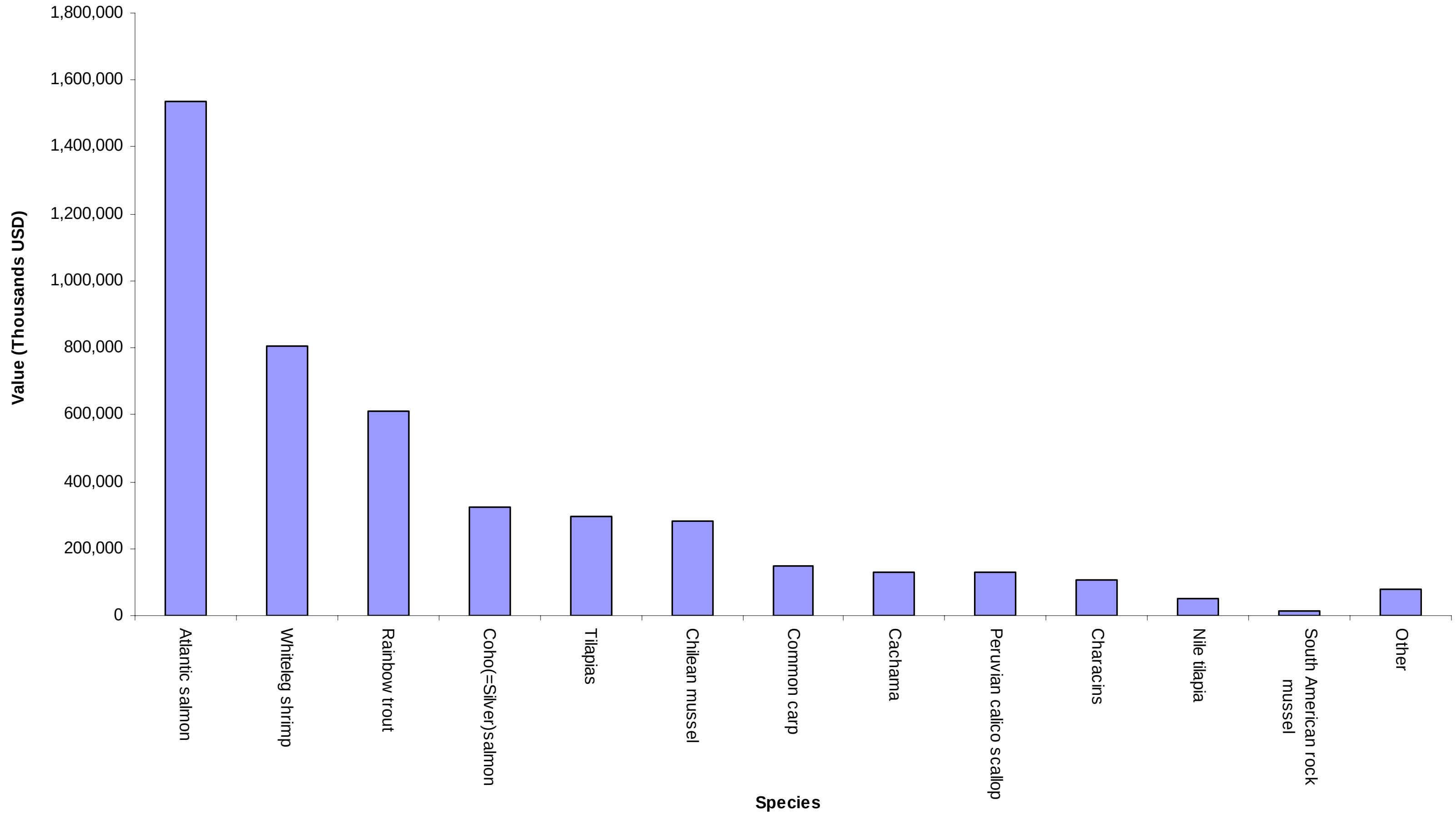

Fig. 10. Value of aquaculture for South America in 2004. Other includes Pacific cupped oyster, South American rock mussel, freshwater siluroids, netted prochilod, channel catfish, abalones, cholga mussel, cupped oysters, prochilods, frogs, giant river prawn, pirapatinga, flatfishes, Chilean flat oysters, North African catfish, pacu, paneus shrimps, atipa, choro mussel, Argentinian silverside, cyprinids, Brycon cephalus, Mozambique tilapia, river plata mussel and blue mussel.

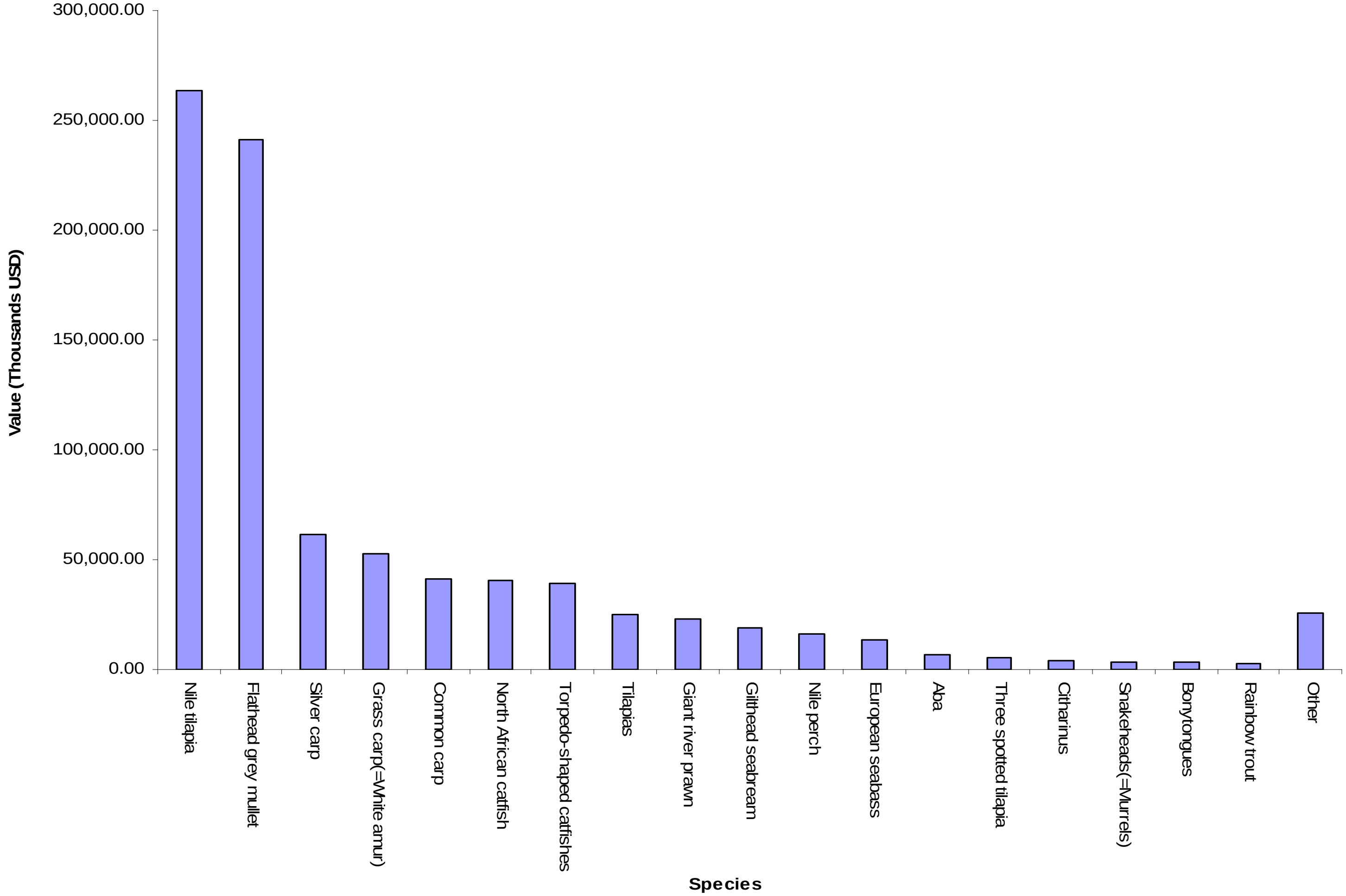

Fig. 11. Value of aquaculture for Africa in 2004. Other includes Nile tilapia, Flathead grey mullet, Silver carp, North African catfish, Giant river prawn, Grass carp(=White amur), Torpedo-shaped catfishes, Perlemoen abalone, Tilapias, Common carp, Gilthead seabream, European seabass, Nile perch, Aba, Rainbow trout, Snakeheads(=Murrels) , Citharinus, Red drum, Three spotted tilapia, Bonytongues, Atlantic bluefin tuna, Kafue pike, Characins, Grass-eaters, Upsidedown catfishes, Indian white prawn, Pacific cupped oyster, European eel, Reticulate knifefish, Blue tilapia, Mediterranean mussel, Bayad, Mudfish, Freshwater siluroids, Bagrid catfish, Drums, Wels(=Som)catfish, Redbreast tilapia, Pike-perch, Mozambique tilapia, Jacks, Cyprinids, Largemouth black bass, Longfin tilapia, Black catfishes, Gasar cupped oyster, Algerian barb, Rudd and Roaches.

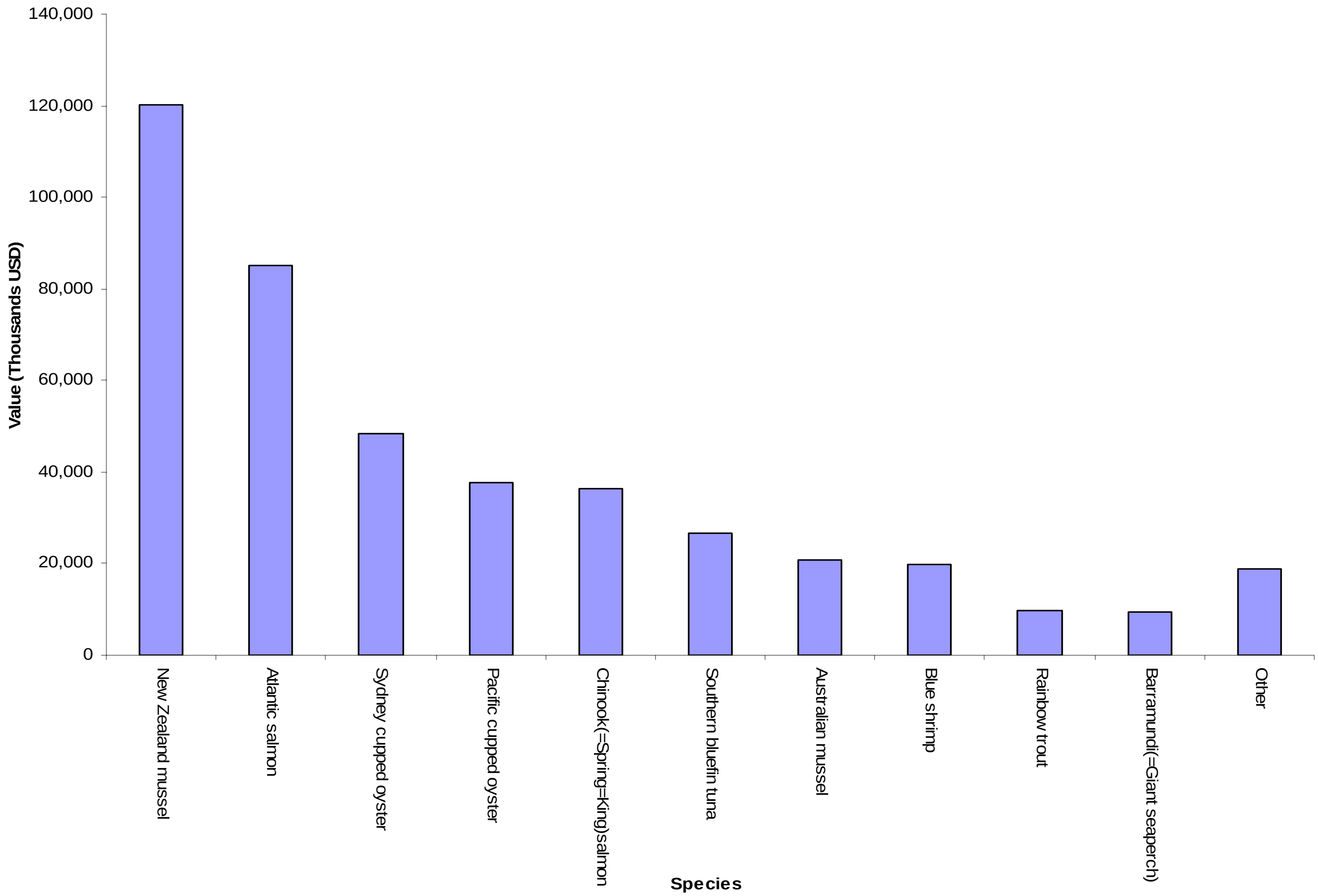

Fig. 12. Value of aquaculture for Oceania in 2004. Other includes Kuruma prawn, Silver perch, Blacklip abalone, Red claw crayfish, Yabby crayfish, Marron crayfish, Murray cod, Giant river prawn.

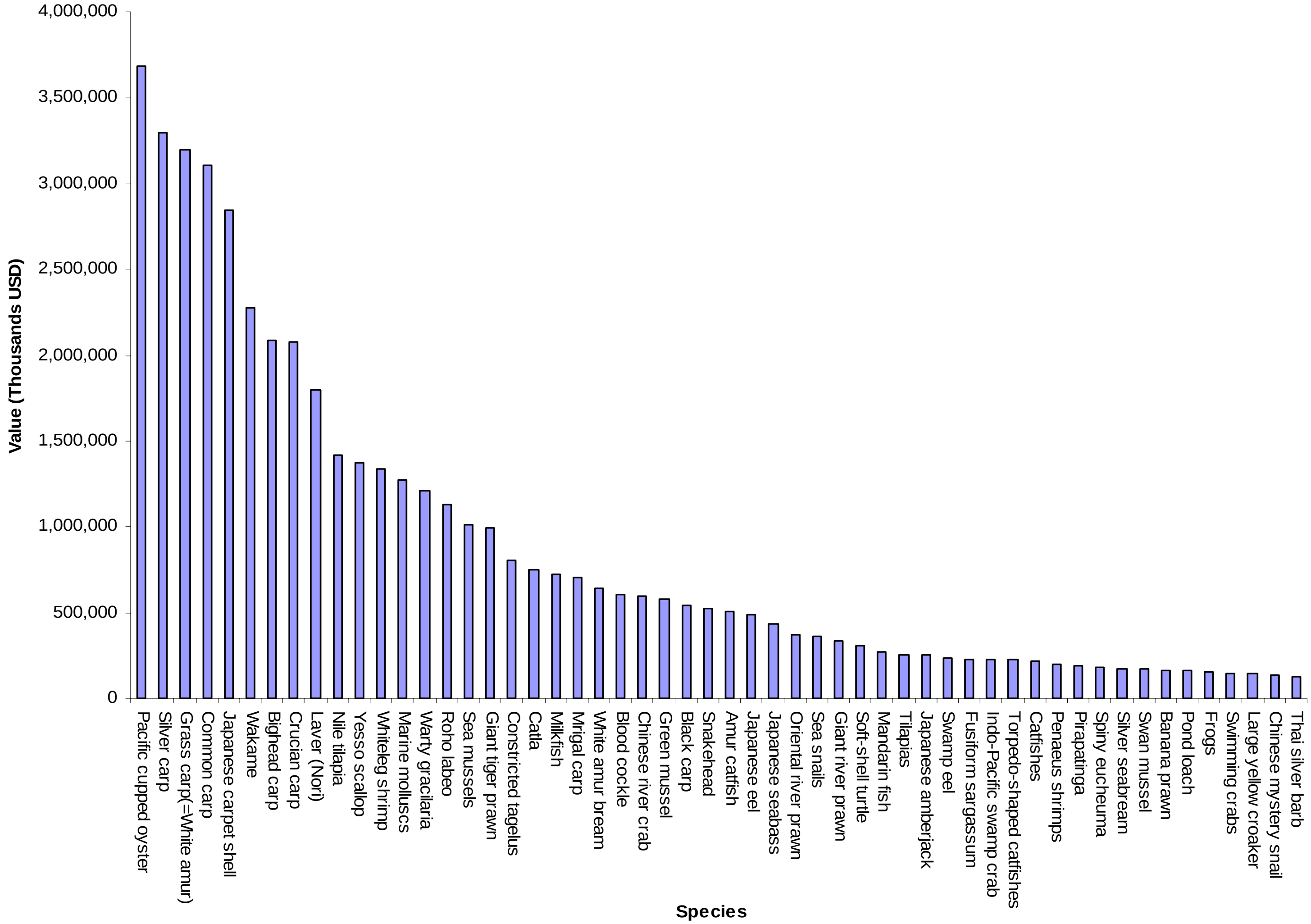

Fig. 13A. Value of aquaculture for Asia in 2004.

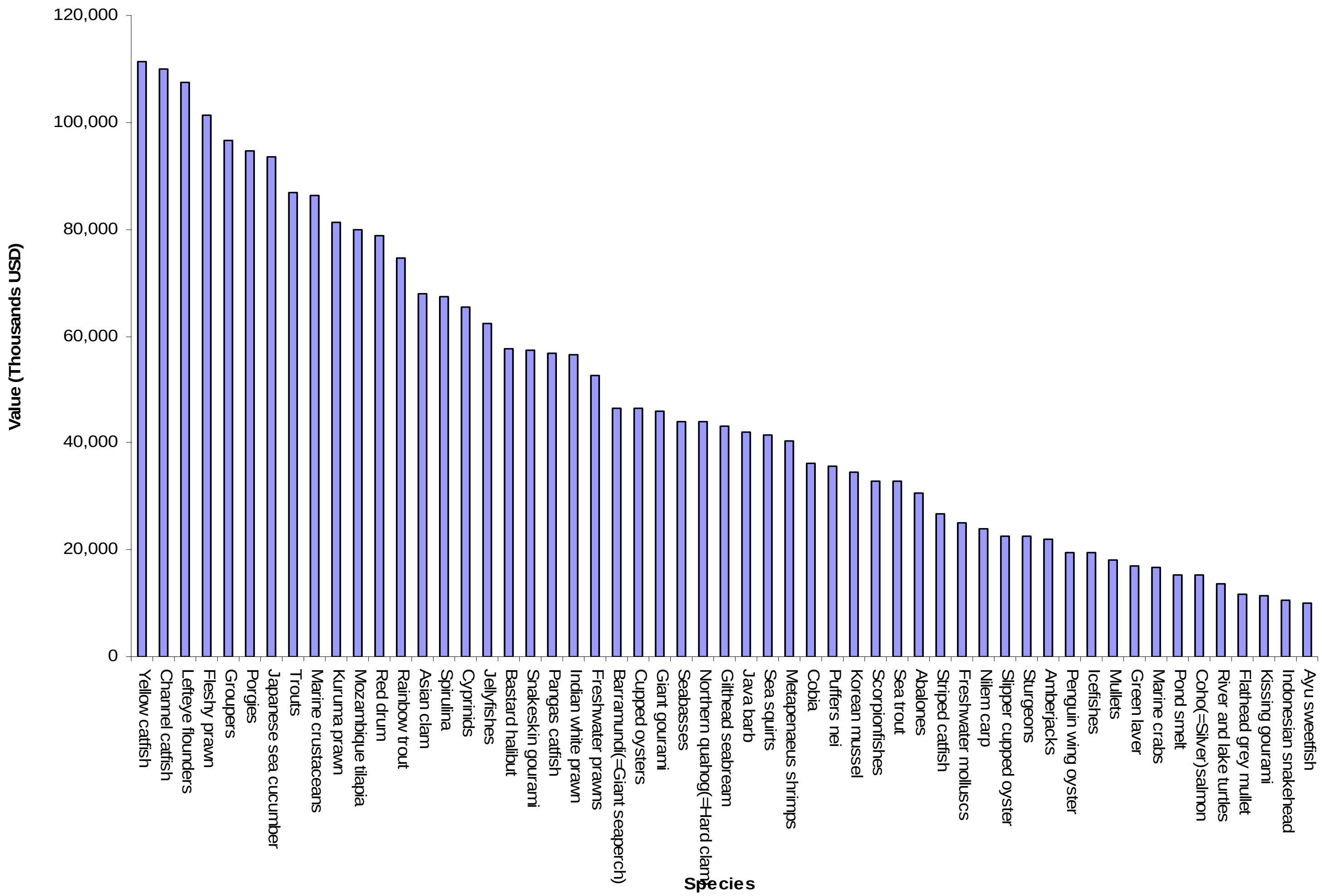

Fig. 13B. Value of aquaculture for Asia in 2004.

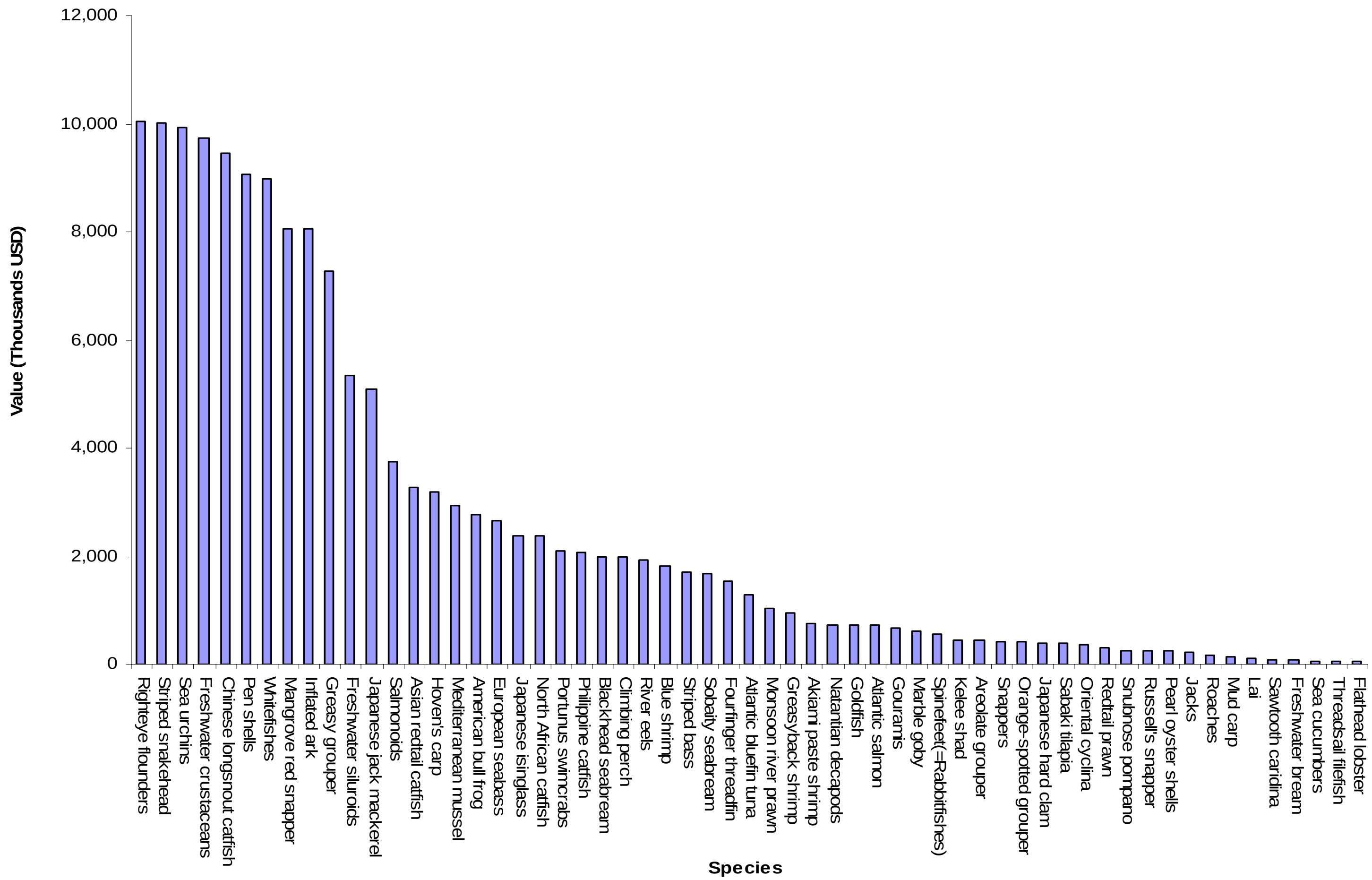

Fig. 13C. Value of aquaculture for Asia in 2004.

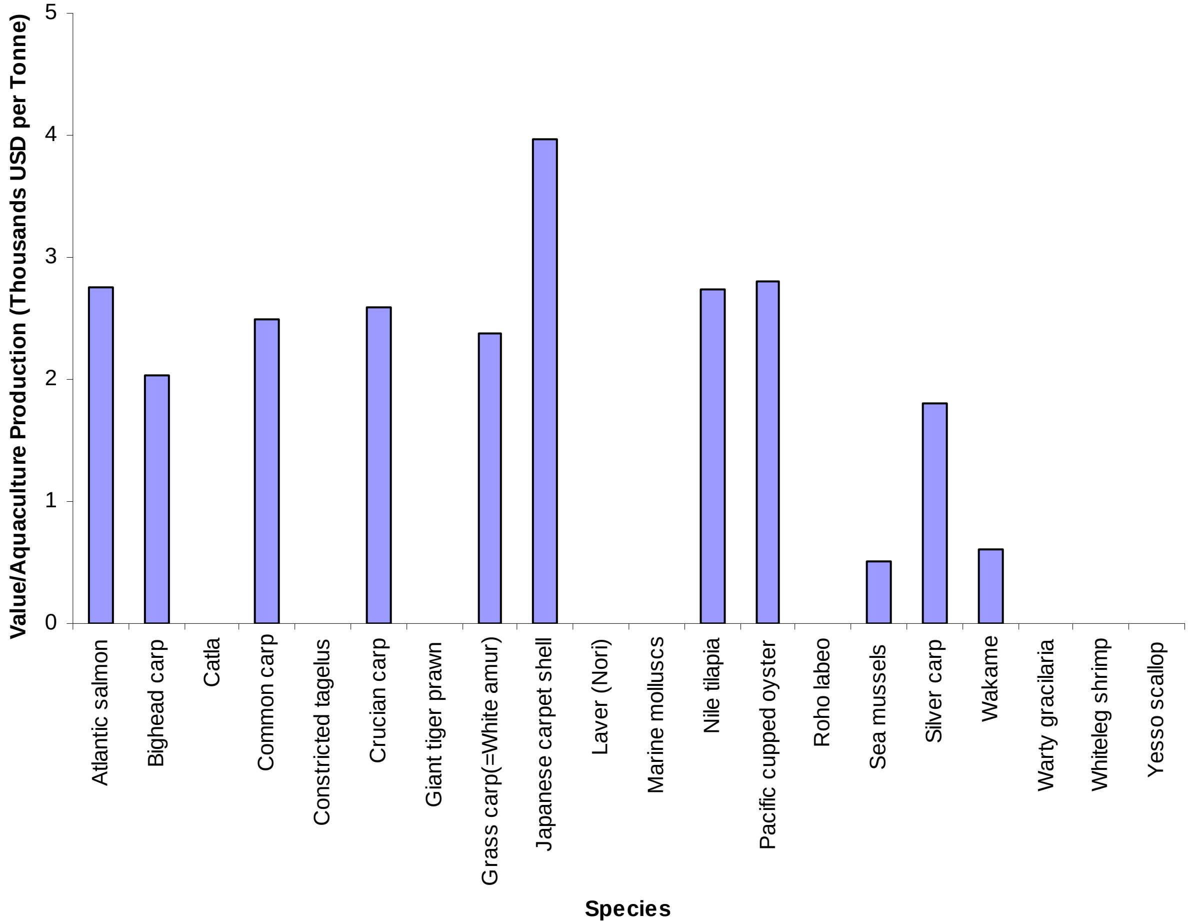

Fig. 14. Value divided by aquaculture production for Europe in 2004.

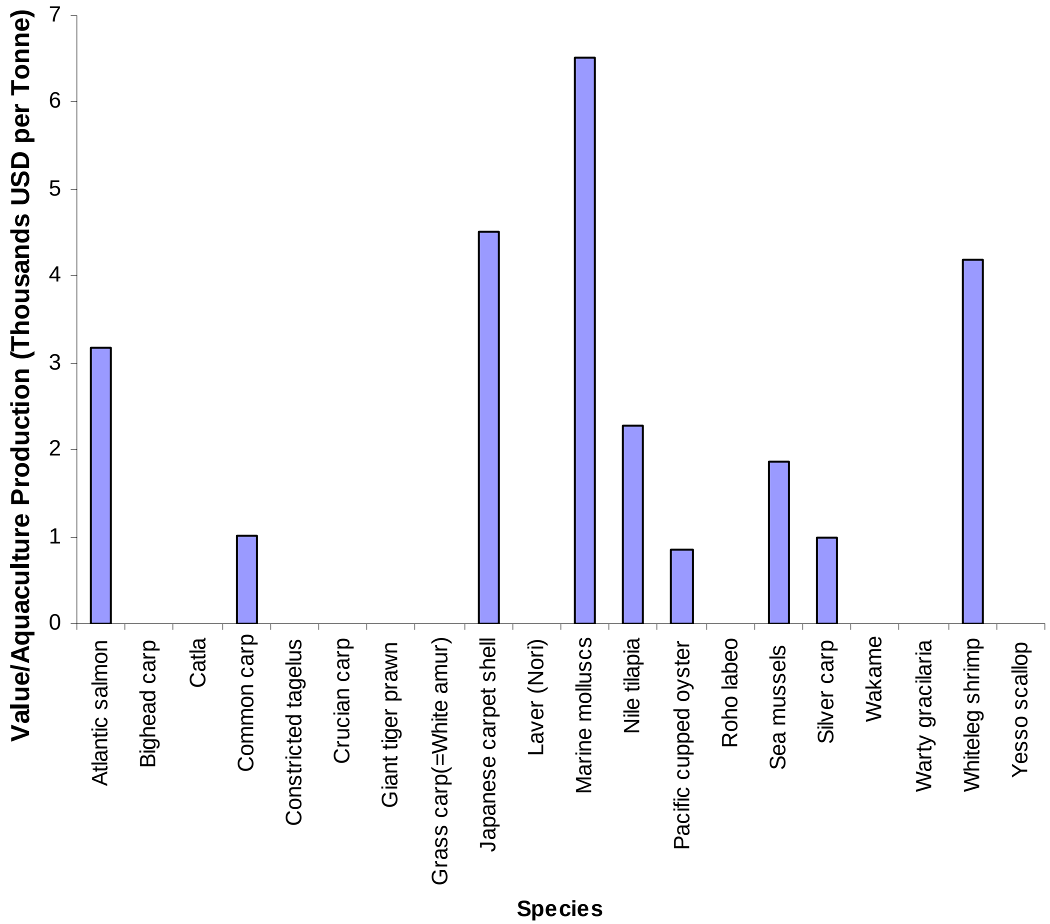

Fig. 15. Value divided by aquaculture production for North America in 2004.

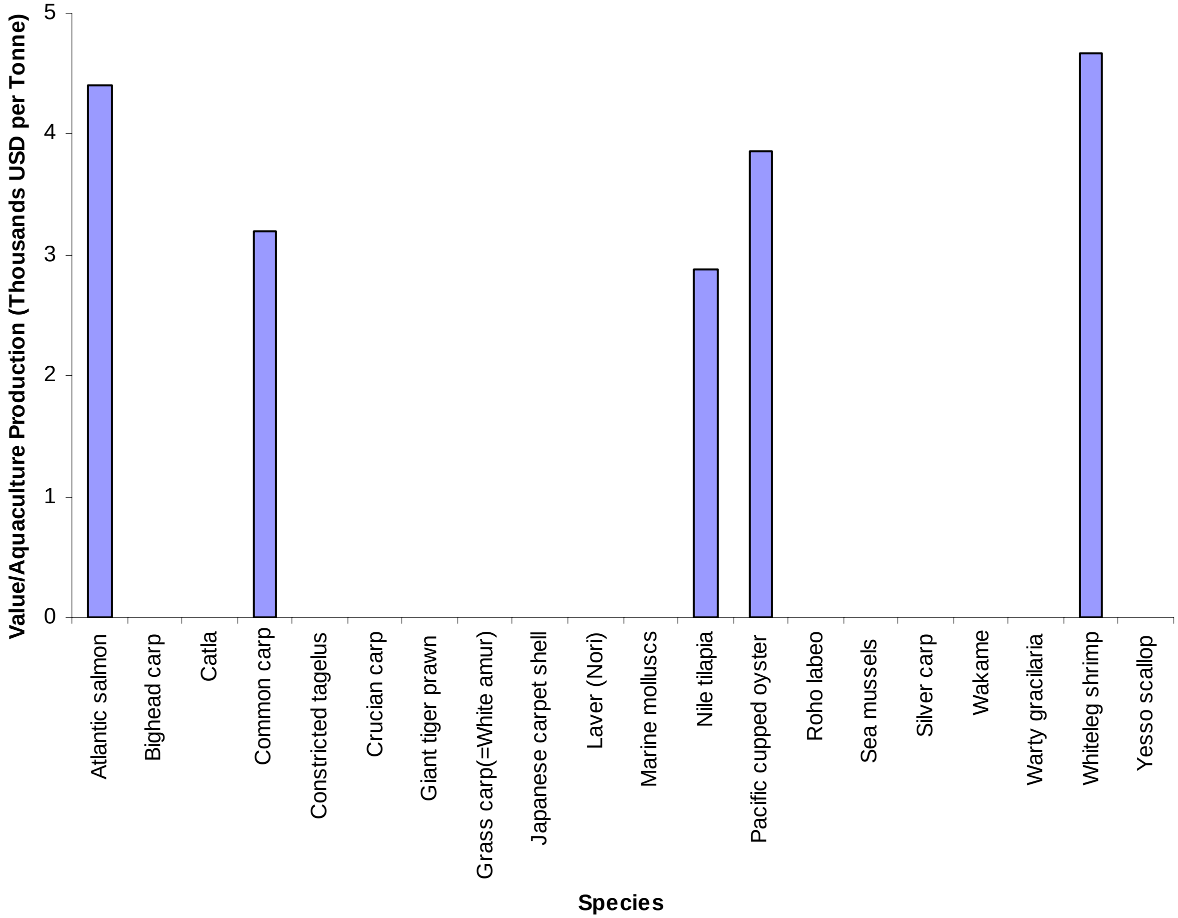

Fig. 16. Value divided by aquaculture production for South America in 2004.

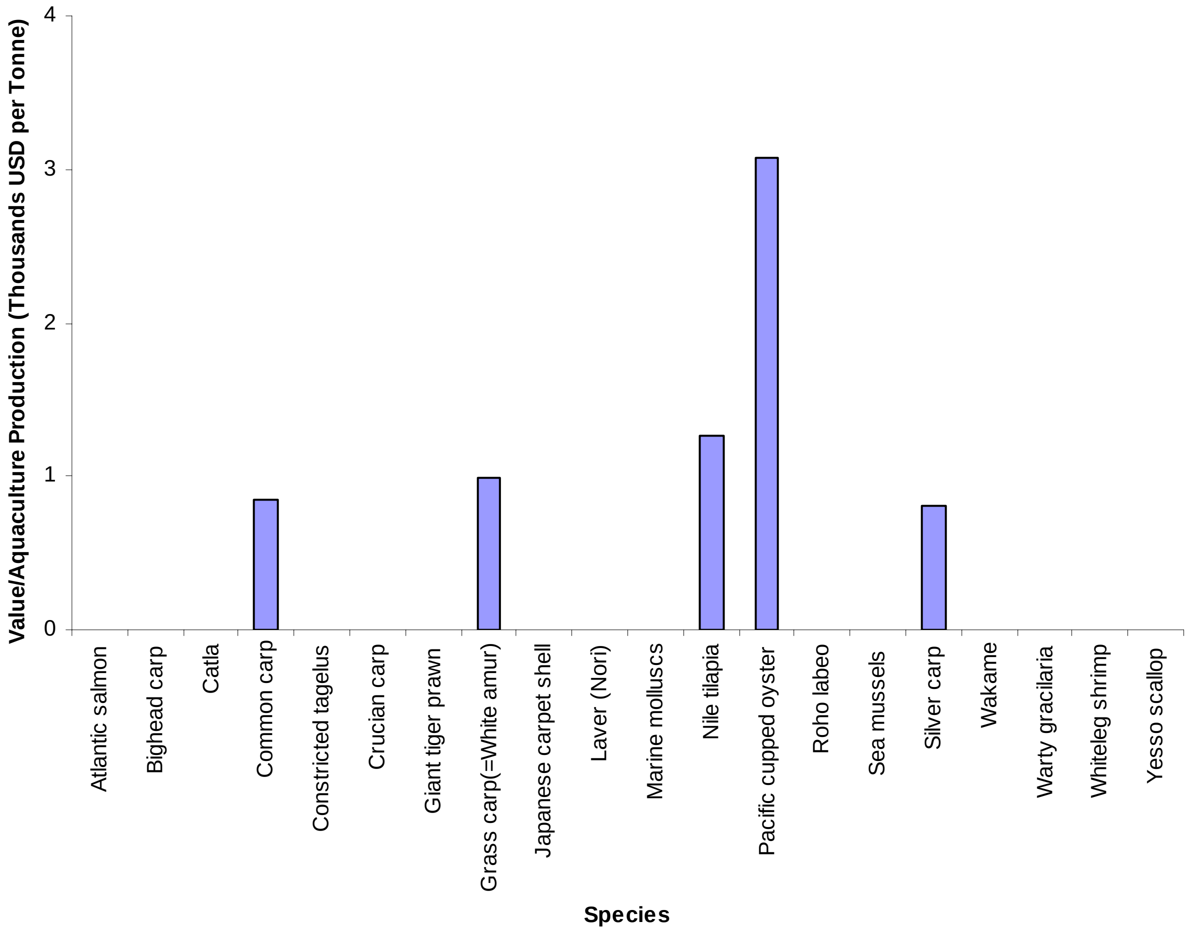

Fig. 17. Value divided by aquaculture production for Africa in 2004.

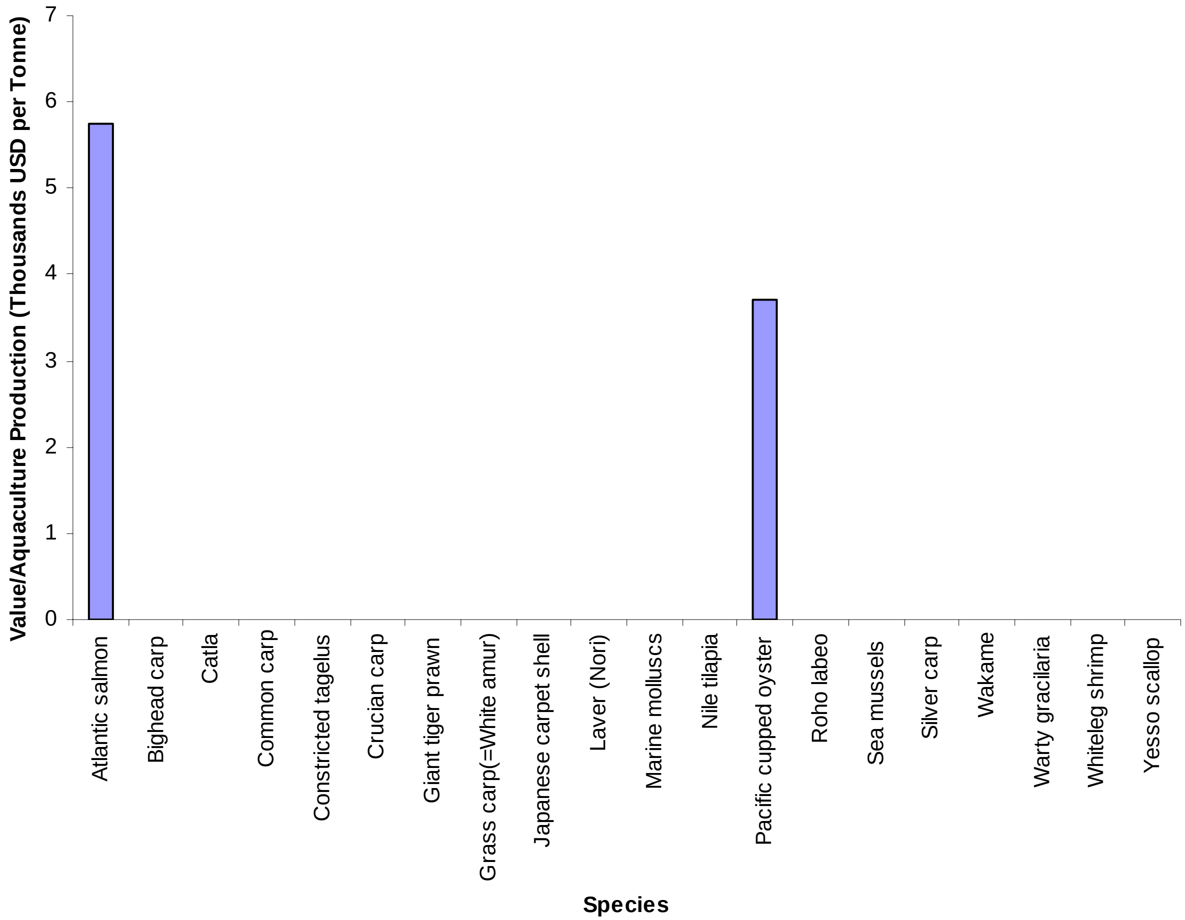

Fig. 18. Value divided by aquaculture production for Oceania in 2004.

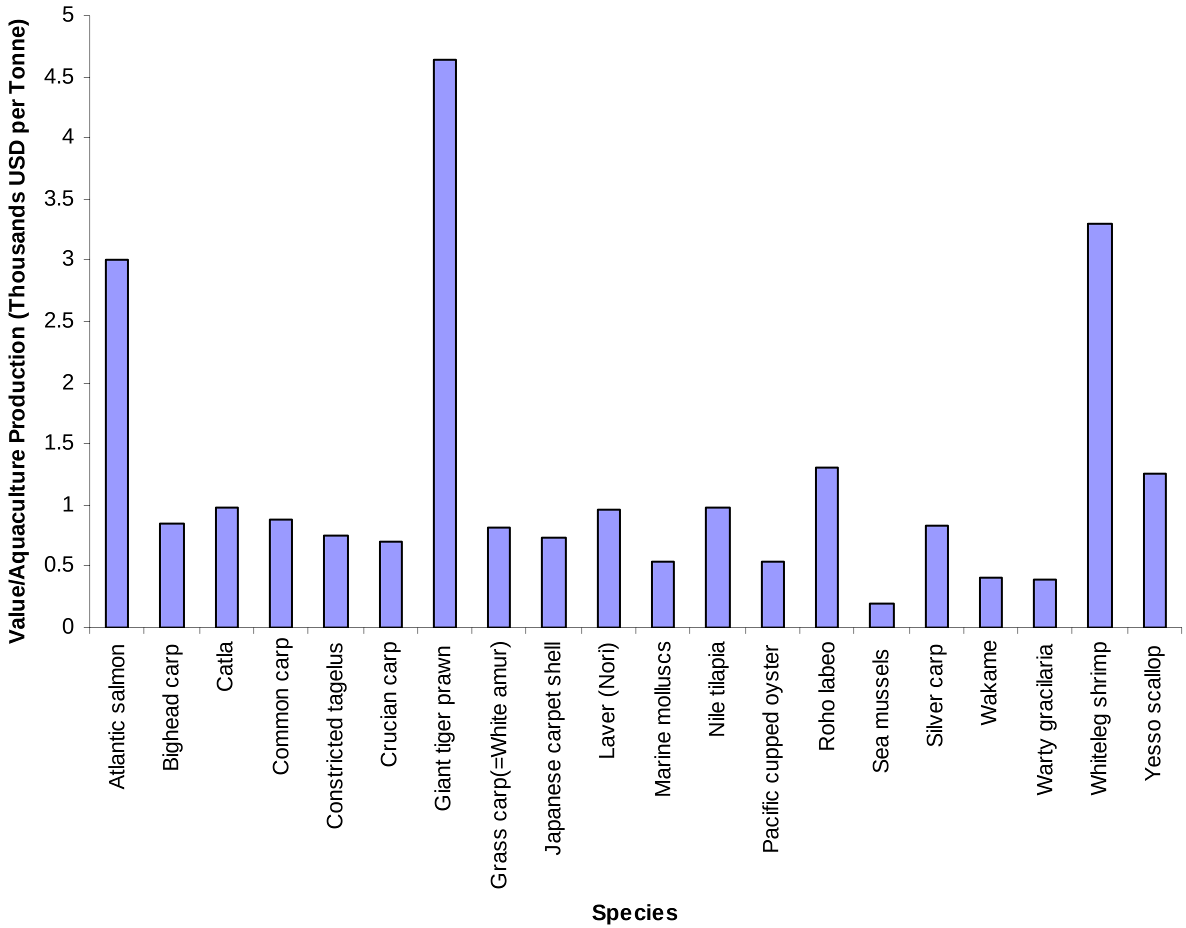

Fig. 19. Value divided by aquaculture production for Asia in 2004.

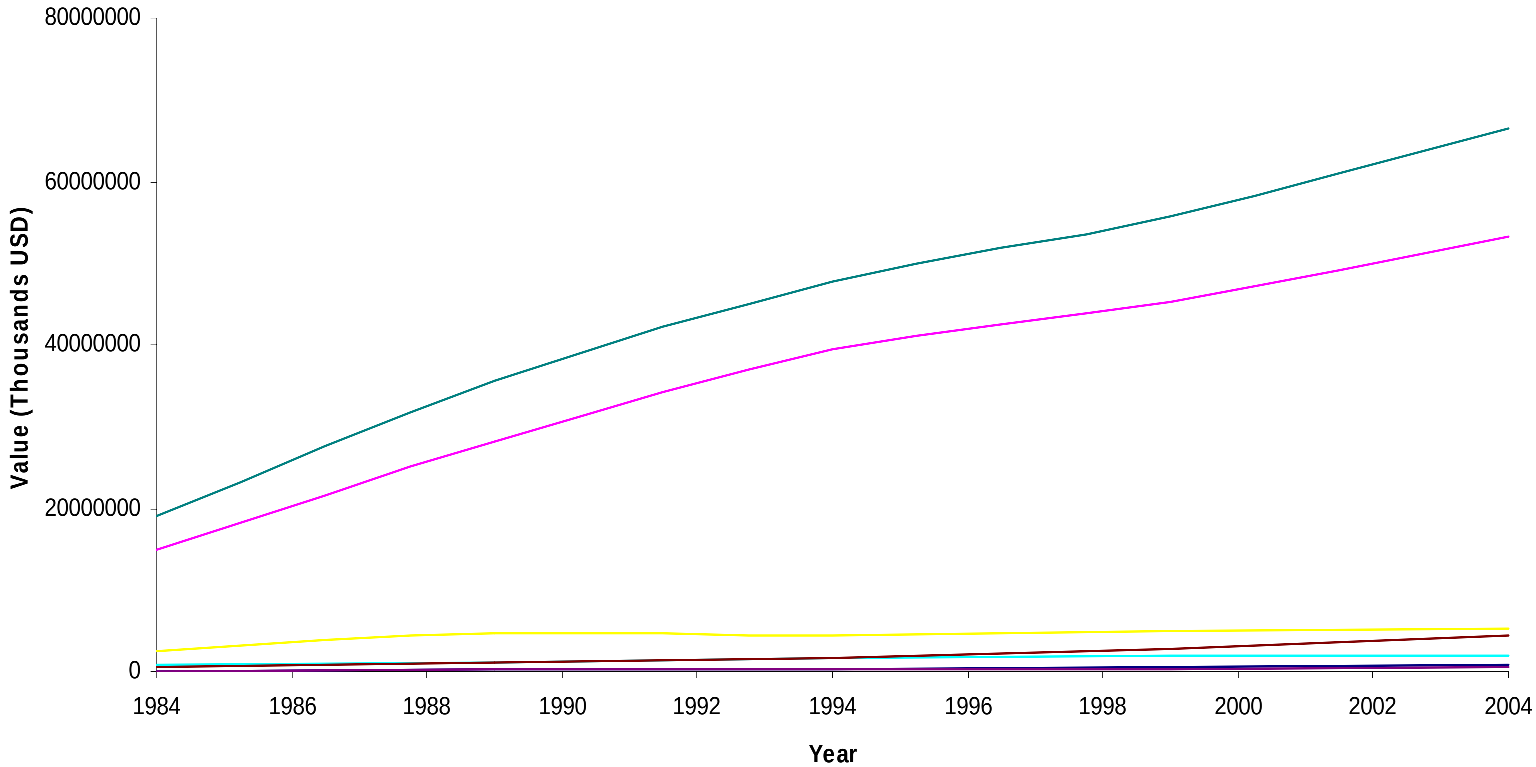

Fig. 20. Value of aquaculture versus time for Europe (yellow), North America (light blue), South America (brown), Africa (dark blue), Oceania (purple) and Asia (pink). Total value is shown by the green line.

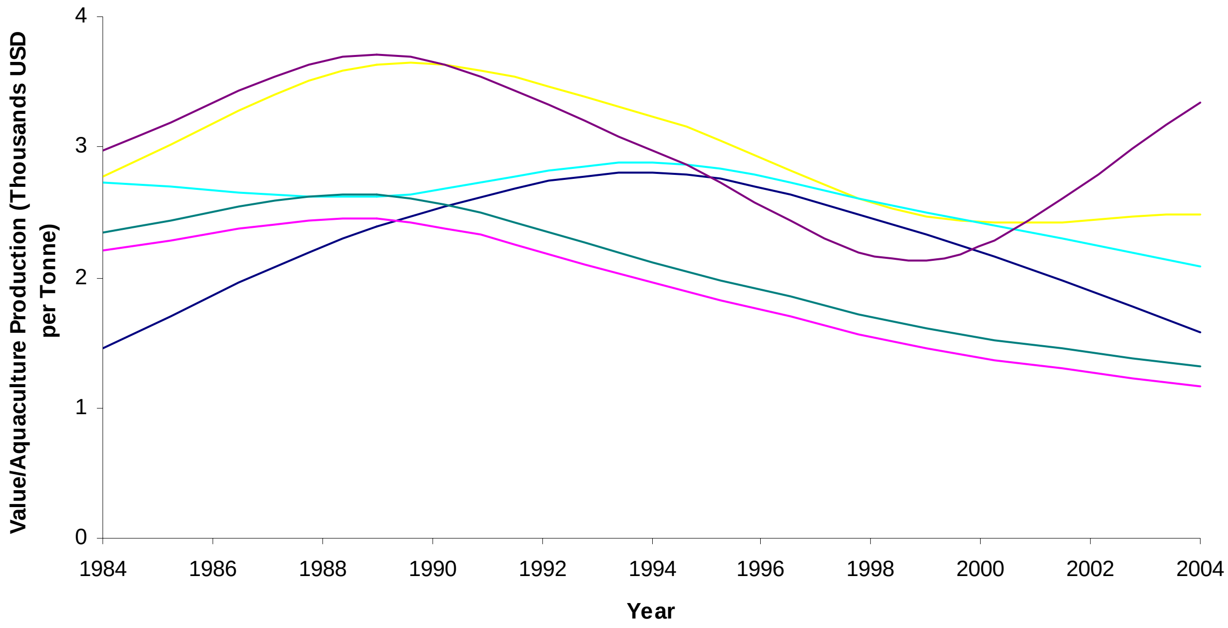

Fig. 21. Value divided by aquaculture production versus time for Europe (yellow), North America (light blue), Africa (dark blue), Oceania (purple) and Asia (pink). Total value divided by aquaculture production is shown by the green line.

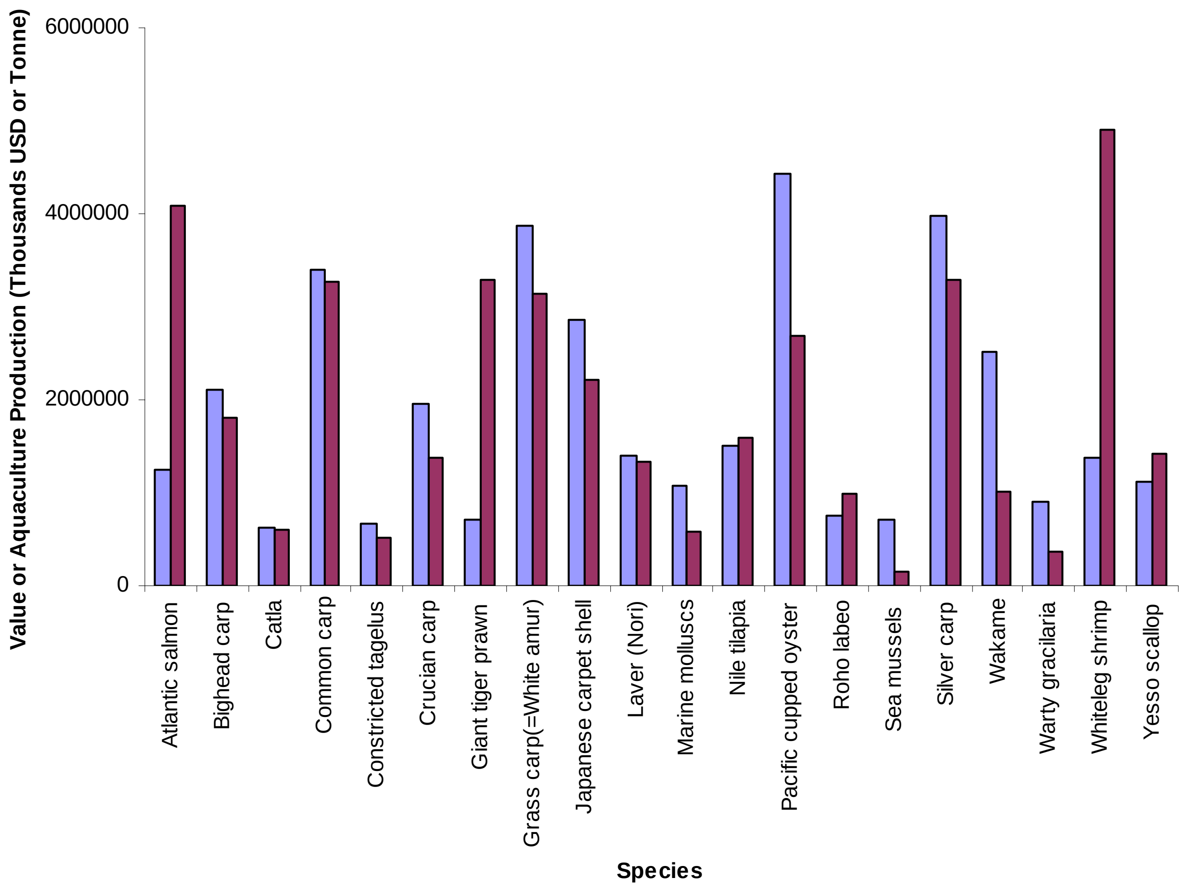

Fig. 22. Value (blue) and production (purple) for the top ranked 20 species in 2004 for the world.

4. DISCUSSION

Consideration of the harvest weight and value of the principle aquaculture species consumed (Figs. 1 - 22) highlights the growing importance of aquaculture produced fish and shellfish for human protein needs. It is clear that there are large regional differences with regard to the contribution of harvest weight (production) and the species reared (Figs. 2 - 7). Asia accounts for the greater part of the aquaculture production (Fig. 7), exceeding that produced by Europe and North America by a factor of 21 and 48 respectively. This circumstance has been the case for the last decade or so. Naylor et al. (2000) employ data on the nine most widely consumed aquaculture species (from: Food and Agriculture Organization Aquaculture production statistics 1987-1996, Fish. Circ. 915 (Rev. 10), 1998, Food and Agricultural Organization Aquaculture Production Statistics 1988-1997, Food and Agricultural Organization, Rome, 1999) to show that in 1997 the harvested weight produced by Asia amounted to 90 % of the global total with China accounting for about two-thirds of Asia's total production. From a global standpoint, the five highest ranked aquaculture species in production are: whiteleg shrimp *P. vannamei,* Atlantic salmon *S. salar,* common carp *C. carpio,* silver carp *H. molitrix* and giant tiger prawn *P. monodon*.

The principle contributor by far to the global shrimp aquaculture supply is Asia (Fig. 7A, B and C) with the balance produced of roughly equal measure by South America and North America (Fig. 3 and 4, respectively). The success of shrimp culture is largely a function of its profitability, defined as the difference between total gross income and total production cost. As in all cases, gross income depends on production level and farm price. Therefore, shrimp culture profitability depends upon production level, production costs and farm price. Production level and cost are a function of aquaculture economics, while farm price is largely related to marketing economics. There are a variety of fixed costs (e.g. facility and equipment depreciation, loan interest, land lease, fixed wages). These fixed costs do not necessarily change with production level and, therefore, the fixed cost per unit weight of shrimp produced decreases. Variable costs (e.g. cost of seed stock, feed, energy) increase with production level and intensity. The largest cost item for shrimp farming is seed and feed, which combined range from about 40 to 80 % of the total operating cost (Shang, 1992). Shrimp are raised in both hatchery and pond rearing operations. The total investment cost decreases as pond size increases and the total operating cost per unit weight of shrimp produced declines as farm and pond sizes increase (Griffin et al., 1985). However, the actual optimal farm or pond size in any given region depends on many biological, technical and socioeconomic factors. World demand for shrimp is growing rapidly and is likely to continue and shrimp aquaculture is the predominant industry filling a gap between the wild caught landings and current demand. The percentage of cultured world shrimp production rose from about 2 % in 1980 to 26 % in 1989 (Aquaculture Digest 1989), with the United States, Japan and Europe being the major importers. Whilst shrimp are commonly produced in high intensity operations and demand is relatively high priced, it is likely that competition between shrimp producing countries and their increased availability in other markets may result in lower prices in the future.

Atlantic salmon *S. salar* culture occurs largely in the North Atlantic where current production levels are of the order of 700,000 tonnes (McGinnity et al., 2003). The principle regional producer is Europe (Fig. 2) followed by South America (Fig. 3), North

America (Fig. 2), Oceania (Fig. 4) and Asia (Fig. 7A). A number of variables (environmental and economic conditions of farms, biological and environmental factors including the number of smolts released and their average size, the season at which the smolts are released, growth, mortality and stocking density, water temperature and feed types) determine the effectiveness of the operation. Economic and financial variables such as capital outlay, insurance costs, the price of feed, harvesting expenses, price of fish, loans and their interest and labor expenses determine the profitability of the operation (Bjorndal and Uhler, 1993). In addition, transportation costs are of importance. For example, most Atlantic salmon *S. salar* produced is consumed outside of the region of production and much of it is exported fresh requiring costly rapid transportation (Bjorndal and Uhler, 1993). All of these factors must be integrated in their efficient way to maintain a competitive position. Countries that have natural Atlantic salmon *S. salar* runs (Europe and the eastcoast of North America) are advantaged relative to areas where eggs are imported (Japan). Most Atlantic salmon *S. salar* are reared in open sea cages as opposed to land based farming systems. Feed is the single most important cost element followed by smolt cost and labour (Bjorndal and Uhler, 1993).

Carp (common carp *Cyprinus carpio*, Crucian carp *Carassius carassius* and silver carp *H. molitrix*) have traditionally been farmed in pond culture in Central Europe largely for regional consumption (EIFAC Technical Paper No. 40 1981). However, over the course of the last 30 years, Asia has become by far and way the world’s predominant producer centering efforts on production of silver carp (Fig. 7C). In 2004, Asia accounted for over 3.8 million tonnes and Europe’s total production amounted to less than 1 % of this figure. Whilst production in Europe is still consumed regionally, global export markets have and continue to be developed in Asia.

Naylor et al. (2000) point out that two subsectors have emerged regarding the nature of aquaculture practices that are characterized by their scale of operation and the value of the species produced. Aquaculture operations in China provide a good example, where local and regional consumption is based largely on family and co-operative farms that produce low value species for domestic consumption and large commercial farms that produce high value species that are largely exported to global markets. Further, most of the internationally traded (high value) aquaculture products (e.g. salmon, shrimp, oysters) produced in Asia are consumed in Europe, North America and Japan (Naylor et al., 2000). While the production, value of various aquaculture species and the nature of the facilities and practices associated with them have been documented in some detail, information of comparable scope and depth on the impacts of international trade on current aquaculture production are scarce. However, it seems that the rapid rise in production (Fig. 1) (and presumably increasing export of high value species) has been associated with a steady decrease in price over the last 20 years or so (Fig. 21). Market dynamics affecting supply and demand aside, it seems clear that global aquaculture production is rapidly approaching that of world wild capture values and likely to exceed them in the near future if current trends continue (Figs. 1, 23, 24 and 25). However, this circumstance is predicted on the basis of the extrapolation of mathematical curve fits to both the wild capture and agriculture based curves and assumes that biological and economic factors determine production in both sectors will continue into the near future. Pauly et al. (2003) address the likely future for wild capture fisheries through the identification and extrapolation of historical and current trends and explore possible futures. Based on the extrapolation of present trends, they suggest the likelihood of expansion of bottom fisheries into deeper waters, reduction on biodiversity and declining global catches. They conclude that the current negative trends regarding wild fisheries can be “turned around,” together with some level of repair to the ecosystems that support them.

Pauly et al. (2003) discuss their ideas in the context of four scenarios developed by the United Nations environment program (United Nations Environment Program, Global Environmental Outlook 3, EarthScan, London, 2002): 1. In situations where market considerations shape environmental policy, gradual elimination of subsidies to overfishing companies should be eliminated which in turn could lead to the elimination of fuel intensive components of distant water fleets (e.g. large trollers) and prompt the development of small scale fleets. It is supposed that this will allow for the spontaneous emergence of marine reserves (i.e. areas that are not economically fishable). It is conceded that high priced bluefin tuna and groupers would remain under pressure; 2. Given the continuing vulnerability of high priced taxa, it is recommended that other possible fisheries be developed for direct human consumption and as feed for aquaculture reared fish (e.g. krill). 3. Regulatory reforms coordinated between countries focusing on marine reserve networks production and effort and minimizing by-catch (e.g. closing profitable fisheries that cause the death of sea turtles or marine mammals). 4. A focus on sustainability and “bottom up” governments of local resources would again enable the development of marine reserves and stock rebuilding. Pauly et al. (2003) point out based

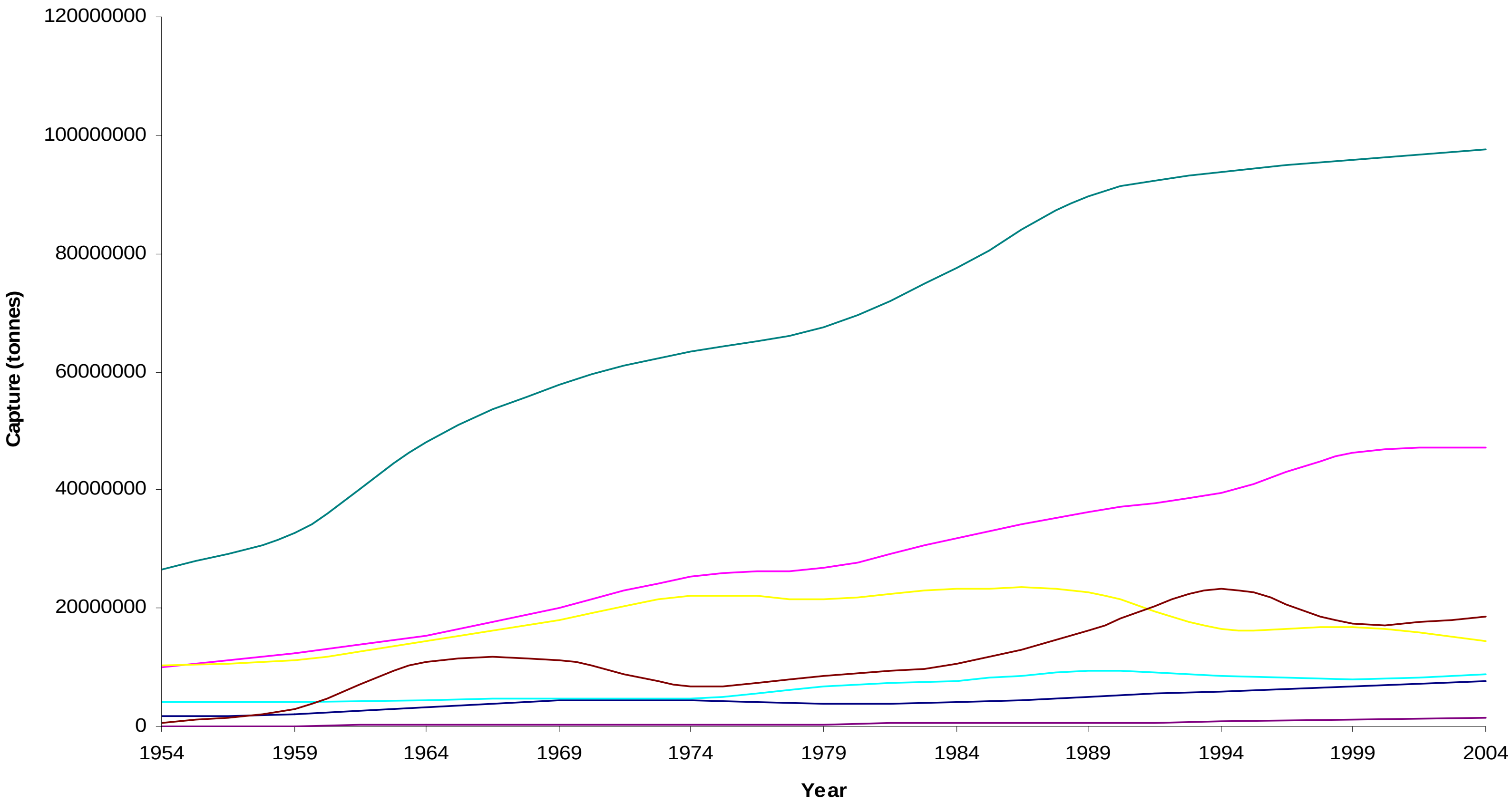

Fig. 23. Capture versus time for Europe (yellow), North America (light blue), South America (brown), Africa (dark blue), Oceania (purple) and Asia (pink). Total production is shown by the green line.

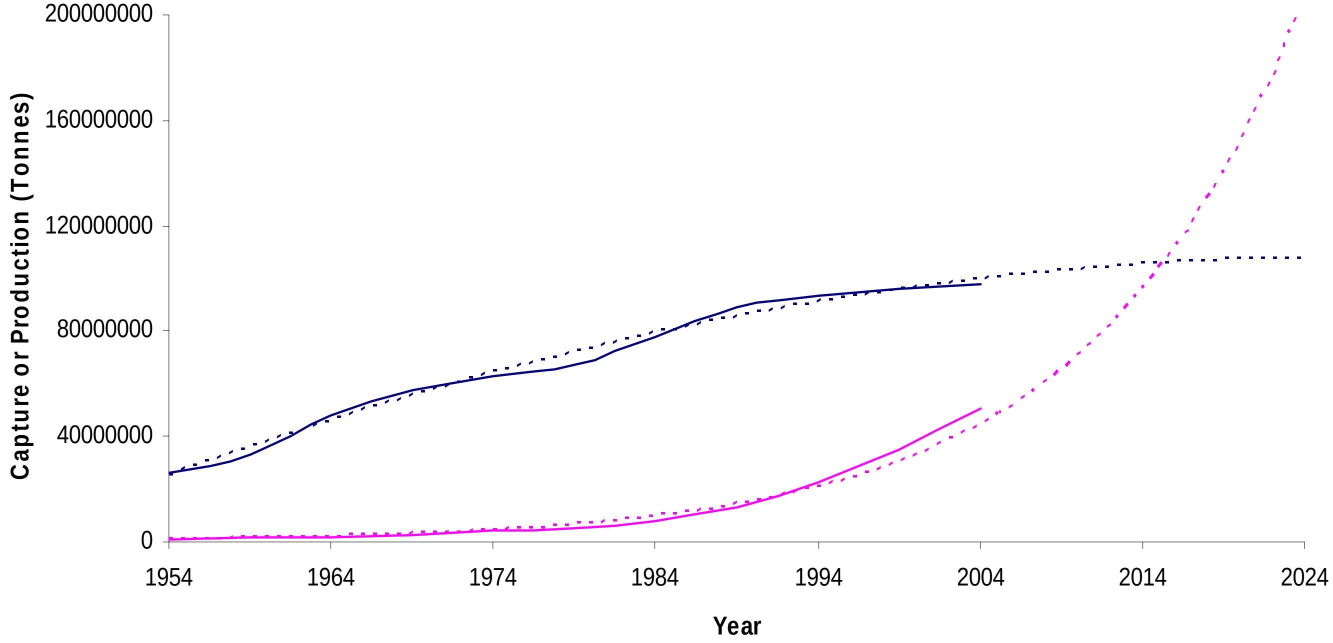

Fig. 24. Capture (dark blue; $y=-15604a^2+6x10^7a-6x10^{10}$) and aquaculture production (pink; $y=8x10^{-60}e^{0.0767a}$) versus time for the world. Future projections are given as dotted lines.

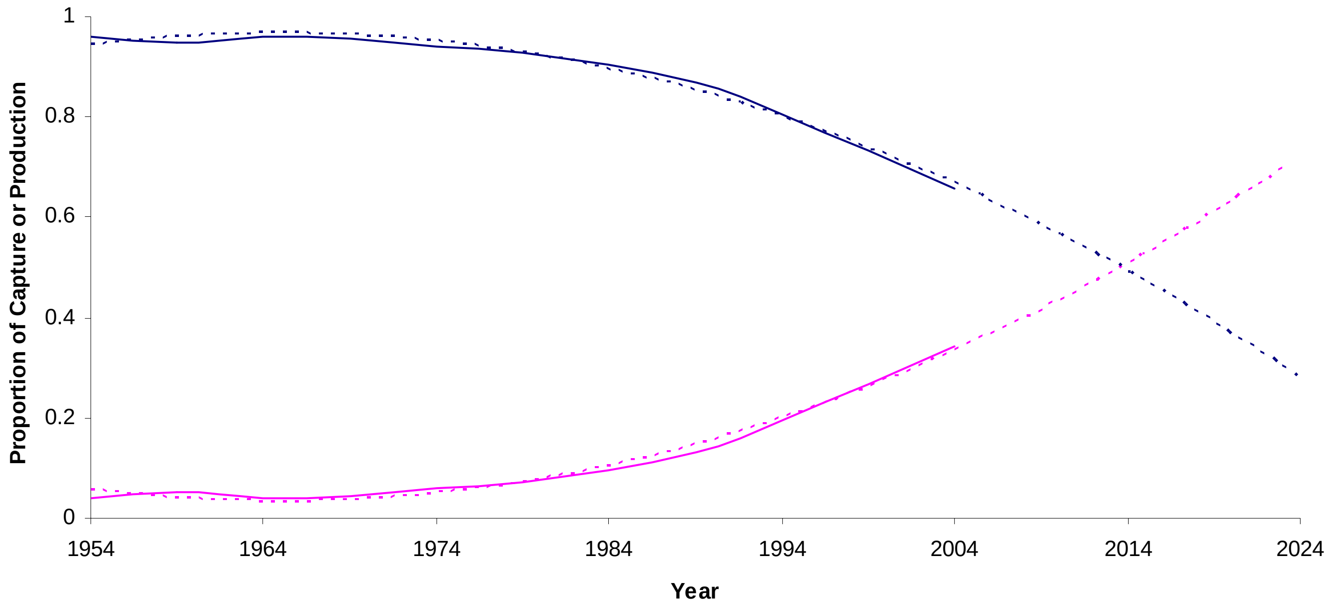

Fig. 25. Proportion of capture (dark blue; $y=-0.0002a^2+0.779a-764.44$) and aquaculture production (pink; $y=0.0002a^2-0.779a+765.44$) versus time for the world. Future projections are given as dotted lines.

on simulation studies that maximizing the biomass of long-lived organisms will require strong decreases in fishing effort of the order of 20 to 30 percent of current levels.

In addition to the obvious growing importance of the contribution of aquaculture to the world protein supply, a number of other possible benefits have been suggested with regard to the rise in aquaculture production, among them, that aquaculture production can alleviate pressure on wild fisheries (Naylor et al., 2000; Goldburg and Naylor, 2005; Pauly et al., 2002). It has been proposed that increased production of farmed fish that compete economically with wild fish (e.g. salmon) reduces prices and results in decreased investment in fishing fleet and, therefore, fishing effort (e.g. Muir and Young, 1998; Naylor et al., 2000). From an ecological standpoint, this would allow wild species subject to high fishing pressure that may be endangered to recover their numbers. However, it has been suggested that the reverse may be the case, at least in some cases. Evidently, despite the rise in aquaculture production in farmed salmon, wild capture has not shown a commensurate reduction. Indeed, worldwide salmon catches increased between 1988 and 1997 (Johnson, 1998).

Goldburg and Naylor (2005) review data regarding recent experiences in the salmon and shrimp sectors to bear upon the dynamics of farmed and wild production. Both farmed and wild caught stock increase significantly between 1998 and 2001. Over 90 % of the production of farmed salmon is Atlantic salmon *S. salar* and prices for all species of salmon have fallen as a result of the increased supply with Atlantic salmon *S. salar* prices falling by 61 % between 1998 and 2002. Capture levels remain higher today than in the period leading up to 1990 when salmon farming was an insignificant component of the global market. Goldburg and Naylor (2005) suggest that it would be premature to conclude salmon farming is supplanting salmon capture worldwide. Over a similar period, the farming of marine shrimp in coastal pond has also increased dramatically but the dynamics between farmed and wild caught shrimp differ from those of salmon driven largely by unbounded market demand for shrimp from the United States, Europe and Japan. The upward trend in shrimp capture indicates that aquaculture is not supplanted from fishing globally. However, Goldburg and Naylor (2005) point out that some types of marine aquaculture may be decreasing fishing activity in some regions. In particular, declining incomes for shrimp fishermen in the southern United States have led fishermen to agent tariffs against the number of shrimp farming countries (Hedlund, 2004). It may be the case that over time aquaculture may reduce the volume of wild caught fish.

Pauly et al. (2002) argue against the likelihood that aquaculture production will "fill the gap" between the global demand for fish protein or that it will provide ultimately as the principle protein source. Their argument is based on three lines of evidence: 1. that the current growth rate in global aquaculture production is inflated through production over-reporting by China; 2. that aquaculture practices are unsustainable due to inefficient energy use and are associated with negative impacts such as pollution; and 3. that, particularly in the developed world, carnivorous fish (e.g. salmon, sea bass) are fed a diet rich in fish meal and oil produced by other fish that are consumed by people (e.g. herring, sardine, mackerel). While the practice seems commercially sound because the farmed fish fetch higher market price than the fish used to feed them, it is nevertheless the case that more fish flesh is used in the process and this is denied to peoples in developing countries that are not in a position to afford the more expensive market fish consumed in Europe and North America.

Of Pauly et al.'s (2002) three lines of argument, there can be little doubt that current aquaculture practices in many regions of the world are indeed largely unsustainable and that at the level of a global assessment feeding carnivorous fishes with products based on fishes lower down the food chain denies developing countries a vital source of protein. However, their first argument is questionable. It is known that China over reports its marine fishery's captures (Rawski and Xiao, 2001). However, as far as I am aware, there is no evidence supporting China's over-reporting of its aquaculture production. It is worth giving further consideration to the significance of the clear trends in the rapid increase in global aquaculture production (Figs. 1, 24 and 25) in the context of Pauly et al.'s (2002) second and third arguments regarding declining wild captures in the context of aquaculture production bridging the gap between fish protein supply and demand.

Pauly et al. (2002) address the unsustainability of aquaculture practices (second argument) from the standpoint of pollution, disease and habitat degradation. In addition to these issues, there are many others that impact public, animal and environmental health issues in industrialized countries including biological hazards (e.g. parasites, bacteria, viruses), chemical hazards (e.g. toxin-producing algae, organochlorine pesticides) and aquaculture drugs (e.g. medicated feeds, chemotherapeutants). Arguably, findings and broadly applying effective solutions to these and other problems that compromise the sustainability of current aquaculture practices would reduce and potentially eliminate

Pauly et al.'s (2002) second line of argument regarding the future role of aquaculture in providing for world fish supply shortfalls.

The third line of argument is a reflection of aquaculture in the context of "farming up the food web." Essentially, this is the opposite of the convincing arguments made by Pauly et al. (1998) regarding wild capture as reflecting fishing down marine food webs (i.e. to lower trophic levels) which leads initially to increased catches followed by stagnating or declining catches. This form of fishing activity has in its turn produced a gradual shift in wild fish capture from large carnivorous species to smaller species that feed at lower trophic levels.

A growth in aquaculture production has led to a situation where four of the top five and eight of the top twenty captured species are small pelagic forms (e.g. anchoveta, mackerels, Atlantic herring *Clupea harengus*) which are used in feed production for the aquaculture and live stock industry (Food and Agricultural Organization, The State of World Fisheries and Aquaculture 1998). The high usage of wild caught pelagic fish for fish meal oils is particularly acute in intensive aquaculture systems which may use two to five times more fish protein, in the form of fish meal, to feed the farm species (Tacon et al., 1996). However, this is not so for non-intensive traditional systems although such operations are currently being intensified as new commercial feed meals develop in Asia (Naylor et al., 2000).

Feed is the largest production cost for commercial aquaculture operations and improving feed efficiency is a priority from the economic standpoint of the operations. This has spurred research into other possible feeding ingredients based on oil seeds, meat byproducts (e.g. bone meal) and microbial proteins (e.g. Tacon et al., 1994; Webster et al., 1999) to reduce feed costs. A possible solution to significantly reduce the scale of the "feeding up the food chain" phenomenon is to adopt optimum feeding regimes that exploit the innate compensatory growth response in fishes (Weatherley and Gill, 1981; Dobson and Holmes, 1984; Quinton and Blake, 1990; Blake and Chan, 2006; Blake et al., 2006). The compensatory growth response occurs upon refeeding after a period of mass loss following a period of food deprivation. There is a phase of rapid growth greater than normal whereby restrictively fed fish regain loss mass upon adequate refeeding. It has been shown that underyearling rainbow trout fed cyclically (three weeks of deprivation followed by three weeks of refeeding) show no significant differences in mass relative to fish fed daily. Essentially, all other things being equal, fish fed cyclically may achieve the same mean growth as fish fed daily on half the total food input (Quinton and Blake, 1990; Blake and Chan, 2006; Blake et al., 2006). If successfully implemented, this practice could reduce the feed cost of certain aquaculture operations by a factor of a half and significantly reduce the impact of the farming up the food chain effect.

Recently, research has begun to focus on ways of making aquaculture more sustainable through dietary changes, in particular, to replace fish meal and oil feed with plant based products. Such diets should be appropriate for those aquaculture fish that are predominantly plant eating (e.g. carp and tilapia). In addition, carnivorous fish (e.g. trout, salmon, cod, sea bass, tuna) may accept a vegetarian component to their diet based on products such as soy beans, corn, rapeseed, sunflower seeds, flaxseeds and wheat gluten. Currently, some farmed salmon are fed up to half of their protein from such ingredients (Refstie et al., 2001). Plant based diets for carnivorous fish require dietary supplements to provide for certain essential amino acids (e.g. methionine) and the addition of missing enzymes to break down phytic acid (storage molecule for phosphorus in seeds; McLean et al., 2002). Grant et al. (2008) have assessed the effects of supplemental dietary canola oil level on the growth, fatty acid composition and osmoregulatory ability in juvenile fall Chinook salmon (*O. tshawytscha*) which was found to be an excellent and cost effective source of supplemental dietary lipid for the fish during freshwater residency. In a related study, Huang et al. (2008) found that dietary canola oil has potential long term promise as a replacement of fish oil in the diet of pre-smolt spring Chinook salmon. However, some marine oil must be present to ensure certain essential fatty acid need of the fish.

The central issue addressed in this thesis is whether aquaculture could or indeed should be viewed as the principle source of fish protein in the future. The evaluation of regional and global aquaculture production supports the possibility of aquaculture's current and long term potential to more than supplement global fish supplies. Whilst the ongoing growth of the aquaculture industry requires a firm footing in ecologically sound and sustainable practices underlain by strict policy and management measures, it is clear that much remains to be done in the context of the development of the aquaculture technology to minimize its environmental impact. The case for continuing reliance on wild capture is being made in the context of reduced fishing efforts, the development of major initiatives to create marine reserves and the elimination of fishing down the food web and all of this with regard to the agreement, establishment and effective implementation of regulatory structures internationally. An optimistic view of these requirements and demand would require time. In the immediate and short term, it is clear that aquaculture production will play an important role in at least supplementing global fisheries markets. The prospects for the longer term are less clear.

The continuing development and expansion of aquaculture over the period from 2001 to 2020 is addressed in the 1997 FAO Report on the State of World Aquaculture. The report recognizes that "increasing demand for fish will require more aquaculture production, because the supply from capture fisheries is static." In addition, five other indicators are stated: 1. that aquaculture is, and will continue to be, recognized as a growth sector of economic importance in many countries and that the development plans of most producing countries are targeted at increasing fish supplies from aquaculture for local and export markets; 2. it is noted that the potential for increases in production in many existing systems can be based on a "vertical expansion of production by simple means." This is particularly so in the case of Asia; 3. in certain areas (e.g. China and India), production areas are expanding (horizontal expansion of production) through the development of areas unsuited for aquaculture (e.g. saline soils, water logged areas, seasonal water bodies). It is thought in the long term integration of aquaculture into watershed and coastal zone management will provide further opportunities for expansion; 4. culture-based fisheries will be developed through the stocking of reservoirs once current cost and benefit problems are resolved; and 5. the presence of awareness of sustainability needs will ensure a continuance of the sector in a long time and involve policy development at the national and international levels to develop guidelines for sustainable practices which together with technical improvements will improve the sustainability of some aquaculture systems. Of all of these issues, the FAO 1997 Report recognizes sustainability as the overriding strategic issue in a broad sense including the need for establishing reliable database and effective information systems, avoiding irreversible damage (i.e. negative human and environmental impacts), reduction of effluence, improvement of waste treatment procedure, increasing the efficiency and resource use and productivity at the farm level (e.g. lowering water system requirements, better feeding strategies, genetically improved stocks) and maximizing the positive sustainable attributes (e.g. food security, reduced pressure on the fishing of wild stocks, contributions to pest control).

Given that marine harvest of wild stocks from most primary fishing areas are approaching or at maximum sustainable yields, that aquaculture production will exceed that from wild stocks by about 2015 and by some estimates the world's population is expected to be approximately 8 billion by 2025, it is likely that the global food security will, at least in the short and medium term, increasingly rely on aquaculture. There is a growing understanding and sensitivity to the need for aquaculture to develop in a sustainable way and as an activity that contributes to maintaining and improving habitat quality and biodiversity. Currently, aquaculture production is largely viewed as a valuable and likely on-going supplement to wild stock capture. However, in the long term the reverse may be the case.

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