COURSE 4

Increase Fish Supply

The global wild fish catch reached a peak in the mid-1990s but it has since stagnated and may even have declined. Roughly one-third of marine fish stocks are now overfished, with another 60 percent fished at maximum sustainable levels. This course explores ways to improve wild fisheries management and raise the productivity and environmental performance of aquaculture to meet rising demand for fish.

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CHAPTER 22

MENU ITEM: IMPROVE WILD FISHERIES MANAGEMENT

Fish are an important source of protein, especially for people in developing countries. Yet the annual amount of fish caught in the wild—particularly from the oceans—has stagnated and may have significantly declined since the 1990s. Continued overfishing threatens future catch levels and improved management will be essential to allow fish stocks to rebound.

The Challenge

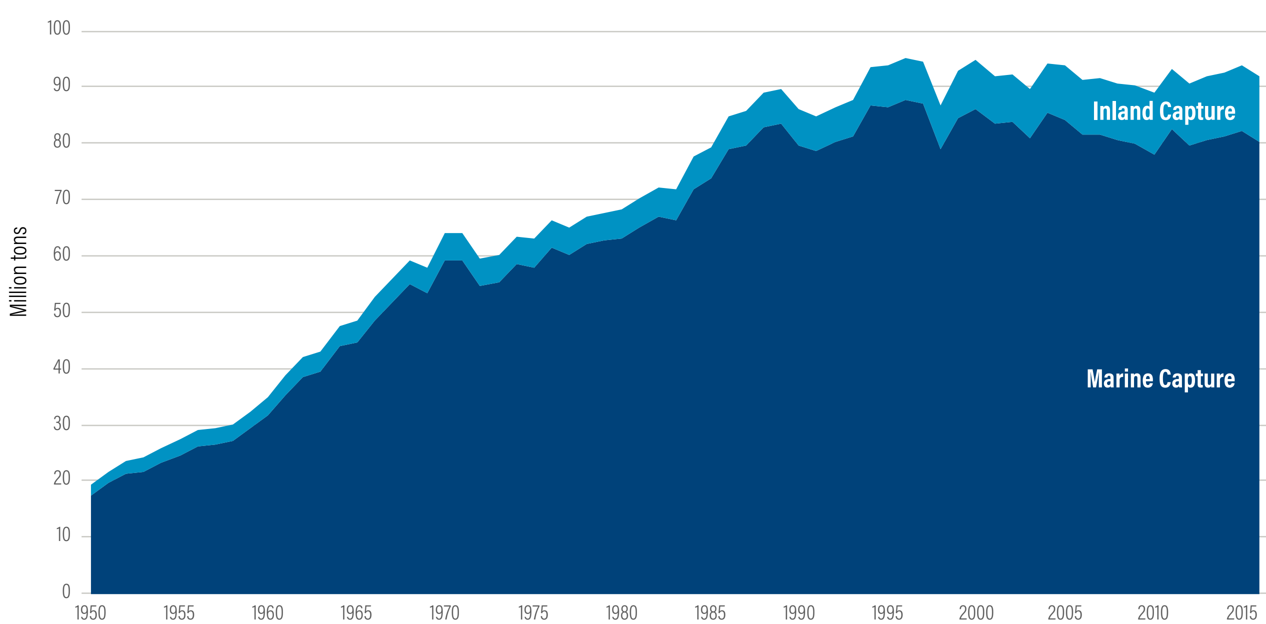
Fish, including finfish and shellfish,[1] are a minor source of the global calorie supply, but they contributed 17 percent of global animal-based protein for human consumption in 2010 (Figure 6-4).[2] Fish are particularly important in developing countries, which consume more than 75 percent, and produce more than 80 percent, of global fish supply.[3] Fish also contain important micronutrients—such as vitamin A, iron, and zinc—and long-chain omega-3 fatty acids that are essential for maternal health and early childhood development but are often deficient in the diets of the poor.[4]

According to the Food and Agriculture Organization of the United Nations (FAO),[5] the world produced 171 million tons (Mt) of fish in 2016. Wild fisheries produced 91 Mt, which provided 71 Mt of fish for people and 20 Mt for animal feed and other nonfood uses.[6] The global fisheries catch has grown almost fivefold since 1950. Yet since the 1990s, the catch has at best stagnated. FAO data show such a stagnation with a slight increasing trend in inland fish landings offsetting a slight decline in marine fish landings (Figure 22-1).[7] Research by Pauly and Zeller (2016) is even more pessimistic, concluding that FAO's numbers underestimate both total marine fish catches and the rate of decline since the 1990s. Using an approach called "catch reconstruction," Pauly and Zeller estimate that the global marine fish catch peaked at 130 Mt in 1996 (nearly 50 percent higher than FAO's estimate for that year) and since then has declined at an average rate of 1.2 Mt per year, with serious implications for the future marine catch.[8]

The percentage of marine fish stocks that are overfished is also near an all-time high. By 2015, 33 percent of marine fish stocks were overfished, with another 60 percent fished at maximum sustainable levels, and only 7 percent fished at less than their full potential (Figure 22-2).[9]

The tropics present particular challenges. Fish catches are greatest in the tropics—particularly in Southeast Asia.[10] Climate change is also likely to have substantial future effects by reducing productivity and fish size, disturbing fish habitats, and changing species composition as fish move toward cooler waters.[11]

Figure 22-1 | The wild fish catch has stagnated (or possibly declined) since the 1990s



Note: "Wild catch" includes finfish, mollusks, crustaceans, and other aquatic animals from marine and freshwater ecosystems. It excludes all aquaculture. It does not include catch reconstruction as in Pauly and Zeller (2016).

Source: FAO (2019b).

The Opportunity

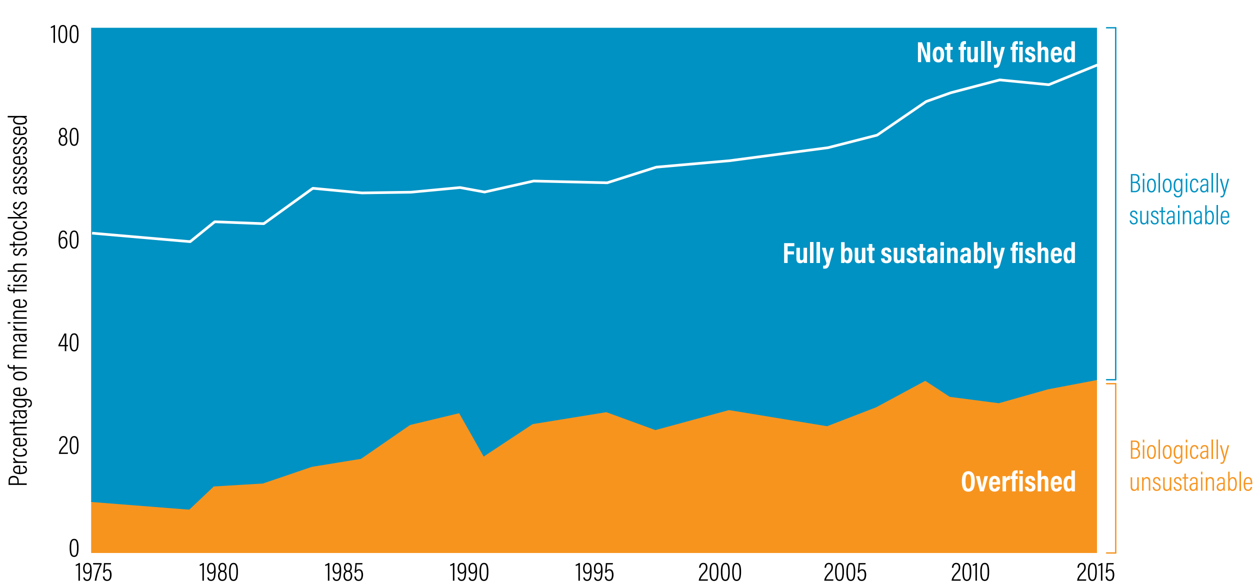
Reducing overfishing, which would prevent future declines and allow depleted stocks to recover, is the first important step toward a sustainable fish supply. The World Bank suggests that world fishing effort[12] needs to decline by 5 percent per year over a 10-year period, which would allow fisheries to rebuild to an ideal level over three decades.[13] Although this approach would likely reduce catches in the short term, it should lead to productive and sustainable wild fish catches over the long term—possibly 10 Mt above 2012 levels.[14] Another study has estimated that economically optimal global fisheries management could even lead to a sustainable annual fish catch 18 Mt above 2012 levels by 2050.[15]

Some recent experience supports this claim. Although fisheries in developed countries have also been overfished, fish stocks appear to be rebounding along the coasts of a few developed countries such as Australia, New Zealand, Norway, and the United States.[16]

The United States has made significant progress in reducing overfishing in recent decades. The Magnuson-Stevens Fishery Conservation and Management Act, signed in 1976 and strengthened through subsequent amendments, created a mandate to rebuild overfished stocks. Since 2000, 44 fish stocks have been rebuilt and, as of 2017, just 15 percent of U.S. stocks were overfished—the lowest percentage since assessments began.[17] Overall U.S. fish catch, which peaked around 6 Mt in the late 1980s and dropped to just over 4 Mt in 2009, seems to be stabilizing around 5 Mt.[18] Success has come about through a variety of measures, notably through strict enforcement of annual catch limits—including use of catch share programs—and monitoring of fish stock health.

In Kenya, a comanagement program between the Fisheries Department and traditional fisheries leaders led to a rebound of coastal coral reef fish populations and increased the profitability of fishing. Two management strategies—gear restriction (a ban on small-meshed beach seine nets, implemented between 2001 and 2004), and closing off areas of the sea from fishing (implemented between 2005 and 2009)—were responsible for these results. In areas where these management strategies were in place, catches per fisher per day rose by approximately 50 percent between 2000 and 2012, and fisher incomes

Figure 22-2 | The percentage of overfished stocks has risen over the past 40 years



Source: FAO (2018).

doubled during this period, all while maintaining overall catch levels. At landing sites near the Mombasa Marine National Park, a no-fishing area, the sizes of fish caught were higher (fetching higher prices). Catches also contained species of higher market value relative to the catches in areas farther from no-fishing areas.[19] These positive changes occurred even in the wake of the 1997–98 El Niño event that caused widespread loss of coral cover in the fishing grounds, suggesting that (at least during the study period) the improved fisheries management practices were able to counter the effects of disturbances from climate change.[20]

We project fish consumption to rise 58 percent between 2010 and 2050,[21] but the wild fish catch peaked at 94 Mt in the mid-1990s and has since stagnated or perhaps declined. For our 2050 baseline scenario, we assume a 10 percent decrease in global wild fish catch between 2010 and 2050 (an annual catch in 2050 that is 9 Mt below 2010 levels). This baseline assumes a continuation of business as usual, with some stocks rebuilding and others continuing to decline due to overfishing.[22] We also use GlobAgri-WRR to model an improvement scenario where wild fish catch—instead of declining between 2010 and 2050—stays constant at 2010 levels, a scenario where many, but not all, stocks have measures in place to stop overfishing and rebuild. The effect in GlobAgri-WRR of being able to harvest an additional 9 Mt of wild fish (relative to 2050 baseline) is to avoid the need for an additional 9 Mt of farmed fish, which reduces aquaculture's total land demand in 2050 by 5 million hectares (Mha), and closes the emissions gap by 0.6 percent (Table 22-1).[23]

Recommended Strategies

Strategies to curb overfishing and maintain harvests at sustainable levels are well documented in other studies.[24] They focus on several key principles:

- Limiting fish catch (including bycatch) to a level that allows the population to reproduce
- Limiting the number of fishers to an economically sustainable level
- Protecting habitat
- Avoiding harvest during important breeding times or in important breeding areas[25]

Tools to implement these strategies include establishing total allowable catches based on optimum sustainable yield, gear restrictions, seasonal limits, regulation or direct government management of key habitats, and closure of breeding areas.

Widespread implementation of these strategies is difficult for various reasons—listed below—most of which are political and socioeconomic and based on the fact that wild fish are a public resource that individual fishers have incentives to exploit before others can do so:[26]

Table 22-1 | Global effects of 2050 fisheries improvement scenario on the food gap, land use, and the GHG mitigation gap

SCENARIO	FOOD GAP, 2010–50 (%)	GHG MITIGATION GAP (GT CO_2E)	AQUACULTURE LAND USE (MILLION HA)		
			Ponds	Cropland for feed	Total
2010	N/A	N/A	19	27	46
2050 BASELINE	**56.5**	**11.1**	**40**	**52**	**92**
Stable wild fish catches between 2010 and 2050 *(Coordinated Effort, Highly Ambitious, Breakthrough Technologies)*	56.3	11.0	38	49	87

Source: GlobAgri-WRR model.

- Rebuilding a fishery or halting overfishing typically involves a decline in fishing activity and landings for some period of time. Consequently, fishers and others in the value chain can experience financial losses over the near to medium term. There is no compelling short-term economic reward for acting sustainably.

- There are economic winners and losers in efforts to rebuild stocks, and the potential losers often wield enough power to thwart reform and fishery restoration efforts.

- Many countries subsidize fishing in a variety of ways that lead to overfishing.[27] Recent studies estimate global annual fisheries subsidies at $35 billion—equivalent to one-third of the value of global fisheries production.[28] In total, the World Bank estimated that annual lost revenues from mismanagement of global fisheries was $83 billion in 2012.[29]

- Because of global power imbalances, foreign fleets from richer countries often are able to obtain "fishery access agreements" to fish in the waters of poorer countries with weaker laws and enforcement capacity.[30]

- Illegal, unregulated, and unreported fishing is a widespread problem, particularly in developing countries. Worldwide, losses from illegal fishing and unreported fishing have been estimated at $10 billion and $23.5 billion per year, respectively, representing an additional catch of between 11 Mt and 26 Mt that goes unmanaged.[31]

- Lack of data and lack of infrastructure and resources for monitoring and enforcement can be a barrier to active management.

- Fishing is often a livelihood of last resort in many poor coastal communities, and small-scale fishing continues to grow across the developing world. In addition, fishing has played an important cultural role in coastal areas for centuries. In the absence of alternative livelihoods, governments can be hesitant to curtail local fishing operations out of social concerns, even in depleted coastal waters.

In recent years, some developed countries have been able to overcome these challenges by limiting the number of fishers and using "catch shares." These systems establish shares of fish that may be taken and allocate them among individual fishers. These fishers therefore acquire a long-term stake in the health of the fishery, and can often trade their shares.

In the United States, progress in rebuilding fisheries has resulted in part from shifting to systems of "catch shares" that reduce the "race to fish."[32] Based on evidence from 39 commercial fisheries, researchers have credited these programs with making catch levels more predictable and stable, reducing the number of fishing boats, improving fishing crew safety, reducing bycatch, and promoting other favorable environmental and economic outcomes.[33] However, because catch share programs can facilitate industry consolidation and the marginalization of small-scale fishers,[34] governments will need to address the social consequences of this consolidation.

In developing countries where oversight, rule of law, and monitoring arrangements are weaker, additional approaches are needed. In these governance environments—as the Kenya example illustrates—community-based comanagement systems may prove more effective. Such systems combine territorial fishing rights and no-take reserves designed and supported by coastal fishing communities.[35]

All told, overcoming the barriers listed above requires a set of complementary strategies, adapted to suit specific circumstances.[36] For example, establishing resource rights and removing perverse subsidies can control access to fish resources at economically and biologically feasible levels. Adoption of sustainable procurement practices and certification systems by actors in fish supply chains could help create demand for sustainably sourced fish. Both these rights and markets strategies, in turn, could build support for governance reforms regarding fishing practices and marine spatial management. However, for these strategies to succeed, enabling conditions such as sound data and science, supply chain transparency, and law enforcement need to be in place.[37] Advocacy, public pressure, technical and financial support, and outreach to major players in fish supply chains can all help put these enabling conditions in place and advance these strategies.

CHAPTER 23

MENU ITEM: IMPROVE PRODUCTIVITY AND ENVIRONMENTAL PERFORMANCE OF AQUACULTURE

Despite stagnating or declining wild fish catches, world fish consumption has continued to increase as aquaculture has grown to meet global demand. This menu item involves increasing production of farmed fish relative to the amount of land, freshwater, feed, and energy used—while minimizing water pollution, fish diseases, and escapes.

The Challenge

The aquaculture (fish farming)[38] sector is diverse. Fish farming produces more than 300 species and occurs in nearly every country in the world.[39] Aquaculture is practiced in three different environments: In 2016, 63 percent of production was in freshwater (mostly in ponds on land), 28 percent in marine waters, and 9 percent in brackish water (coastal ponds).[40]

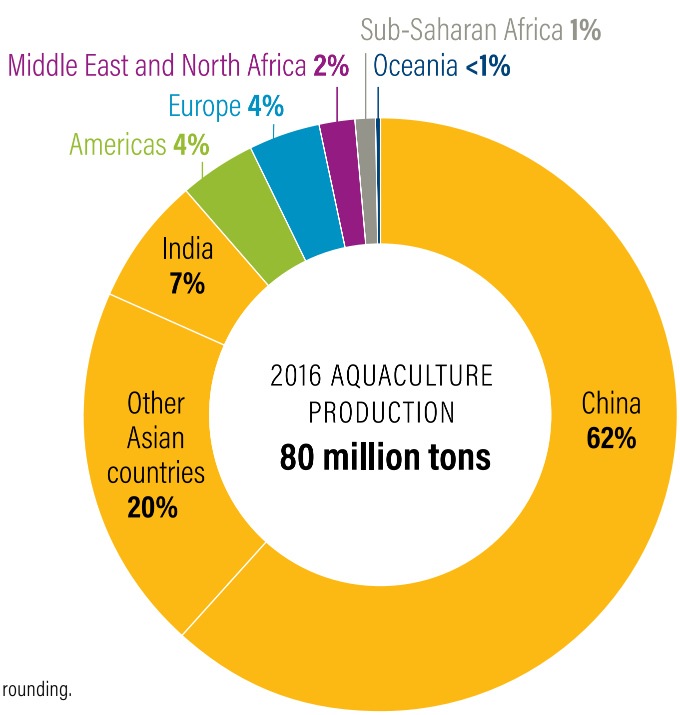
Between 2011 and 2016, aquaculture production rose in every world region.[41] In 2016, aquaculture provided more than half of all fish people consumed—80 Mt—making it one of the world's fastest-growing animal food-producing sectors.[42] Asia accounted for nearly 90 percent of global aquaculture production in 2016, and China alone accounted for more than 60 percent (Figure 23-1). In terms of percentage increase, sub-Saharan Africa had the fastest rate of growth—increasing production by nearly 50 percent between 2011 and 2016—but because its baseline was low, the region contributed less than 1 percent of global aquaculture production in 2016.

Because the wild fisheries catch peaked years ago, virtually all of the future increase in world fish consumption will need to come from aquaculture. If global per capita fish availability is to meet projected demand under our 2050 baseline scenario, where wild fish supply declines by 10 percent, we estimate that aquaculture production would need to more than double between 2010 and 2050, rising from 60 Mt in 2010 to roughly 140 Mt in 2050 (Figure 23-2). Meeting this demand presents environmental, production, and social challenges.[43]

Land-use change

In 2010, global aquaculture occupied an estimated 19 Mha of land—an area the size of Syria—including 13 Mha of inland (freshwater) areas and 6 Mha of coastal (brackish water) ponds. Aquaculture also indirectly used an additional 27 Mha that year—an area larger than the United Kingdom—to grow plant-based feeds.[44] In total, aquaculture occupied about 1 percent of global agricultural land,[45] and conversion of agricultural lands or natural ecosystems to aquaculture contributes to the overall competition for land.

Figure 23-1 | Nearly 90 percent of aquaculture production is in Asia



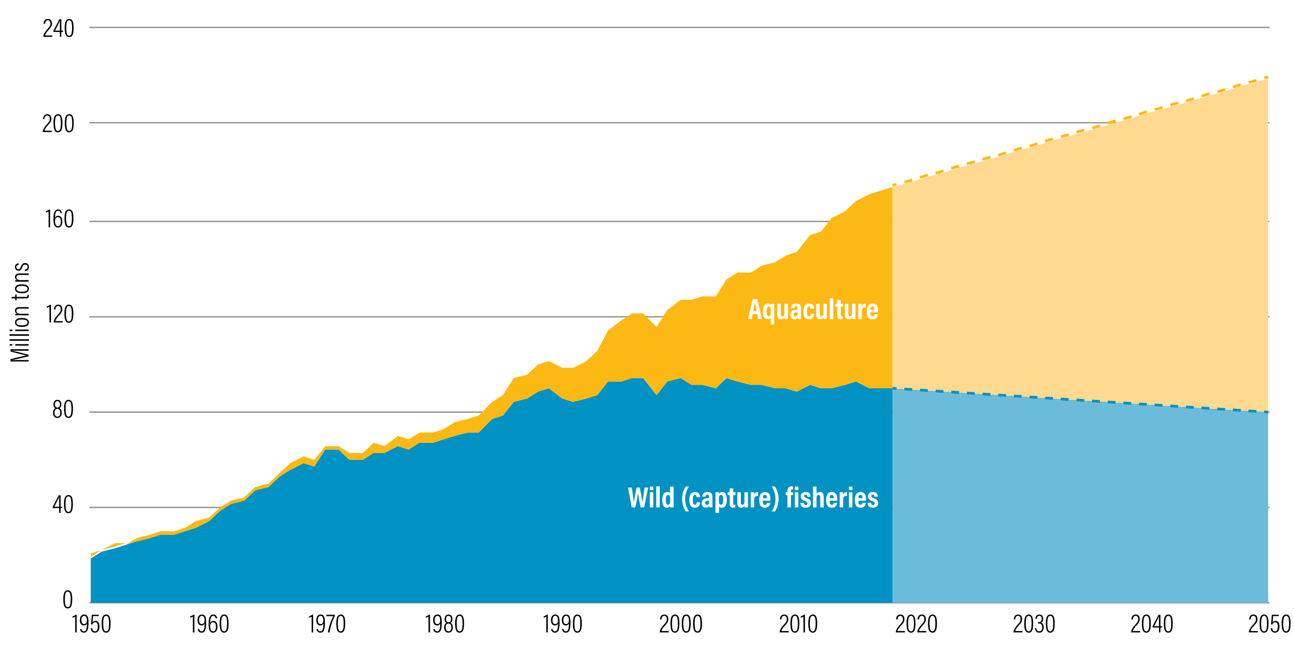
Note: Data may not sum to 100% due to rounding.
Source: FAO (2019b).

Aquaculture's impact on mangroves raises particular concerns. Mangroves are among the most productive ecosystems in the world, serving as nursery grounds for many fish and protecting coastlines. In the 1980s and 1990s, a largely unregulated boom in shrimp aquaculture led to clearing of significant areas of mangroves for aquaculture ponds.[46] Conversion of mangroves to aquaculture has slowed since 2000, thanks to improvements in shrimp-farming practices and mangrove protection policies.[47] Between 2000 and 2012, however, the world lost 192,000 hectares of mangroves, about 1 percent of total global mangrove cover,[48] with more than 100,000 hectares being lost in Southeast Asia alone. Richards and Freiss (2016) estimate that 30 percent of the mangrove losses in Southeast Asia in this period were due to aquaculture expansion (followed by clearing for rice [22 percent] and oil palm [16 percent]). Indonesia, in particular, witnessed major aquaculture expansion: of 60,000 hectares of mangroves lost, half were cleared for aquaculture.[49] It remains an ongoing challenge in some areas to reconcile plans for increasing aquaculture production with mangrove protection.[50]

Greenhouse gas emissions

In 2010, we estimate that aquaculture production was responsible for greenhouse gas (GHG) emissions of 332 million tons of carbon dioxide equivalent (Mt CO_2e)—less than 1 percent of total human emissions but 5 percent of emissions from agricultural production.[51] Aquaculture's emissions arise from on-farm energy use; feed production; transportation, processing, and packaging of produce; and disposal of wastes. Aquaculture's largest energy demands tend to occur during production of fish and feeds.[52] Untreated pond sediments can lead to methane emissions.[53] A further source of emissions is the conversion of land and coastal habitats for aquaculture development, both directly through conversion of carbon-rich ecosystems (such as mangroves, seagrass beds, and wetlands) and indirectly by displacing croplands.

Figure 23-2 | Aquaculture production must continue to grow to meet world fish demand



Source: Historical data 1950–2016: FAO (2019b) and FAO (2018). Projections to 2050: calculated at WRI; assume 10% reduction in wild fish catch from 2010 levels by 2050, linear growth of aquaculture production of 2 Mt per year between 2010 and 2050.

Additional environmental challenges

Aquaculture can trigger other environmental challenges, as well. First, the use of wild fish as feed ingredients can exacerbate pressure on marine ecosystems. The small, oily fish commonly harvested for aquaculture feed—such as anchovy—are near the bottom of the marine food chain. In 2016, 15 Mt of wild fish (or nearly one-fifth of the marine catch) was converted to fishmeal and fish oil, most of which was consumed by aquaculture.[54]

Another challenge is water pollution. Discharges can contain excess nutrients from fish feed and waste, antibiotic drugs, other chemicals (e.g., pesticides, hormones, antifoulants), and inorganic fertilizers. In comparison to terrestrial livestock production, it is difficult to collect wastes from aquaculture production because they are rapidly dispersed into the surrounding water.[55] Pollution associated with aquaculture can cause degradation of aquatic habitats and eutrophication of lakes or coastal zones, and can even directly threaten the aquaculture operation itself.[56]

A third challenge is infectious disease, which has devastated shrimp production in parts of Asia. Early Mortality Syndrome (first noted in 2009) presents ongoing threats to the shrimp sector. Parasites, such as sea lice, have caused problems for salmon production, for example in Chile and Norway.[57] Diseases and parasites can also be transferred from farmed to wild fish (and vice versa) in open production systems.[58]

Another concern is that farm-raised fish can escape, or be intentionally released, from aquaculture facilities and cause genetic contamination. Escaped fish can breed with, outcompete, or prey on native fish, altering ecosystem structure and composition.[59]

Finally, food safety worries exist, too. These include the excessive use of antimicrobial products at fish farms, which can spread antimicrobial resistance in human pathogens (e.g., *Salmonella*). Another is the potential for farmed fish to contain high levels of chemical contaminants, such as persistent organic pollutants, pesticides, and heavy metals, which could be harmful to consumers.[60]

Social concerns associated with aquaculture

Human nutrition. Farmed fish are generally as lean and protein-rich as chicken,[61] but one concern of aquaculture is that farmed fish as a whole tend to have lower levels of long-chain omega-3 fatty acids than wild fish.[62] Nutrient composition of fish depends on a number of factors including the species, whether the fish is wild or farmed, and the feeding methods.[63] If fish are to continue to meet this valuable nutritional need, they will require an enhanced, alternative supply of complex oils.

Availability and affordability of fish for human consumption. The use of wild fish for aquaculture feed is a complicated issue. On the one hand, it may reduce the amount of wild fish available for direct human consumption while it produces relatively large fish targeted at middle-class markets.[64] As the vast majority of the small fish harvested for feed is of food-grade quality, aquaculture could reduce fish access for the poor. On the other hand, there is limited market demand for direct consumption of these small fish.[65] Aquaculture can also benefit the poor if its output becomes cheap enough. For example, in Egypt and Bangladesh, strong recent growth of aquaculture production has pushed the prices of farmed fish below those of wild fish, making fish more broadly accessible to the poor.[66]

Input constraints and climate change

Land-use limitations are a key constraint on aquaculture growth. In Asia, for instance, little land is available for aquaculture (or any agricultural) expansion.[67] An important challenge will be for aquaculture to more than double production between 2010 and 2050 while minimizing land expansion.[68]

In 2010, aquaculture consumed an estimated 201 cubic kilometers (km^3) of freshwater, accounting for approximately 2 percent of global agricultural water consumption.[69] Freshwater inland aquaculture uses water to maintain pond levels, compensating for water lost through seepage, evaporation, and intentional discharge. More intensive systems use frequent water exchanges to aerate and filter ponds.

Production of plant-based fish feeds also consumes water.[70] However, freshwater is becoming increasingly scarce in many aquaculture-producing areas because of upstream dams and diversion of water for agriculture and urban uses.[71]

Feed could be another constraint. In 2016, at least 70 percent of aquaculture production used some form of feed, whether fresh feeds (e.g., crop wastes), feed mixed and processed on the farm, or commercially manufactured feed.[72] Carnivorous species[73]—such as salmon, shrimp, and many other marine finfish—tend to rely on wild-caught fish (in the form of fish meal and fish oil in commercially manufactured feeds) to receive adequate protein and lipids in their diets.[74] Conversely, roughly 80 percent of aquaculture production in 2014 consisted of omnivores, herbivores, and filter feeders that consume little to no fish-based ingredients.[75] Commercial feeds for omnivores and herbivores tend to contain cereals, oilseeds, and pulses, often in the form of meals and oils.[76] The fact that the supply of fish meal and fish oil from wild sources is already near its historical highs and ecological limits represents a clear constraint on aquaculture production growth, particularly of farmed carnivorous fish.[77] However, it will also be a challenge to ensure an adequate supply of plant-based proteins, oils, and carbohydrates for aquaculture feed as the sector grows, while minimizing the associated land and water-use impacts.[78]

Land, water, and feed are all likely to be adversely affected by climate change.[79] Farms in deltas and coastal and marine areas are most immediately exposed to flooding, sea level rise, and extreme weather events. Increases in water temperature will likely increase the occurrence of harmful algal blooms, which reduce water quality and can render farmed fish unfit for human consumption.[80] Ocean acidification also threatens the long-term viability of shellfish aquaculture.[81] At the same time, climate change may also open up new production opportunities in certain areas and make aquaculture an adaptation strategy. In colder regions, warmer temperatures may enable aquaculture, and in coastal land areas that become too saline for agriculture, aquaculture could become an important adaptation strategy (Chapter 15).[82]

The Opportunity

If annual aquaculture production were to increase from 60 Mt in 2010 to 140 Mt by 2050, as projected in our baseline food demand scenario, significant food security and development benefits could result. For example, this level of growth would boost annual fish protein supply to 19 Mt, or 6 Mt above 2010 levels.[83] Such an increase would meet 13 percent of the increase in global animal protein supply between 2010 and 2050 under our baseline scenario.[84] It would boost income and employment, particularly in developing countries, where most aquaculture growth will occur.[85] And the global value of farmed fish could increase from $120 billion in 2010 to $308 billion in 2050, with the number of people engaged in aquaculture for a living increasing from 100 million in 2010 to 176 million by midcentury.[86]

Even though aquaculture poses environmental challenges, it has potential advantages relative to most other animal-based foods. Because finfish live in an environment that supports their body weight, are cold-blooded, and excrete waste nitrogen directly as ammonia, they devote less energy to metabolism and bone structure than terrestrial animals.[87] As a result, most farmed species convert feed into edible meat quite efficiently. As discussed in Chapter 6 on shifting diets, farmed finfish are similar in feed conversion efficiency to poultry, and much more efficient than beef and sheep (Figure 6-5).[88] Filter-feeding carp and mollusks are even more efficient producers of animal protein, as they require no human-managed feeds and can improve water quality by removing excess microalgae and nutrient pollution from lakes and coastal waters.[89] Furthermore, expansion of marine aquaculture could help alleviate the land constraint relative to other animal-based foods and their associated emissions from land-use change.

Per ton of edible protein, aquaculture species require between 0 ha (mollusks) and 16 ha (shrimp) of land per year, which is less than pork and chicken (both around 20 ha per year) and far less than beef (140 ha per year) (Figure 6-6).[90] Aquaculture also produces lower GHG emissions than ruminant meats. Per ton of edible protein, farmed fish production emits around 30 tons of CO_2e per year, which is similar to emissions from pork and chicken production, and again far less than emissions from beef production (more than 200 tons of CO_2e per year). Another consideration is that, because the aquaculture sector is relatively young compared with terrestrial livestock sectors, there is great scope for technical innovation to further increase its resource efficiency.

Opportunities to sustainably intensify aquaculture production (Box 23-1), to reduce its environmental impacts, and to overcome basic production constraints exist in at least five interrelated areas:[91]

BOX 23-1 | Classifying aquaculture production systems by intensity

The aquaculture literature commonly classifies production systems by their level of intensity. Intensity of production runs along a spectrum from *extensive* (less than 1 ton of fish per hectare per year [t/ha/yr]) through *semi-intensive* (2–20 t/ha/yr) and *intensive* (20–200 t/ha/yr) farms.[a] Yields from intensive cage, raceway, or recirculating systems can be higher still.[b] In general, according to Hall et al. (2007), levels of intensity can be summarized as follows:

- *Extensive* production requires a low level of control, relies on natural productivity and crop wastes as feed, and has relatively low operating costs.
- *Semi-intensive* production uses fertilizers and farm-made feed to boost fish yields, which requires a higher level of management control and involves higher operating costs.
- *Intensive* production requires the highest degree of management control, relies completely on off-farm inputs (e.g., high-quality feed, seed, and fertilizers), and uses more energy, leading to high operating costs.

Sources:
a. Bunting (2013).
b. Dugan et al. (2007).

Breeding and genetics

To overcome land-use constraints, aquaculture needs to improve growth rates and conversion efficiencies. Fish bred for faster growth rates[92] could lead to more efficient use of land and sea area, water, feed, and labor.[93] Fortunately, there are large opportunities to breed more efficient fish, as aquaculture lags far behind crop and livestock agriculture in the use of selective breeding; in 2010, less than 10 percent of world aquaculture production was based on genetically improved stocks.[94] Because feed often accounts for 50 percent or more of all production costs, these efficiencies should also improve the economics of production.[95]

Of the approximately 100 large-scale aquaculture breeding programs in the world in 2010, more than half were focused on just three species: Atlantic salmon, rainbow trout, and Nile tilapia. Less than 10 percent focused on carp, which is by far the most abundant aquaculture species group.[96] Selective breeding efforts could be expanded, aimed at countries and species with the highest levels of production (e.g., Chinese carps), and at areas of current low productivity yet high need for aquaculture growth (e.g., sub-Saharan Africa). Selective breeding also could reduce disease problems, enable increased use of plant-based ingredients in feed, and lead to the eventual development of truly domesticated fish that do not survive or breed in the wild, lessening problems of escapes.

Fish oil alternatives and other feed improvements

Aquaculture continues to rely heavily on wild fish-derived fish meal and fish oil. However, since both are finite resources, the aquaculture industry cannot continue this reliance as it continues rapid growth into the future. The supply of fish meal and fish oil from wild sources is already at historical highs and is near ecological limits, which represents a clear constraint to aquaculture growth.[97] To continue its growth, the aquaculture industry will therefore need an alternative source of the key nutrients found in fish oil—omega-3 eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) (Box 23-2). Both EPA and DHA omega-3 are required for optimal fish health and growth and are also important essential fatty acids for human nutrition.

Microalgae (the origin of omega-3 fatty acids in fish oil) can provide a viable substitute for wild fish-based ingredients and use much less land and water than is required for plant-based oil crops.[98] Another possible plant-based substitute for fish oil is genetically engineered yeasts or oilseed plants (e.g., rapeseed) that produce omega-3 fatty acids.[99] However, further investments in research and development will be necessary to bring costs of these replacement ingredients below fish oil prices. Continued research is also necessary to further improve understanding of optimal omega-3 fatty acid nutritional efficiency of all important aquaculture species, while also minimizing waste and production costs.

Disease control

Disease outbreaks continue to constrain aquaculture production, especially in more intensive systems. New technologies will be essential to lessen risks from disease and reduce the need for antibiotics.[100] Promising technologies include advanced diagnostics, vaccines, dietary supplements, and genetic improvements. Also helpful will be wider application of best management practices, such as reducing water exchange in ponds or tanks, reducing water seepage in ponds, improving feed and feeding practices, improving sanitation, and not stocking fish too densely in ponds or cages.

Water recirculation and other pollution control

Recirculating water used in aquaculture can save water and allow the producer greater control over water temperature, oxygen levels, and other aspects of water quality. As a result, conditions improve for the farmed fish, allowing for better growth, lower disease levels, more predictable harvests, and higher levels of intensity. However, recirculation also adds to operating costs and energy use (and production-related GHG emissions).[101] Water recirculation is not the only option for pollution control; other improved management practices, such as using settling ponds before releasing wastewater, can also reduce waste.

BOX 23-2 | Microalgae are a promising alternative to fish oil in aquaculture feeds

Fish and the fish-derived product, fish oil, currently represent the main dietary source of long-chain omega-3 fatty acids for human nutrition. Omega-3 fatty acids generally refer to three fats, namely alpha-linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA). Of these, EPA and DHA are the long-chain omega-3s, which are naturally present in fish, marine algae, krill, and human milk. They are associated with key human health benefits. Daily intake of at least 250 mg of EPA and DHA has been shown to benefit eye, brain, and heart health.[a] However, there are currently no large-scale alternatives to fish oil that are rich in both EPA and DHA omega-3 fatty acids, meaning that fully replacing fish oil in aquaculture feed with other animal or plant-based oils would reduce the level of EPA and DHA omega-3 and therefore the nutritional benefit of farmed fish to the consumer.[b]

The omega-3 fatty acids EPA and DHA are naturally produced by algae in the natural marine food chain and gradually accumulated in larger fish. These larger fish are harvested for fish oil production, and fish oil therefore contains EPA and DHA omega-3 fatty acids. Fish oil alternatives are essentially based on utilizing the ability of microalgae to produce omega-3 fatty acids, either by direct production of microalgae or by transferring their biochemical capability (e.g., genes) to other organisms such as yeast or oilseed plants through genetic engineering. Although it remains to be seen which technologies ultimately prove to be economically viable, and socially acceptable, at large scale, it appears that several fish oil alternatives will be available on the market within the next few years.

One example of a promising fish oil alternative is an algal strain of *Schizochytrium sp.* that naturally produces both EPA and DHA omega-3 through fermentation. Using sugar as an energy source, the algae cells grow, multiply, and convert sugar into the omega-3 fatty acids EPA and DHA. A refining process then produces an algal oil rich in both EPA and DHA that can substitute for fish oil—as well as a by-product that can be used for animal feed or bioenergy. Evonik and DSM have founded a joint venture, Veramaris®, to commercialize this technology, which they say will be on the market in 2019 and initially able to meet 15 percent of the salmon aquaculture industry's demand for EPA and DHA.[c]

Sources:
a. Zhang et al. (2018).
b. Sprague et al. (2016).
c. Van der Hoeven (2018); Veramaris (2018).

Expansion of marine-based systems

Offshore marine aquaculture, which would avoid additional land-use change as well as problems of competition for space in coastal areas by locating farms in the open sea, is still in its infancy.[102] One recent study found that the global physical potential for expanding marine aquaculture is vast—that marine aquaculture could fully supply farmed fish demand by 2050 even if only 1 percent of the suitable area in each coastal country were developed. However, the study did not assess important economic or biodiversity-related constraints to expansion of marine-based systems, suggesting that the true growth potential was still significant, but lower than the pure physical potential.[103]

To better understand the efficacy of various strategies to meet these challenges while boosting aquaculture production to 140 Mt by 2050, we use GlobAgri-WRR to build on lifecycle assessments performed by WorldFish and Kasetsart University. These assessments are reported in more detail in Mungkung et al. (2014) and Waite et al. (2014).[104] The analysis divides world aquaculture into 75 major production systems, which accounted for more than 80 percent of total world aquaculture production in 2010. We integrated this analysis into the GlobAgri-WRR model and used the model to explore a 2050 baseline and three additional aquaculture production scenarios with the following characteristics:

- **Baseline**. Aquaculture production rises to 140 Mt in 2050. Proportions of fish species cultivated and production systems used (e.g., composition of feeds, intensity level of production) remain unchanged between 2010 and 2050. But increasing resource scarcity leads to market conditions that cause farmers to improve their production efficiency so that they produce each kg of fish with 10 percent less use of all major inputs (e.g., water, feed, energy, fertilizers).
- **Doubling efficiency gains** (Coordinated Effort scenario). Between 2010 and 2050, farmers improve production efficiency by 20 percent instead of 10 percent thanks to further improvements in fish breeding, feeds, and disease and pollution control.
- **Accelerated intensification on land** (Highly Ambitious scenario). Freshwater pond farming—the current dominant production system around the world—becomes significantly more intensive as farmers invest in the technologies described in the preceding

Table 23-1 | Global effects of 2050 aquaculture improvement scenarios on the food gap, land use, and the GHG mitigation gap

SCENARIO	FOOD GAP, 2010–50 (%)	GHG MITIGATION GAP (GT CO_2E)	AQUACULTURAL LAND USE (MILLION HA)		
			Ponds	Cropland for feed	Total
2010	N/A	N/A	19	27	46
2050 BASELINE	**56.5**	**11.1**	**40**	**52**	**92**
Doubling efficiency gains (from 10% to 20% between 2010 and 2050) *(Coordinated Effort)*	56.3	11.0	36	49	85
Accelerated intensification on land *(Highly Ambitious)*	57.0	11.1	27	60	87
Doubling efficiency gains plus accelerated intensification on land *(Breakthrough Technologies)*	56.7	11.0	24	56	80

Source: GlobAgri-WRR model.

section. Fifty percent of all farms classified as "extensive" (Box 23-1) in 2010 shift to "semi-intensive" by 2050, and 50 percent of "semi-intensive" farms in 2010 shift to "intensive" by 2050.

- **Doubling efficiency gains plus accelerated intensification on land** (Breakthrough Technologies scenario). This scenario is a combination of the two previous scenarios.

Table 23-1 shows the results from these scenarios. Under the 2050 baseline scenario, land under aquaculture ponds doubles between 2010 and 2050 and cropland for aquaculture feeds also doubles because there is no additional potential to provide more feed from wild fish.

Doubling the increase in production efficiency from 10 percent (under baseline) to 20 percent reduces total land demand by 7 Mha relative to the baseline scenario, closing the food gap by 0.4 percent and the GHG emissions gap by 0.8 percent.

The scenario of accelerated intensification on land leads to a trade-off among two types of land use. The switch to more intensive production systems by 2050 leads to a savings in 13 Mha of land under aquaculture ponds relative to baseline. However, since more intensive production systems tend to require more feeds—and we required all additional feeds to be crop-based rather than wild-fish-based—the land savings from the reduced pond area are offset by an 8 Mha increase in cropland used to produce aquaculture feeds. This surprising result suggests that extensive ponds are essentially functioning both as homes for the fish and as producers of algae for feed. GlobAgri-WRR also estimated that overall emissions (even with the reduced land overall relative to baseline) would actually *increase* by 19 Mt per year, due to the higher energy use in intensive ponds.

The third scenario, which combines the doubled efficiency with the accelerated intensification on land, eases the trade-offs from the intensification-only scenario. Under this third scenario, cropland use rises by only 4 Mha relative to baseline (instead of 8 Mha in the intensification-only scenario), while the use of land for ponds falls by 16 Mha relative to baseline (instead of 13 Mha in the intensification-only scenario). Overall, emissions would decrease by 66 Mt per year relative to baseline, as the avoided land-use change offsets the higher energy use in intensive ponds.

Overall, we favor shifts toward more intensive ponds in part because land "saved" overall from pond expansion is likely to be more carbon-rich than the additional land required for feed crop expansion. This is because ponds must generally use wet, flatter lands. In addition, potential exists to reduce the land-use demands for feed either by further increasing crop yields or by further accelerating efficiency gains (e.g., breeding fish to convert feed to flesh more efficiently or to grow faster and therefore increase output per hectare of pond). Connecting intensive ponds to renewable sources of energy could reduce production emissions from intensive aquaculture.

This analysis, and the broader life cycle assessment done by Mungkung et al. (2014) that examined additional aquaculture growth scenarios and other environmental factors, including water use and pollution, illustrate a real challenge. Under a projected doubling in global aquaculture production between 2010 and 2050, it will be hard enough to hold aquaculture's environmental impacts to 2010 levels, let alone reduce them. Mungkung et al. (2014) also showed that intensification, while reducing aquaculture's freshwater demand, would lead to a rise in water pollution unless accompanied by further technological advances. A deeper analysis of the trade-offs under scenarios of aquaculture growth, with more detailed data, is needed to provide insights at finer scales (e.g., national level). For example, Phillips et al. (2015) analyzed scenarios of Indonesian aquaculture growth to the year 2030. Their analysis underscored the challenges of meeting projected fish demand while safeguarding high-conservation-value ecosystems such as mangroves and wetlands, limiting freshwater use, and finding alternatives to wild-fish-based feed ingredients.

Recommended Strategies

If aquaculture is to more than double production, sustainably, between 2010 and 2050, the sector must increase its natural resource efficiency and reduce other environmental impacts, including fish diseases and escapes. Several strategies are necessary to realize this potential.

Increase investment in technological innovation and transfer

Technological advances by scientists, researchers, and innovative farmers—and widespread uptake of improved technologies—will be necessary to address the various land and feed constraints and to fully exploit the opportunities for aquaculture to grow efficiently and with minimal environmental impacts, as demonstrated by the salmon farming industry in Norway (Box 23-3). These advances could also help aquaculture adapt to a changing climate.[105] While numerous initiatives are directed at technological innovation and transfer, their present scale is insufficient to achieve the necessary change by 2050. Because most aquaculture occurs in

developing countries, where production growth in coming decades is expected to be highest, initiatives should focus on helping small- and medium-scale producers in developing countries access and adopt improved technologies.[106] In India, for example, small-scale shrimp farmers organized into "societies" that enabled them to access new technologies, services, and markets that otherwise might have been limited to large-scale farmers.[107]

National governments, development agencies, the aquaculture industry, international organizations, nongovernmental organizations (NGOs), private foundations, and farmers all have a role to play. Because public budgetary resources are limited, innovative financing arrangements with the private sector, such as private equity investment, will be needed.[108]

Use spatial planning to optimize aquaculture siting

Much of aquaculture growth to this point has been "organic" or "opportunistic" and led by a dynamic private sector.[109] Resource and economic constraints, the potential for increased conflicts between resource users, and the need to boost production significantly in a short time mean that the locations of future aquaculture systems must be chosen more strategically.

Spatial planning and zoning include processes and tools such as land-use planning, water-use planning, ecosystem modeling, marine spatial planning, integrated coastal zone management, and integrated watershed management. These approaches can lessen the conflicts between a growing aquaculture industry and other economic actors competing for the same resources, such as land, especially if done in a participatory way. Planning focused at the landscape and seascape level can also reduce cumulative impacts caused by many farmers operating in the same area and help minimize risks associated with climate change. In Norway, for example, zoning laws ensure that salmon producers are not overly concentrated in one area, reducing disease risk and helping mitigate environmental impacts.

BOX 23-3 | Sustainability gains in Norway's salmon farming industry

Norway, the world leader in salmon (*Salmo salar*) production, has made dramatic sustainability gains over the past 30 years. The share of fishmeal and fish oil in salmon diets has been reduced by about two-thirds between 1990 and 2013, antibiotic use virtually eliminated, and fish escapes reduced from nearly 1 million in 2006 to roughly 143,000 in 2018.[a] Meanwhile, salmon production has grown from about 150,000 tons in 1990 to 1.2 million tons in 2016.[b]

Technological improvements, stimulated by high levels of public and private investment in research and development, have been at the core of these improvements in productivity and environmental performance. Development of vaccines and disease control methods has greatly reduced the need for antibiotics.[c] Selective breeding and improved feeds have both led to greater production efficiency and reduced the reliance on wild fish for feed.[d] Industry consolidation and vertical integration has enabled companies to invest heavily in research and development, increasing production efficiency and driving down production costs. And public policies—including permitting, spatial planning and monitoring systems, as well as establishing protected areas for wild salmon—have helped stimulate and support these improvements.[e]

In the last few years, salmon farming has encountered an enhanced problem from sea lice, a parasite that thrives in confined salmon pens, kills or makes unmarketable large numbers of fish, and spreads to wild salmon, possibly reducing their numbers greatly. The lice problem has become sufficiently large that farmed salmon production fell between 2015–16, both in Norway and globally.[f] Overall, parasites and disease present some of the biggest threats to continued aquaculture expansion.

Sources:
a. Ytrestøyl et al. (2015); Taranger et al. (2014); WHO (2015); Directorate of Fisheries (2019).
b. FAO (2019b).
c. WHO (2015).
d. Ytrestøyl et al. (2015).
e. Torgersen et al. (2010).
f. Castle (2017).

Spatial planning and zoning can also prevent aquaculture development in high-conservation-value areas, such as mangroves (as in Thailand) or wild salmon areas (as in Norway), and protect upstream areas essential to maintaining coastal water quality (as in the United States).

More national and subnational governments need to establish legal frameworks for spatial planning and zoning for aquaculture, create aquaculture development plans that link to wider development plans, and invest in monitoring and enforcement to ensure plan implementation. A number of initiatives are already in place that promote participation in aquaculture planning and take landscape- and seascape-level concerns into account,[110] but additional effort is necessary.

Introduce policies to reward sustainable intensification

Complementary policies, namely regulations, standards, taxes, subsidies, and market-based mechanisms, can encourage sustainable intensification. For example, in Thailand, the government has provided shrimp farmers operating legally in aquaculture zones with access to free training, water supply, and wastewater treatment. The Thai government has also provided low-interest loans and tax exemptions to small-scale farmers, helping them adopt improved technology that increased productivity, reducing pressure to clear new land.[111] Similar policies have helped stimulate the growth and intensification of the catfish industry in Vietnam (Box 23-4). And in Denmark, stringent wastewater standards have encouraged investment in recirculating aquaculture systems.[112]

Establish aquaculture monitoring systems

Advances in satellite technology, digital mapping, ecological modeling, open data, and connectivity mean that global-level aquaculture monitoring and planning systems may now be possible. A global-scale platform that integrates these technologies and builds on existing information-sharing efforts could help companies, governments, and civil society encourage and support sustainability in the aquaculture sector. Such a platform could combine national- or global-level map layers (e.g., on farm locations, land use and type, water quality, weather), georeferenced data (e.g., on fish production and value, fish trade, environmental performance), and bottom-up crowdsourcing of information (e.g., photos or stories to report successes, best practices, or areas of concern). Many different users could benefit from information technologies:

- Fish buyers could ensure that their purchases are from responsible suppliers, and producers and suppliers could use objective data to demonstrate that their operations are sustainable.
- Producers could access market information, as well as early warnings about water quality issues, disease outbreaks, and risks associated with natural disasters.
- Producers could communicate success stories, access technical guidance, and network with other producers and technical assistance agencies to improve operations.
- Governments could use data on current facility locations and environmental and social factors to improve spatial planning, detect illegally sited operations, and target monitoring and law enforcement efforts.
- NGOs and communities could report stories of improvements in productivity and social and environmental performance that could inspire actors in other areas. Conversely, they could monitor aquaculture operations in their area and raise an alarm if laws are being broken or resources are threatened.

A globally applicable monitoring and planning system could also help concerned citizens everywhere learn more about this dynamic, rapidly growing food production sector, helping to ease often polarized debates around aquaculture and build coalitions in favor of sustainable aquaculture growth.

For more detail about this menu item, see "Improving Productivity and Environmental Performance of Aquaculture," a working paper supporting this World Resources Report available at www.SustainableFoodFuture.org.

BOX 23-4 | Technology and government support drive intensification of catfish farming in Vietnam

In Vietnam's upper Mekong Delta region, striped catfish (*Pangasius hypophthalmus*) production grew 20-fold between 2000 and 2010, while catfish farming areas only roughly doubled, indicating a very rapid period of intensification. Catfish exports brought in $1.4 billion in foreign exchange in 2010.[a] This rapid production increase has led to the development of other sectors along the value chain, including hatchery production, fillet processing, and feed production. The catfish boom during the first decade of the 21st century created nearly 180,000 new jobs in the Mekong Delta, the majority of which are performed by rural women in the processing sector.[b] A recent life cycle analysis noted that pollution from catfish ponds was equal to or less than that of other food production sectors in the Mekong Delta, and that water quality had not degraded to a point where it threatened the viability of aquaculture production or compromised other downstream water uses.[c]

Technological improvements—including a breakthrough in artificial propagation of striped catfish in hatcheries around the year 2000, adoption of higher-quality pelleted feed, and improvements in pond farming techniques—combined to trigger the boom in catfish production. Supportive government policies, including research and extension programs, subsidized bank loans for producers and processors, and trade liberalization and promotion, have also helped to grow and support this export-oriented industry, and allow it to provide an affordable "white fish" substitute in Europe and the United States.[d]

Going forward, the biggest short-term risk to the industry's sustainability is the continued economic viability of farm operations if production costs (e.g., feed) rise. Protectionism in importing countries also poses a threat; wild fishing and aquaculture sectors in the United States and Europe have lobbied during the past 15 years to restrict imports of Vietnamese catfish.[e] In addition, the Vietnamese catfish industry will also need to secure sustainable supplies of feed and water, while continuing to limit disease outbreaks.[f]

Sources:
a. De Silva and Phuong (2011).
b. De Silva and Phuong (2011).
c. Bosma et al. (2009).
d. Phuong and Oanh (2010).
e. Little et al. (2012).
f. Phuong and Oanh (2010).

ENDNOTES

1. Throughout this report, "fish" refers to both finfish and shellfish. More precise definitions of these terms, and others used throughout this report, include *finfish*—a cold-blooded animal that lives in water, breathes with gills, and has fins and scales; *shellfish*—refers to both crustaceans and mollusks; *crustacean*—an animal belonging to the phylum Arthropoda that (usually) lives in water, has several pairs of legs, a body made up of sections, and is covered in a hard outer shell; *shrimp*—a decapod crustacean of the suborder Natantia; and *mollusk*—an animal belonging to the phylum Mollusca that has a soft unsegmented body without a backbone and usually lives in a shell (FAO 2008).
2. Authors' calculations from FAO (2019a). In 2015, fish provided roughly 3.2 billion people with 20% of their animal protein intake (FAO 2018).
3. Authors' calculations from FAO (2019a). In 2013, 77% of the human food supply of fish was located outside of North America, Europe, Oceania, and other OECD countries, suggesting a similar percentage of world fish consumption in developing countries.
4. Allison (2011).
5. Many figures in this report are based on statistics from the FAO FishStat global database of wild fisheries and aquaculture production (FAO 2019b) and the FAO's *State of World Fisheries and Aquaculture* (FAO 2018). However, the FAO fisheries and aquaculture production data rely on reports of member countries, and the quality of the data varies by country and may be subject to reporting bias. Many member countries have been found to misreport fisheries landings, catch levels may be underreported as discussed in note 9, and collection of aquaculture data remains relatively new. See Kura et al. (2004) (Annex B); Campbell and Pauly (2013); CEA (2012); and Pauly and Zeller (2016) for further discussion of FAO fisheries and aquaculture data, limitations, and caveats.
6. FAO (2018).
7. FAO (2019b). While the FAO capture fisheries data show a decline in marine fish catch since the 1990s, the data also show that the inland fish catch is still slightly rising. As with marine fisheries, inland fisheries are important to human protein consumption, especially for the poor. However, the slight increase in inland fish catch in the FAO data is probably a result of better reporting of actual catches rather than an increase in the amount of fish landed, and many believe that inland fisheries are in decline as well because of overfishing and aquatic ecosystem degradation (Welcomme 2011).
8. Pauly and Zeller (2016) cited underestimates in the FAO FishStat data around small-scale (both commercial and subsistence) fisheries, recreational fisheries, discarded bycatch, and illegal or otherwise unreported catch—and estimated the extent of these missing components to "reconstruct" true levels of marine fish catches.
9. FAO (2018). Data are from periodic FAO fish stock assessments. According to FAO (2018), *overfished* stocks produce lower yields than their biological and ecological potential, *maximally sustainably fished* stocks produce catches that are very near their maximum sustainable production, and *underfished* stocks are under relatively low fishing pressure and have some potential to increase their production.
10. Watson and Tidd (2018).
11. Cheung et al. (2010, 2013).
12. As defined by the World Bank (2017d), fishing effort is a composite indicator of "the size and efficiency of the global fleet, usually measured in terms of the number of vessels, vessel tonnage, engine power, vessel length, gear, fishing methods, and technical efficiency."
13. World Bank (2017d).
14. World Bank (2017d).
15. Costello et al. (2016).
16. Examples summarized in CEA (2012); and Worm et al. (2009).
17. NOAA (2018).
18. FAO (2019b).
19. McClanahan and Abunge (2014); McClanahan (2010); McClanahan et al. (2008).
20. McClanahan and Abunge (2014).
21. Authors' calculations, assuming a 12% increase in per capita consumption between 2010 and 2050 due to growth in income and urbanization. This projection corresponds well to recent trends; fish demand and supply would match if wild fish supply were to fall by 10% between 2010 and 2050 and aquaculture supply were to continue to expand at its recent rate of ~2 Mt per year during that period.
22. This 10% decline to 2050 is also in line with the "business as usual" fisheries management scenario in Costello et al. (2016) (Table S15).
23. GlobAgri-WRR model.
24. See, for example, Worm et al. (2009); CEA (2012); Melnychuk et al. (2016); and World Bank (2017d).
25. CEA (2012).
26. The following observations about these six factors are based on and more thoroughly examined in CEA (2012).
27. World Bank (2017d).
28. Sumaila et al. (2010, 2012, 2016).
29. World Bank (2017d).

30. Worm et al. (2009).

31. Agnew et al. (2009). Some recent estimates of fish catch underreporting are even higher; Pauly and Zeller (2016) estimated that true marine fish catches could be 53% higher than those reported in FAO (2019b).

32. Birkenbach et al. (2017).

33. Grimm et al. (2012); Essington (2010); Brinson and Thunberg (2013); Birkenbach et al. (2017).

34. Spalding (2013); Costello et al. (2008). Although individual transferable quota (ITQ) programs have reduced fishing effort and improved the economic efficiency of the fishing industry, these programs also have disadvantages (the following examples are summarized in Kura et al. 2004). As with other forms of catch limits, it can be difficult to determine the optimal sustainable yield level of a given fishery, leading to continued overexploitation. ITQs can give fishers incentive to discard smaller or lower-priced fish back into the sea to avoid counting these fish against the quota, again leading to continued overexploitation. There are also social and equity issues associated with ITQs. ITQs reduce the number of fishers and vessels in a fishery, leading to increased unemployment and vulnerability in fishing-dependent communities in the short term. ITQs often encourage consolidation within a fishery, and as quota prices increase these programs may become monopolized by larger, better-funded fishing companies at the expense of more vulnerable small-scale fishers. The design of ITQ programs, like the overall regulation of fisheries, must be sensitive to the socioeconomic factors facing fisher communities, which vary considerably among countries.

35. CEA (2012).

36. The following observations are based on and more thoroughly examined in CEA (2012).

37. Melnychuk et al. (2016).

38. Aquaculture is commonly defined as the farming of aquatic organisms, which include both animals and plants (FAO 2008). Because the focus of this report is on aquaculture's potential to contribute to fish supplies, all data on aquaculture production omit production of aquatic plants (seaweeds). For the rest of the report, *aquaculture* is used to mean "the farming of aquatic animals."

39. FAO (2019b).

40. FAO (2019b).

41. This paragraph contains authors' calculations from FAO (2019b).

42. FAO (2018). Aquaculture is the fastest-growing animal production sector when measured by annual percentage rate of growth. By absolute annual amount of growth, aquaculture, poultry, and pork production have all grown at roughly 2–2.5 Mt per year since 1990, although aquaculture's growth since 2010 has been even faster at roughly 3.5 Mt per year.

43. The discussion below, unless otherwise cited, is from Tacon et al. (2010); Kura et al. (2004); Costa-Pierce et al. (2012); and Bunting (2013). Note also that aquaculture can have sometimes positive ecosystem effects; for example, providing seed for restocking of overexploited fish populations, or by providing wastes that can be used to fertilize terrestrial crops (Soto et al. 2008, 16).

44. Authors' calculations from GlobAgri-WRR model and Mungkung et al. (2014) (unpublished data). Assumes the following: all bivalves and coastal cage/pen aquaculture (e.g., of salmonids) occupied marine area and thus no land; everything classified as "coastal ponds" occupied brackish water area; everything else occupied freshwater area.

45. Authors' calculations. According to the GlobAgri-WRR model, total agricultural land was 4,785 Mha in 2010.

46. Lewis et al. (2002).

47. Lebel et al. (2016).

48. Strong and Minnemeyer (2015).

49. Richards and Freiss (2016).

50. See Phillips et al. (2015) for an example from Indonesia.

51. Mungkung et al. (2014). Figures do not include emissions from land-use change associated with aquaculture or agriculture.

52. Hall et al. (2011b).

53. Bunting and Pretty (2007).

54. FAO (2018).

55. Bouwman et al. (2013).

56. Kura et al. (2004).

57. Castle (2017); Bravo (2003).

58. Cooke (2018). Looking beyond issues of disease, some groups have raised concerns about the welfare of farmed fish—especially those raised in intensive systems. These groups make the case that fish are sentient beings and self-aware organisms, capable of feeling pain and stress. Intensive aquaculture systems raise concern about the well-being of fish as they undergo and experience stressful situations and conditions.These concerns are similar to animal welfare concerns related to intensive livestock farming, including overcrowding, feeding and handling, transport, and stunning and slaughter methods.

59. Lorenzen et al. (2012).

60. Hine et al. (2012).

61. USDA (2013a).

62. Beveridge and Brummett (2013).

63. Beveridge and Brummett (2013).

64. Cai et al. (2012).

65. Cashion et al. (2017).

66. Beveridge and Brummett (2013); Belton et al. (2012); Hernandez et al. (2017).

67. FAO (2007).

68. Croplands that have become too saline for rice cultivation are an example of such lands with low economic and environmental value.

69. Authors' calculations. Aquaculture water consumption given in Mungkung et al. (2014), global agricultural water consumption of 8,363 km^3 per year (not counting aquaculture) given in Mekonnen and Hoekstra (2012).

70. Beveridge and Brummett (2013).

71. Costa-Pierce et al. (2012).

72. FAO (2018). As a low-bound estimate, "fed aquaculture production" consisted of at least 56 Mt of fish (out of 80 Mt of total aquaculture production in 2014, excluding seaweeds). This estimate excludes filter-feeding fish species (silver carp and bighead carp), freshwater fish production not reported down to the species level, and bivalve mollusks. Because even filter-feeding carp can be fed formulated feeds, the true amount of "fed aquaculture production" is likely higher than 70% of all production (Tacon et al. 2011).

73. Although the terms *carnivore*, *omnivore*, and *herbivore* are commonly used when describing the feeding habits of a fish species, it is more scientifically and etymologically correct to use the trophic level, which is an indication of how high a species sits in the aquatic food chain. For example, the "carnivorous" Atlantic salmon has a trophic level of 4.43, while the "herbivorous" common carp has a trophic level of 2.96 (Tacon et al. 2010). Farmed fish species have varying digestive and metabolic capacities to deal with different feed resources; for example, a high-trophic level "carnivore" requires a relatively high level of protein in its feed (Tacon et al. 2010). However, distinctions between "carnivores" and other groups can be misleading in aquaculture, because fish diets can be altered. For example, although the average salmon diet in 2008 contained 25% fishmeal and 14% fish oil (Tacon et al. 2011), it is technically possible to feed an Atlantic salmon using no fish-based ingredients at all. Still, in this section, we follow common usage to use the term *carnivores* to refer to salmonids, shrimp, and most marine finfish, and *omnivores/herbivores* to refer to other fed fish species.

74. Tacon et al. (2011).

75. Authors' calculations from FAO (2019b).

76. Tacon et al. (2011).

77. Naylor et al. (2009).

78. Tacon et al. (2011).

79. De Silva and Soto (2009).

80. De Silva and Soto (2009).

81. Watson et al. (2012).

82. De Silva and Soto (2009).

83. Authors' calculations based on an assumption of the same ratio of fish protein weight to total fish weight in 2050 as in 2010 (implying the same mix of fish species).

84. Authors' calculations.

85. See Hall et al. (2011b) for a discussion predicting the geographic distribution of aquaculture growth to 2030.

86. Authors' calculations:

    Global value of farmed fish. Here, we assume that between 2010 and 2050, real prices of fish rise on average by 10%. The World Bank, FAO, and IFPRI (2013) project that real prices of all farmed fish will rise between 2010 and 2030, by 5 to 10% depending on the species. We therefore believe that a global real price increase of 10% by 2050 is reasonable.

    Livelihoods from aquaculture. Here, we assume that between 2010 and 2050, average family sizes will remain constant, and that aquaculture labor productivity will continue to grow at its 2000–10 historical rate. FAO data show that between 2000 and 2010, world aquaculture production grew by 82%, while aquaculture employment grew by only 47% (FAO 2014a, 2014b). A similar trajectory between 2010 and 2050—where the aquaculture employment growth rate is only 57% of the aquaculture production growth rate—would lead to the industry providing livelihoods for 176 million people by 2050.

87. Costa-Pierce et al. (2012).

88. Costa-Pierce et al. (2012). However, while the feed efficiency figures in Figure 7-4 count grass consumed by terrestrial animals, they do not count plankton and other organic (nonfeed) matter consumed by fish, as data on volume of aquatic organic matter consumed by fish are sparse. Fry et al. (2018) come to a similar conclusion on the relative conversion efficiency of aquaculture and terrestrial livestock, while also noting that farmed fish and shrimp require higher levels of protein and calories in feed compared to chickens, pigs, and cattle.

89. Hall et al. (2011b). However, in order to provide food that is safe for consumers, filter-feeders must be raised in high-quality waters. And although coastal waters tend to have more than abundant nutrients, there are often many competing uses of these areas (analogous to competition for agricultural land), limiting scope for expansion of aquaculture.

90. GlobAgri-WRR model; Waite et al. (2014).

91. Volpe et al. (2010); Asche (2008).

92. This section focuses on "conventional" selective breeding (as opposed to genetic modification).

93. Gjedrem et al. (2012).

94. Gjedrem et al. (2012). Nearly all Atlantic salmon production is based on genetically improved stock, but the rates of use of improved stock for production of other species is much lower.

95. Garnett and Wilkes (2014).

96. Gjedrem et al. (2012).

97. Naylor et al. (2009).

98. Smith et al. (2010); Taelman et al. (2013). Table 4 in Taelman et al. (2013), which displays the results of a lifecycle assessment comparing algae-based feeds to conventional aquaculture feed, shows that algae-based feeds reduced land use demands by 90% and water use by 67% relative to the conventional feed. GHG emissions for the algae-based feed were 40% higher than those of the conventional feed, but this increase may be offset by the reduced land-use requirement (and avoided emissions from land-use change).

99. Ruiz-Lopez et al. (2014).

100. Browdy et al. (2012).

101. Bregnballe (2015).

102. Kapetsky et al. (2013).

103. Gentry et al. (2017) found that if all suitable marine areas were developed for aquaculture, approximately 15 billion tons of finfish could be grown annually—more than 100 times our projection of aquaculture demand in 2050 (140 million tons). However, the study did not filter out areas that would be uneconomic due to distance from ports, access to markets, or shoreside infrastructure—as well as environmentally sensitive areas such as coral reefs—which would limit suitable areas.

104. WorldFish's *Blue Frontiers* report (Hall et al. 2011b) used the life cycle assessment (LCA) method to examine, quantify, and compare the environmental performance of major aquaculture production systems around the world. The LCA compiled data on inputs (e.g., land, water, feed, and energy) and environmental releases (e.g., waste nitrogen and phosphorus), and evaluated the potential environmental impacts associated with each. *Blue Frontiers* analyzed environmental impacts of 75 major aquaculture production systems that accounted for 82% of total world aquaculture production in 2008. For this World Resources Report, WorldFish and Kasetsart University updated the *Blue Frontiers* data to assess the environmental performance of aquaculture in 2010 and developed a baseline production scenario for 2050 and several alternative scenarios. Environmental impacts associated with each of the 75 major production systems, in each of the scenarios, were modeled using the LCA. As in *Blue Frontiers*, the scope of analysis was from cradle to farmgate, covering raw material production (crops, fishmeal, and fish oil), feed production, aquaculture production (farming), and water emissions (nitrogen and phosphorus). The LCA did not cover infrastructure, seed production, land-use change, packaging and processing of produce, transport of feed and produce, or waste disposal. See Mungkung et al. (2014) for more details.

105. De Silva and Soto (2009).

106. Brummett et al. (2008).

107. Umesh et al. (2010).

108. Fort (2013).

109. See, for example, Hernandez et al. (2017) on the growth of aquaculture in Bangladesh just over the past decade.

110. Global examples include the FAO/World Bank Ecosystem Approach to Aquaculture; the Assessment of Sustainable Development of Aquaculture (EVAD) initiative, led by the French National Research Agency; and the Global Aquaculture Alliance initiative on best aquaculture practices for zone management. Regional initiatives include the FAO, Asia-Pacific Fishery Commission (APFIC), and Network of Aquaculture Centres in Asia-Pacific (NACA) initiative on Sustainable Intensification of Aquaculture in Asia-Pacific; the New Partnership for Africa's Development (NEPAD) Action Plan for Development of African Fisheries and Aquaculture; and the European Aquaculture Technology and Innovation Platform.

111. See Waite et al. (2014).

112. Heldbo and Klee (2014).

REFERENCES

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