



Promoting the Science of Ecology

: i hi fY GYUdYgž: ]g\ ]b[ ž'UbX': ]g\ : Ufa ]b[
5i h\cf fjt: F YVYWU; c`XVi f [ `UbX`F cglā cbX`B Um`cf
Gci fW.: fcbh]Yfg`]b`9Vt`c[m`LbX`h\Y`9bj ]fcbā Ybhž`J c`"" ž`B c""%ž`J ]g]cbg`Zcf`Ub`9Vt`c[ ]WU`m
G`ghU]bU`Y: i hi fY`fl YV`ž`&\$\$) Ł`dd"" &% &,
Di V`]g\ YX`Vm`9Vt`c[ ]WU`GcWYhm`cZ`5a`Yf]WU
GhU`Y`I`F`@` <http://www.jstor.org/stable/3868441>
5 WVggYX. `%`#`\$`#`&\$\$-`%`\*`%\$

Your use of the JSTOR archive indicates your acceptance of JSTOR's Terms and Conditions of Use, available at <http://www.jstor.org/page/info/about/policies/terms.jsp>. JSTOR's Terms and Conditions of Use provides, in part, that unless you have obtained prior permission, you may not download an entire issue of a journal or multiple copies of articles, and you may use content in the JSTOR archive only for your personal, non-commercial use.

Please contact the publisher regarding any further use of this work. Publisher contact information may be obtained at <http://www.jstor.org/action/showPublisher?publisherCode=esa>.

Each copy of any part of a JSTOR transmission must contain the same copyright notice that appears on the screen or printed page of such transmission.

JSTOR is a not-for-profit organization founded in 1995 to build trusted digital archives for scholarship. We work with the scholarly community to preserve their work and the materials they rely upon, and to build a common research platform that promotes the discovery and use of these resources. For more information about JSTOR, please contact support@jstor.org.



Ecological Society of America is collaborating with JSTOR to digitize, preserve and extend access to Frontiers in Ecology and the Environment.

<http://www.jstor.org>

# Future seascapes, fishing, and fish farming

Rebecca Goldberg and Rosamond Naylor

The depletion of many marine fisheries has created a new impetus to expand seafood production through fish farming, or aquaculture. Marine aquaculture, especially of salmon and shrimp, has grown considerably in the past two decades, and aquaculturists are also beginning to farm other marine species. Production data for salmon and shrimp indicate that farming supplements, rather than substitutes for fishing. Since most farmed marine fish are carnivores, farming them relies on the capture of finite supplies of wild fish for use in fish feeds. As aquaculture is not substituting for wild fisheries, heavy dependence on wild fish inputs is a concern as marine aquaculture grows. Other likely impacts include escapes of farmed fish and large-scale waste discharges from fish farms. A viable future for marine ecosystems will require incorporation of ecological perspectives into policies that integrate fishing, aquaculture, and conservation.

*Front Ecol Environ* 2005; 3(1): 21–28

People have long regarded the oceans as vast, inexhaustible sources of fish – a view reinforced by the copious catches of the past. Even when fish became scarcer or harder to catch, many people continued to assume that more fish were available (Kurlansky 1997). In the past decade or two, this view of fisheries has been transformed. Fisheries statistics suggest that annual global fish catches have plateaued at roughly 90 million metric tons (mt) per year (FAO 2002), or may even be declining (Watson and Pauly 2001). Global catch statistics present only part of the picture, however. Many fisheries are overfished or heading towards depletion (Hilborn *et al.* 2003). The mean trophic level of fish caught worldwide has declined substantially, in part because humans tend to consume larger, predaceous fish (Pauly *et al.* 2002; Hilborn *et al.* 2003). According to one estimate, commercial fishing has wiped out 90% of large fish, including swordfish, cod, marlin, and sharks (Myers and Worm 2003).

The oceans may now be poised for another transforma-

tion. Fisheries depletion has created new impetus to expand seafood production through fish farming, often known as aquaculture. Aquaculture is frequently cited as a way to increase seafood supply in a world where greater quantities of fish cannot be obtained from the oceans. It has become an increasingly important source of food; between 1992 and 2002, global production of farmed finfish and shellfish (“fish”) almost tripled in weight and nearly doubled in value (FAO 2003). Currently, roughly 40% of all fish directly consumed by humans worldwide originate from commercial farms.

To date, most aquaculture production has been of freshwater fish, such as carp and tilapia, in Asia (Naylor *et al.* 2000; FAO 2003). However, marine aquaculture, particularly production of salmon and shrimp, has been growing rapidly. Salmon aquaculture originated in Norway in the 1970s, and has since boomed worldwide. Global production of farmed salmon roughly quadrupled in weight from 1992 to 2002, and farmed salmon now constitute 60% of fresh and frozen salmon sold in international markets (FAO 2003). This spectacular increase and the resulting decline in salmon prices (Naylor *et al.* 2003) have encouraged aquaculturists to begin farming numerous other marine finfish species, many of them now depleted by overfishing. New species being farmed include Atlantic cod (*Gadus morhua*), Atlantic halibut (*Hippoglossus hippoglossus*), Pacific threadfin (*Polydactylus sexfilis*), mutton snapper (*Lutjanus analis*), and bluefin tuna (*Thunnus* spp).

As with salmon, these new species are typically farmed in netpens or cages, anchored to the ocean bottom, often in coastal waters. In the US, where expansion of salmon farms in coastal waters has been met with local opposition and state-level restrictions, the US National Oceanic and Atmospheric Administration (NOAA) is pursuing the development of large offshore aquaculture

## In a nutshell:

- Fish farming appears to be supplementing, not substituting for, capture fishing
- The growth in marine fish farming may lead to increased competition for small fish, which serve as feed inputs for farmed fish and as prey for commercially valuable predatory wild fish
- Farming of new marine species may lead to increased impacts from marine fish farming, including greater numbers of escaped farmed fish that interact with wild fish, and significant cumulative impacts from farm wastes
- Policies governing marine ecosystems must incorporate ecological perspectives and integrate fishing, aquaculture, and conservation objectives

<sup>1</sup>*Environmental Defense*, 257 Park Avenue South, New York, NY 10010 (bgoldburg@environmentaldefense.org); <sup>2</sup>*Stanford University, Center for Environmental Science and Policy*, Stanford, CA 94305



Courtesy of The David Suzuki Foundation

**Figure 1.** A salmon farm in British Columbia.

operations, primarily in the exclusive economic zone (EEZ), away from coastal activities and beyond the reach of state laws (DOC 2004). In some areas, such as the Gulf of Mexico, there are plans to use offshore oil and gas rigs, some of which would otherwise have to be decommissioned, as platforms for new aquaculture facilities.

Taken together, these developments signal a new trend in marine fisheries production, away from capture of wild fish to human-controlled production. Supplementation of wild fish populations with hatchery-produced fish is also part of this trend, particularly since hatchery production of salmon set the stage for salmon farming.

Does this mean that production of farmed fish will supplant wild fisheries in the future? Aquaculture development is sometimes promoted as a means to relieve the pressure on wild fisheries. Some authors argue that capturing fish is akin to hunting terrestrial animals for food, an activity that has almost entirely been replaced by farming livestock (eg Avery 1996). This comparison is imperfect, however, in part because fish tend to have much higher reproduction rates than warm-blooded land animals and therefore can generally sustain higher capture rates. Nevertheless, expanding production of farmed fish could lower prices and create economic conditions that, over time, will decrease investments in fishing.

### ■ Will fish farming supplant fishing?

Recent experiences in the salmon and shrimp sectors provide insights into the dynamics of farmed and wild production. The late 1980s marked a transition in global salmon markets. Quantities of both farmed stock and wild-caught fish jumped, causing total salmon output to increase from 776 thousand mt in 1988 to two million mt in 2001 (Figure 2). Farmed salmon production reached 1217 thousand mt in 2002, 68% higher than the 722 thousand mt of wild-caught fish.

Over 90% of the farmed product is composed of

Atlantic salmon (*Salmo salar*), a species that is nearly extinct in the wild. With a high degree of consumer substitution among salmon species, prices for all species have fallen as a result of increased market supplies. Between 1988 and 2002, the price of farmed Atlantic salmon fell by 61% and the price declines for North American Pacific salmon ranged from 54% for chinook (*Oncorhynchus tshawytscha*) to 92% for pink salmon (*Oncorhynchus gorbuscha*) (Naylor *et al.* 2003).

While global salmon catch has fluctuated between 720 thousand and 1 million mt since 1989 – during a time when aquaculture was expanding – capture levels remain higher today than in the period leading up to 1990, when salmon farming was insignificant in global markets. It would therefore be premature to conclude that salmon farming is sup-

planting wild capture worldwide.

Moreover, “wild” salmon stocks are not entirely wild. Salmon capture has increased and salmon prices have fallen, in part because wild salmon populations have been supplemented by hatcheries. An estimated 4.4 billion salmon fry were released by hatcheries in Japan, the US, Russia, and Canada in 2001 (NPAFC 2004). Despite extremely low survival rates, hatchery fish currently account for one-third of the total salmon catch in Alaska (averaged across all species; ADFG 2004) and virtually the entire chum catch of 211 thousand mt in Japan (FAO 2003; G Knapp pers comm).

Farming of marine shrimp in coastal ponds boomed during the same period as salmon farming, but the dynamics between farmed shrimp and wild-caught shrimp differ from those seen in salmon. There is no hatchery supplementation of wild shrimp, and market demand for shrimp from the US, Europe, and Japan is seemingly limitless. Commercial farmed shrimp production began in the late 1970s, grew substantially in the 1980s, and reached 42% of total shrimp production by 2001 (Figure 3). At the same time, the quantities of wild-caught shrimp increased from 1.3 million mt in 1980 to about 1.8 million mt in 2001, and the total quantity of farmed and wild shrimp roughly doubled. Shrimp prices have generally fallen over this period; for example, prices for “26/30 count” frozen white shrimp (*Litopenaeus vannamei*) fell approximately 13% between 1990 and 2002 (HM Johnson pers comm). However, shrimp prices have been much more volatile than salmon prices (FAO 2003), in large part because outbreaks of various shrimp diseases have caused large country-specific fluctuations in shrimp numbers. Prices aside, the upward trend in shrimp capture indicates that aquaculture has not supplanted shrimp fishing globally.

There are signs that at least some types of marine aquaculture may be decreasing fishing activity in some regions, despite the lack of clear evidence that salmon and shrimp aquaculture are replacing fishing. Many Alaskan salmon

fishermen have seen their incomes decline and some have quit fishing altogether (Naylor *et al.* 2003, in press). Declining incomes for shrimp fishermen in the southern US have led the fishermen to press for anti-dumping tariffs against a number of major shrimp farming countries (Hedlund 2004). Over time, aquaculture may reduce the volume of wild-caught fish. However, economic inertia in the fishing industry, due to capital investments in fishing vessels, an inelastic labor force, and government subsidies, may mean that the fishing industry is slow to reduce capture rates in response to price declines (Naylor *et al.* 2000; Eagle *et al.* 2004).

### ■ Ecological impacts of fish farming

The growth in marine aquaculture, and possibly also in hatchery production, will alter not just sources of marine fish and the economics of fishing, but may also transform the character of the oceans from relatively wild, or at least managed for fishing, to something more akin to agriculture. It is tempting to compare the future of the oceans to that of the North American prairie 150 years ago, which was mostly plowed under to grow crops. However, there are important differences. First, most marine fish farms will essentially be feedlots for carnivores, particularly if the salmon farming model is copied. Second, although fish farms are unlikely to occupy a large area, the ecological impact on marine resources could be much greater than the geographical extent of fish farms implies. This is because fish farming depends heavily on, and interacts with, wild fisheries.

#### *Farming carnivores*

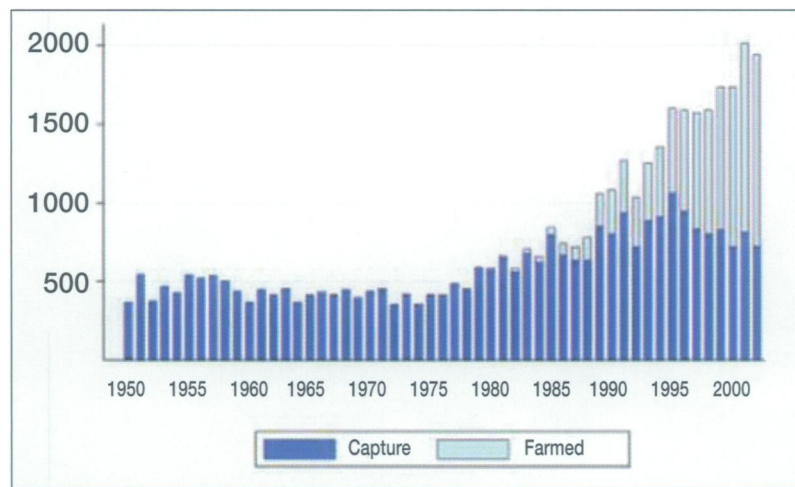
One obvious consequence of the proliferation of aquaculture is that more marine resources are required as inputs. Over the past two decades, roughly 30 million mt per year – close to one third of the current annual global fish catch – has been used for the production of fishmeal and fish oil for animal feeds. An increasing proportion of this catch is used in fish farming, as aquaculture production grows and the livestock and poultry sectors replace fishmeal with less expensive ingredients. In 2001, 17.7 million mt of marine and freshwater farmed fish were fed fishmeal containing ingredients derived from 17–20 million mt of wild-caught fish, such as anchovies, sardines, and capelin (Tacon 2003). Other farmed species, such as filter-feeding carp and mollusks, require no feeding.

Most farmed marine finfish are carnivores and are much more dependent on wild fish-

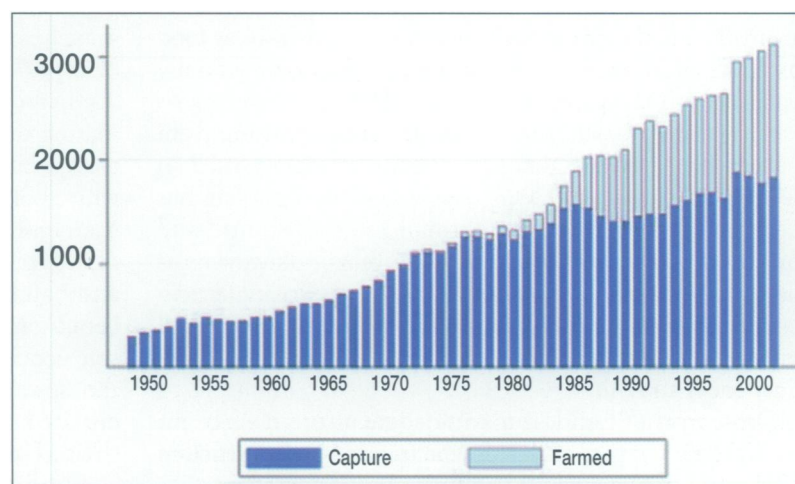
eries for the fishmeal and fish oil used in fish feeds than are farmed freshwater fish, which tend to be herbivores or omnivores (Naylor *et al.* 2000; Delgado *et al.* 2003). Fishmeal (at 38%) and oil (at 18%) are dominant components of salmon feeds (AGJ Tacon pers comm).

Continued growth in marine aquaculture production could outstrip the current supply of fish used for fishmeal and oil production, potentially jeopardizing the industry's economic sustainability (Naylor *et al.* 2000; Delgado *et al.* 2003). In early 2004, fishmeal prices rose to \$650 per ton, the highest price since the 1997–98 El Niño event and close to the record high (CRB 1998; FAO 2004). Moreover, this price seems to reflect a longer term trend rather than the result of a sudden climatic event. Because feeds account for a large share of variable costs, aquaculturists raising carnivorous species are increasingly replacing fish-based products with plant-based ingredients in fish feeds (Powell 2003), but not fast enough to reverse the trend in fishmeal use caused by rising aggregate production (Aldhous 2004).

Farming salmon and other carnivorous marine fish rep-



**Figure 2.** Global farmed and capture production of salmon, 1950–2002. Data in thousands of metric tons. From FAO (2003).



**Figure 3.** Global farmed and capture production of shrimp, 1950–2002. Data in thousands of metric tons. From FAO (2003).





Courtesy of the NOAA

**Figure 4.** Gillnetter F/V Helen Marg putting out nets for salmon in Bristol Bay, Alaska.

resents a net loss of fish protein, as about two to five times more wild-caught fish are used in feeds than are harvested from aquaculture (Naylor *et al.*, 2000; Weber 2003). Some aquaculturists argue that catching small, low trophic level fish to feed large, high trophic level farm fish is desirable, because this is more efficient than leaving small fish in the ocean to be consumed by wild predatory fish caught by fishermen (Hardy 2001). The relative efficiency of fish farming versus fishing is difficult to quantify, in part because energy transfer between trophic levels in marine systems is not well documented, and some farmed species, such as marine shrimp, feed at a higher trophic level than they would in the wild. Nevertheless, fish farming is probably more efficient than catching wild fish, because farmed fish are protected from some causes of mortality, especially predators.

Even if fish farming is comparatively efficient, its heavy dependence on wild fish inputs is both economically and ecologically problematic if aquaculture is supplementing, rather than substituting for, capture fisheries. Not only is the supply of these low trophic level fish finite, but the small fish used to make fishmeal and oil are critical food for wild marine predators, including many commercially valuable fish (Naylor *et al.* 2000).

Growth in aquaculture may shift fishing pressure from output fish such as salmon to the input species used in feeds (Delgado *et al.* 2003). Fisheries management has kept the total global catch of small fish for fishmeal and oil relatively constant in recent years. However, as demand for these commodities increases, rising prices could increase the incentives and therefore the political pressure to allow capture of a larger fraction of fish to produce meal and oil.

On the other hand, if marine aquaculture does begin to supplant capture fisheries, the impetus will shift from managing the oceans for fisheries production to managing them for aquaculture production. In this scenario, capturing low trophic level wild fish for aquaculture

feeds, with little concern for the effect on higher trophic level wild fish, could form the basis for economically rational – although not ecologically sound – ocean management.

### Stocking the oceans

Another impact of the growth in marine aquaculture and supplementation of wild stocks stems from interactions between escaped farmed fish, hatchery fish, and wild fish. Escapes of farmed salmon from pens, both in episodic events and through chronic leakage, are well documented (Naylor *et al.* in review). The expansion of marine aquaculture and hatchery supplementation could substantially increase the numbers of introduced fish in marine waters.

Numerous studies have documented the ecological damage caused by escaped farm fish, especially among wild salmon, although some authors have found otherwise (Waknitz *et al.* 2003). Depending on the location, these may include the introduction of non-native fish species and reduced fitness of wild fish as a result of interbreeding with escapees of the same species (McGinnity *et al.* 2003; Naylor *et al.* 2004). Ocean “ranching” of hatchery fish, which are often genetically distinct from their wild counterparts, can cause similar problems (NRC 1996; Levin *et al.* 2001; Kolmes 2004). The impacts of fish escapes may not be recognized until they are irreversible (Naylor *et al.* 2004).

Most of the literature on the harmful effects of interbreeding between introduced and wild fish concerns salmon. These anadromous fish spawn in freshwater and will not reproduce in ocean pens. Other truly marine finfish, such as cod, do produce fertilized eggs in ocean enclosures (Bekkevold *et al.* 2002). Although cages used for offshore farming are more secure than salmon netpens, neither pens nor cages will prevent fish eggs from escaping. Farming at least some fish species might lead to “escapes” on a much larger scale than is seen in salmon.

One potentially mitigating factor is that populations of marine fish species may be less genetically differentiated than salmon, which have subpopulations adapted genetically to local conditions in river drainages. Salmon are therefore particularly prone to reduced fitness as a result of interbreeding with escaped, genetically distinct farmed and hatchery fish. Interbreeding may therefore have less genetic impact in truly marine fish species. All the same, some marine fish also have distinct subpopulations. Atlantic cod form aggregations that are genetically differentiated and there appears to be little gene flow between them (Ruzzante *et al.* 2001).

Both hatchery supplementation and escapes have the potential to supplant wild fisheries by reducing their fitness as well as their market share. Ironically, salmon aqua-

culture has provided the fishing industry with incentives to restructure and become more efficient (Eagle *et al.* 2004), yet part of the response to date has been to release more hatchery fish, making up in volume what is lost in value. If aquaculture begins truly to replace capture fishing, however, the impetus for hatchery supplementation will be reduced. Meanwhile, escaped farmed fish and wild-farmed crosses are likely to become increasingly prevalent, unless new technology is developed that prevents the escape not only of adult fish but also of their gametes and embryos.

### Nutrient loading

Most marine aquaculture is modeled after terrestrial feedlots or “industrial” farms used to raise most hogs and poultry in the US and elsewhere. Large numbers of animals are confined in a small area, and their feed imported, often from distant sources. Industrial animal facilities typically cluster geographically to benefit from economies of scale and favorable politics (L Cahoon pers comm). One consequence is water pollution, since a substantial fraction of nutrients in animal feeds ends up in animal wastes, which often cannot all be assimilated by local croplands (Aneja *et al.* 2001; Gollehon *et al.* 2001; Mallin and Cahoon 2003). Water pollution from animal wastes is a major environmental issue in coastal North Carolina and other areas where animal production has concentrated.

Waste from finfish netpens and cages flows directly into marine waters and, in contrast to terrestrial farms, there is usually no attempt to capture it. Nutrients and suspended solids discharged by salmon farms can have considerable effects on a local scale (Goldberg *et al.* 2001), although salmon farms sited in well flushed areas often have minimal impact on the quality of surrounding waters (Brooks and Mahnken 2003). Dilution of nutrients means that widely spaced marine fish farms sited in areas with strong currents will probably have little impact, an argument for moving marine aquaculture out of coastal waters and into the open ocean (Marine Research Specialists 2003).

It is instructive to examine the potential cumulative impact of expanded marine aquaculture. NOAA’s stated goal is the development of a \$5 billion US aquaculture industry by 2025. Using figures from salmon farming in British Columbia, we estimate how much nitrogen (N), the nutrient primarily responsible for eutrophication in marine waters, a \$5 billion marine finfish aquaculture industry might discharge.

Producing a kilogram of salmon releases approximately 0.02 to 0.03 kg of N, excluding losses from uneaten feed (Brooks and Mahnken 2003). About 70 000 mt of salmon were produced in British Columbia in 2003 (C Matthews pers comm) with a gross domestic product value of C\$91 million, or approximately US\$66 million (Marshall



Figure 5. Wild Atlantic salmon.

Courtesy of the US Fish and Wildlife Service

2003). Thus the BC salmon farming industry discharged about 1435 mt to 2100 mt of nitrogen. Extrapolating from these figures, a \$5 billion would therefore discharge approximately 108 000 mt to 158 000 mt of nitrogen per year.

Americans excrete approximately 0.016 kg of N per day (Stipanuk 2000). Assuming conservatively that a \$5 billion aquaculture sector discharges 100 000 mt of N per year, this discharge is equivalent to the amount of N in untreated sewage from approximately 17.1 million people for one year.

Every ton of hog waste contains about 12.3 lbs of N and a hog produces about 1.9 tons of waste per year (Shaffer 2004). Converting these numbers to metric figures, the North Carolina hog industry of 10 million hogs (USDA 2004) produces about 106 000 mt of N per year – roughly equivalent to the output from a \$5 billion aquaculture industry.

Thus a \$5 billion marine finfish aquaculture industry would discharge annually an amount of N equivalent to that in untreated sewage from 17.1 million people or the entire North Carolina hog industry of about 10 million hogs. On the other hand, a \$5 billion offshore aquaculture industry would produce only about one tenth of one percent as much N as the 121 million mt annual biological nitrogen fixation in the world’s oceans (Galloway 2003). On balance, therefore, the potential impacts of wastewater from marine aquaculture facilities are not cause for alarm, but should not be ignored, either, especially if such facilities are to be clustered geographically or sited in only moderately flushed areas.

### ■ Envisioning the future

A viable future for marine ecosystems will almost certainly require integrating management for fisheries, fish farming, and conservation. Even if aquaculture begins to supplant wild fisheries, this process will probably be gradual, and fisheries will continue to be a major component of seafood production for some time.





Courtesy of the NOAA

**Figure 6.** View from inside a Hawaii offshore aquaculture cage containing Pacific threadfin (moi).

Greatly improved fisheries management is essential (Pauly *et al.* 2002). Current management is based largely on single species models for which there is often inadequate data and which do not reflect interactions in marine ecosystems. Many scientists have called for a more risk-averse, ecosystem-based approach to fisheries management (NRC 1999; Dayton *et al.* 2002). As aquaculture grows, a more ecosystem-based approach will be critical in helping to balance the competing demands for low trophic level fish used either as feed or left in the oceans to support capture fisheries and conservation objectives. We are only just beginning to work out what an ecosystem-based approach to fisheries management should entail, so this is a topic that still requires extensive research (Pikitch *et al.* 2004).

Improving fisheries management is not solely a matter of better management science. Economic (and therefore political) factors also play a major role. Fisheries are generally a “commons” and fishermen lack a financial incentive to leave fish in the water for the future (NRC 1999). Steps that would alter this economic distortion include the removal of fishing subsidies (Milazzo 1998), the use of tools such as individual fishing quotas that create long-term fishing rights and incentives for fisheries conservation (Fujita *et al.* 1996), and the establishment of consumer and corporate purchase preferences for more sustainably produced seafood (Duchene 2004). Although economic, policy, and business research on these and related subjects is largely outside this paper’s ecological focus, the success of new approaches will need to be validated by biologists as well as other experts.

Policy measures will also play a major role in marine aquaculture development. The Pew Oceans Commission (2003) called for a halt to the expansion of marine finfish farms until national standards and a comprehensive permitting authority are established for the siting, design, and operation of ecologically sustainable marine aquacul-

ture facilities. Standards for environmentally sound marine finfish farming need to be defined, especially to implement NOAA’s policies concerning offshore aquaculture development. Further research on the population genetics of marine fish species, related to the potential impacts of farmed fish escapes, is particularly important for setting standards. Innovative approaches to fish farming, as well as a better understanding of the potential cumulative impacts of large-scale ocean farming, could help marine aquaculture to become more environmentally sustainable.

The industry is already addressing some important issues, driven at least partly by financial considera-

tions. Feed is a major cost, and potential future increases in the price of fishmeal and fish oil could make it a larger one. There has already been a substantial reduction in the fishmeal and oil content of aquaculture feeds, and increased efficiency of feed use, particularly for salmonids (AGJ Tacon per comm).

Identifying lower trophic level marine finfish suitable for farming may be another step towards more sustainable aquaculture. Integrated systems, in which mussels, seaweeds, and other species are grown in close proximity with finfish to recycle wastes, shows great promise (Neori *et al.* 2004), but a greater understanding of the interactions and processes that take place among jointly cultured species, as well as larger scale experimentation, are necessary to help make integrated marine aquaculture commercially viable (Troell *et al.* 2003). Market research on products from integrated systems is also needed, particularly if chemicals or pharmaceuticals are used in the finfish netpens.

One recent, comprehensive analysis (Delgado *et al.* 2003) identifies fish, fishmeal, and fish oil as commodities almost certain to increase in price by the year 2020, while prices for commodities such as beef, eggs, and vegetable meals are likely to come down. Rising prices for fish will probably cause further exploitation of the oceans for fishing and aquaculture, and make competition for marine resources more intense. Protecting ocean resources may require deliberative processes to partition them – for example, designating certain areas of the ocean for certain uses or for non-use. The development of marine protected areas where fishing and other activities are not permitted is under active testing as a tool for both conservation and fisheries management (Lubchenco *et al.* 2003), but there has been little systematic investigation of possibilities for demarcating the ocean in other ways (eg temporally) or for other purposes (eg aquaculture).

The future prospects for ocean fisheries appear grim,

given current trends in fish production. Many capture fisheries are declining, and marine aquaculture – the alleged escape valve for fisheries – offers its own challenges, including a heavy dependence on robust fisheries resources. Establishing viable, long-term solutions to problems in fisheries and marine aquaculture will require the incorporation of ecological perspectives into the policies governing fisheries management, aquaculture systems, and the rationalization of ocean resources.

### ■ Acknowledgements

We thank M Burke, S Lamster, L Jantzen, and B Goodman for comments and assistance, and the David and Lucile Packard Foundation for funding.

### ■ References

- ADFG (Alaska Department of Fish and Game). 2004. Alaska Salmon Enhancement Program – 2003 Annual Report. Juneau: Alaska Department of Fish and Game.
- Aldhous P. 2004. Fish farms still ravage the sea: sustainable aquaculture takes one step forward, two steps back. [www.nature.com/nsu/040216/040216-10.html](http://www.nature.com/nsu/040216/040216-10.html). Viewed 25 June 2004.
- Aneja VP, Roelle PA, Murray GC, *et al.* 2001. Atmospheric nitrogen compounds II: emissions, transport, transformation, deposition and assessment. *Atmos Environ* 35: 1903–11.
- Avery D. 1996. Farming: a fish story. *Journal of Commerce* September 27, 1996.
- Bekkevold D, Hansen MM, and Loeschcke V. 2002. Male reproductive competition in spawning aggregations of cod (*Gadus morhua* L). *Mol Ecol* 11: 91–102.
- Brooks KM and Mahnken CVW. 2003. Interactions of Atlantic salmon in the Pacific Northwest environment II: organic wastes. *Fish Res* 62: 255–93.
- CRB (Knight-Ridder Commodity Financial Research Bureau). 1998. Commodity Yearbook. New York: John Wiley & Sons.
- Dayton PK, Thrush R, and Coleman FC. 2002. Ecological effects of fishing in marine ecosystems in the United States. Arlington, VA: Pew Oceans Commission.
- Delgado CL, Wada N, Rosegrant MW, *et al.* 2003. Fish to 2020: supply and demand in changing global markets. Washington, DC: International Food Policy Research Institute and Penang, Malaysia: WorldFish Center.
- DOC (Department of Commerce). 2004. US Department of Commerce Aquaculture Policy. [www.lib.noaa.gov/docaquac/docaquapolicy.htm](http://www.lib.noaa.gov/docaquac/docaquapolicy.htm). Viewed 25 June 2004.
- Duchene, L. 2004. Eco-buying ups the ante. *Seafood Business* 20: 1, 22–40.
- Eagle J, Naylor R, Smith WL, *et al.* 2004. Why farm salmon out-compete fishery salmon. *Mar Policy* 28: 259–70.
- FAO (Food and Agriculture Organization of the United Nations). 2002. The state of world fisheries and aquaculture 2002. Rome, Italy.
- FAO (Food and Agriculture Organization of the United Nations). 2003. FishStat – Fishery Information, Data and Statistics Unit, Rome, Italy.
- FAO (Food and Agriculture Organization of the United Nations). 2004. International Commodity Prices website. [www.fao.org/es/esc/prices/PricesServlet.jsp?lang=en&ccode](http://www.fao.org/es/esc/prices/PricesServlet.jsp?lang=en&ccode). Viewed 25 June 2004.
- Fujita R, Hopkins DD, and Willey WR. 1996. Creating incentives to curb overfishing. *Forum for Applied Research and Public Policy* 11: 29–34.
- Galloway JN, Dentener FJ, Capone DG, *et al.* 2004. Nitrogen cycles: past, present, and future. *Biogeochemistry* 70: 153–226.
- Goldberg RJ, Elliott MS, and Naylor RL. 2001. Marine aquaculture in the United States. Arlington, VA: Pew Oceans Commission.
- Gollehon N, Caswell M, Ribaldo M, *et al.* 2001. Confined animal production and manure nutrients. USDA ERS Agriculture Information Bulletin No. 771. 40 pp, June 2001
- Hardy RW. 2001. Urban legends and fish nutrition, part 2. *Aquaculture* 27: 57–60.
- Hedlund S. 2004. Antidumping cases cloud shrimp market. *Seafood Business* 23: 1, 12.
- Hilborn R, Branch TA, Ernst B, *et al.* 2003. State of the world's fisheries. *Ann Rev Env Resour* 28: 359–99.
- Kolmes SA. 2004. Salmon farms and hatcheries. *Environment* 46: 40–43.
- Kurlansky M. 1997. Cod: biography of the fish that changed the world. New York: Penguin Books.
- Levin PS, Zabel RW, Williams JG, *et al.* 2001. The road to extinction is paved with good intentions: negative association of fish hatcheries with threatened salmon. *P Roy Soc Lond B* 268: 1153–58.
- Lubchenco J, Palumbi SR, Gaines SD, *et al.* 2003. Plugging a hole in the ocean: The emerging science of marine reserves. *Ecol Appl* 13 Supplement 2003, S3–S7.
- Mallin MA and Cahoon LB. 2003. Industrialized animal production – a major source of nutrient and microbial pollution to aquatic ecosystems. *Popul Environ* 24: 369–85.
- Marine Research Specialists. 2003. Hubbs–Sea World Research Institute Platform Grace Mariculture Project final report.
- Marshall D. 2003. Fishy business – the economics of salmon farming in BC. British Columbia, Canada: Canadian Center for Policy Alternatives.
- McGinnity P, Prodohl P, Ferguson A, *et al.* 2003. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salmo salar*, as a result of interactions with escaped farm salmon. *P Roy Soc Lond B* 270: 2443–50.
- Milazzo M. 1998. Subsidies in world fisheries: a re-examination. World Bank Technical Paper No. 406.
- Myers RA and Worm B. 2003. Rapid worldwide depletion of predatory fish communities. *Nature* 423: 280–83.
- Naylor RL, Goldberg RJ, Primavera JH, *et al.* 2000. Effect of aquaculture on world fish supplies. *Nature* 405: 1017–29.
- Naylor R, Eagle J, and Smith W. 2003. Salmon aquaculture in the Pacific Northwest: a global industry with local impacts. *Environment* 45: 18–39.
- Naylor R, Hindar K, Fleming I, *et al.* Fugitive salmon: assessing risks of escaped fish from aquaculture. In review.
- Naylor R, Eagle J, and Smith W. Response of Alaska fishermen to aquaculture and the salmon crisis. *Proceedings of the American Fisheries Society*. In press.
- Neori A, Chopin T, Troell M, *et al.* 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture* 231: 361–91.
- NPAFC (North Pacific Anadromous Fish Commission). 2004. 2001 Statistics Tables. [www.npafc.org](http://www.npafc.org). Viewed 25 June 2004.
- NRC (National Research Council). 1996. Upstream: salmon and society in the Pacific Northwest. Washington, DC: National Academy Press.
- NRC (National Research Council). 1999. Sustaining marine fisheries. Washington, DC: National Academy Press.
- Pauly D, Christensen V, Guenette S, *et al.* 2002. Towards sustainability in world fisheries. *Nature* 418: 689–95.
- Pew Oceans Commission. 2003. America's living oceans: charting a course for sea change. Arlington, VA: Pew Oceans Commission.
- Pikitch EK, Santora C, Babcock EA, *et al.* 2004. Ecosystem-based fishery management. *Science* 305: 346–47.
- Powell K. 2003. Fish farming: eat your veg. *Nature* 426: 378–79.
- Ruzzante DE, Taggart CT, Doyle RW, *et al.* 2001. Stability in the



- historical pattern of genetic structure of Newfoundland cod (*Gadus morhua*) despite the catastrophic decline in population size from 1964 to 1994. *Conserv Genet* 2: 257–69.
- Shaffer KA. 2004. Livestock manure production rates and nutrient content. North Carolina Agricultural Chemicals Manual. College of Agriculture and Life Sciences, North Carolina State University.
- Stipanuk, MH. 2000. Biochemical and physiological aspects of human nutrition. Philadelphia, PA: WB Saunders.
- Tacon AGJ. 2003. Sustainable aquaculture feeds: an overview and global perspective. Abstract, SEAfeeds Workshop, April 2003, Stirling, Scotland, UK.
- Troell M, Hallig C, Neori A, *et al.* 2003. Integrated mariculture: asking the right questions. *Aquaculture* 226: 69–90.
- USDA (United State Department of Agriculture). 2004. National Agricultural Statistics Service. 2002 Census of Agriculture – State Data, Table 12. [www.nass.usda.gov/census/census02/volume1/us/index1.htm](http://www.nass.usda.gov/census/census02/volume1/us/index1.htm). Viewed 23 June 2004.
- Waknitz FW, Iwamoto RN, Strom MS. 2003. Interactions of Atlantic salmon in the Pacific Northwest IV. Impacts on the local ecosystems. *Fish Res* 62: 307–28.
- Watson R and Pauly D. 2001. Systematic distortions in world fisheries catch trends. *Nature* 414: 534–36.
- Weber ML. 2003. What price farmed fish: a review of the environmental and social costs of farming carnivorous fish. Providence, RI: SeaWeb Aquaculture Clearinghouse.