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Richard Waite, Malcolm Beveridge, Randall Brummett, Sarah Castine, Nuttapon Chaiyawannakarn, Sadasivam S. Kaushik, Rattanawan Mungkung, Supawa Nawapakpilai, Michael Philips

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Installment 5 of “Creating a Sustainable Food Future”

IMPROVING PRODUCTIVITY AND ENVIRONMENTAL PERFORMANCE OF AQUACULTURE

RICHARD WAITE, MALCOLM BEVERIDGE, RANDALL BRUMMETT, SARAH CASTINE, NUTTAPON CHAIYAWANNAKARN, SADASIVAM KAUSHIK, RATTANAWAN MUNGKUNG, SUPAWAT NAWAPAKPILAI, AND MICHAEL PHILLIPS

SUMMARY

Fish—including finfish and shellfish—are an important item in the human food basket, contributing 17 percent of the global animal-based protein supply in 2010. They are an especially valuable food source in developing countries, where more than 75 percent of the world’s fish consumption occurs. In addition to protein, fish contain micronutrients and long-chain omega-3 fatty acids that are essential for maternal and child health, but often deficient in the diets of the poor.

However, the global supply of wild-caught fish has long peaked and is unlikely to rise again unless overexploited stocks are rehabilitated. As world fish consumption continues to grow, aquaculture (fish farming) has emerged to meet demand. Already, just under half of all fish that people consume come from aquaculture, which is one of the world’s fastest-growing animal food producing sectors. With the supply of wild-caught fish stagnant, any future increase in world fish consumption will need to be supplied by aquaculture.

In a resource-constrained world, aquaculture could be an attractive option for expanding animal protein supply. Farmed finfish are similar in feed conversion efficiency to poultry, and much more efficient than beef. 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. Because the aquaculture sector is relatively young compared with terrestrial live-stock sectors, it offers great scope for technical innovation to further increase resource efficiency.

Note: All dollars are U.S. dollars. All tons are metric tons.

CONTENTS

Summary	1
Fish and Food	4
Beyond Peak Wild Fish: The Rise of Aquaculture	7
Growth of Aquaculture Production to 2050 and Possible Socioeconomic Benefits.....	14
Sustainability Challenges of Aquaculture	16
Evaluating Aquaculture’s Performance Today	20
Scenarios of Aquaculture’s Growth and Environmental Impacts in 2050.....	25
Case Studies: Learning from the Past.....	29
Recommendations.....	33
A Call to Action	40
Appendix.....	41
References.....	49
Endnotes	54

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For global fish availability to meet projected demand, we estimate that aquaculture production will need to more than double by midcentury, rising from 67 million tons (Mt) in 2012 to roughly 140 Mt in 2050. This level of growth could bring about significant food security and development benefits. For example, we estimate it could close roughly 14 percent of the “gap” between global animal protein consumption today and that needed in 2050. In addition, it could boost income and employment, particularly in developing countries where most aquaculture growth will occur.

However, as aquaculture assumes greater significance as a global food production system, concerns about its environmental and social impacts have arisen. As in other animal production sectors, several aquaculture inputs—land, freshwater, feed, and energy—are associated with significant environmental impacts. At the same time, the availability of these inputs is limited, and will likely become even more so in the future. Unless the aquaculture industry finds a way to produce more fish while minimizing its reliance on these limited inputs, its growth will be hampered. In addition, water pollution, fish diseases, and escapes continue to compromise the sustainability of the sector.

Therefore, for aquaculture to more than double production—and for that growth to be sustainable—the sector must improve its productivity while at the same time improving its environmental performance. To achieve “sustainable intensification,” aquaculture must:

- Advance socioeconomic development;
- Provide safe, nutritious food;
- Increase production of fish relative to the amount of land, water, feed, and energy used; and
- Minimize water pollution, fish diseases, and escapes.

How large could aquaculture’s resource demands and environmental impacts be in 2050? To answer this question, we used a new life cycle assessment conducted by WorldFish and Kasetsart University. We first assessed aquaculture’s environmental performance in 2010, and found that environmental impacts varied greatly depending on the species farmed (e.g., carp, mollusks, shrimp, tilapia, catfish, salmon):

- Freshwater ponds (e.g., for carp or tilapia) required the most land and freshwater per unit of farmed fish produced, while marine cages (e.g., for salmon)

required only a very small amount of land and water (for production of crop-based feeds).

- Production of catfish and shrimp stood out for its high greenhouse gas intensity.
- Production of salmon, shrimp, and other marine fish used the largest amounts of wild fish-based feed per unit of farmed fish produced, while species that feed lower on the food chain (e.g., carp, tilapia, catfish) used smaller amounts.
- Of all species groups, only bivalve mollusks (e.g., oysters, clams, mussels, scallops) performed well across all environmental impact categories.

We also found that aquaculture’s environmental impacts in 2010 varied by level of production intensity. Intensification pulled impact indicators in two directions. To date, intensification has led to a decrease in the use of land and freshwater per unit of farmed fish produced. However, intensification has also led to an increase in the use of energy and fish-based feed ingredients, as well as an increase in water pollution, per unit of farmed fish produced. Disease risks also rise in intensive systems. These tradeoffs suggest that “sustainable intensification” is easier said than done—and that efforts to intensify aquaculture production should aim at mitigating the negative impacts of intensification.

We then projected environmental impacts under “business as usual” aquaculture production of 140 Mt in 2050, as well as seven alternative scenarios:

- **Scenario 1:** 10 percent improved efficiency in input use
- **Scenario 2:** Significant intensification (50 percent of extensive farms become semi-intensive, 50 percent of semi-intensive farms become intensive)
- **Scenario 3:** Shifting energy supply (higher use of renewable energy)
- **Scenario 4:** Adoption of current best practices (all farmers in 2050 achieve efficiency of the best farmers in 2010 in terms of feed conversion ratios)
- **Scenario 5:** Shifting species mix (higher share of freshwater species, lower share of marine species)
- **Scenario 6:** Replacement of fishmeal and fish oil with crop-based ingredients

■ **Scenario 7:** Combined effect of Scenarios 1, 3, 4, and 6.

We found that holding aquaculture’s environmental impacts to 2010 levels—let alone reducing them—will be a real challenge, given the sector’s projected rapid growth to 2050. Under most scenarios, most impacts roughly double between 2010 and 2050, although impacts range from slightly below 2010 levels (e.g., greenhouse gas emissions decline with higher use of renewable energy) to nearly tripling (e.g., greenhouse gas emissions rise under significant intensification). Scenarios 1, 3, and 4 reduce nearly all environmental impacts relative to “business as usual” growth. Scenarios 2, 5, and 6 offer mixed results and tradeoffs across the impact categories. Scenario 7 exhibits the lowest impacts, indicating that for maximum effect, a variety of solutions should be implemented at the same time.

How can the world lift constraints to aquaculture’s growth while minimizing associated environmental impacts? We analyzed eight case studies from around the world to answer this question, and found four categories of factors that have improved aquaculture’s productivity and environmental performance:

- Technological innovation and adoption (in breeding, feeds, production systems, disease control, and environmental management)
- Market forces (related to resource scarcity and price signals)
- Public policy (regulation and standards; spatial planning and zoning; fiscal incentives; publicly funded research, extension, and training)
- Private initiatives (certification programs, purchasing standards, codes of conduct, research, advocacy, service delivery)

Resource scarcity will intensify between now and 2050, and rising input prices will continue to provide some incentive for producers to improve productivity and environmental performance. But our analysis shows that the scale of projected aquaculture production growth will likely offset efficiency gains achieved from market forces alone. How can the world accelerate further gains in productivity and environmental performance? We offer five recommendations aimed at catalyzing transformational change in the aquaculture sector:

1. Increase investment in technological innovation and transfer.

Technological advances will be needed in four interrelated areas:

■ **Breeding and genetics.** Establish or expand selective breeding efforts—aimed at countries and species with the highest levels of production (e.g., Chinese carps) and at areas of low productivity and high need for aquaculture growth (e.g., in sub-Saharan Africa)—to promote efficient resource use, reduce problems of disease and escapes, and lower production costs.

■ **Disease control.** Combine new technologies (e.g., diagnostic technologies, vaccines) and wider application of best management practices to combat disease problems.

■ **Nutrition, feeds, and feeding management.** Minimize farmers’ costs and aquaculture waste by increasing feeding efficiencies, and continue to develop alternatives to fish oil in aquaculture feeds.

■ **Low-impact production systems.** Recirculating aquaculture systems, biofloc technology, and integrated systems perform well across most indicators of productivity and environmental performance. Conduct additional research to understand and manage resource tradeoffs, bring down production costs, and develop additional low-impact systems that ease resource constraints.

2. Use spatial planning and zoning to guide aquaculture growth at the landscape and seascape level.

If conducted in a participatory way, these approaches can lessen the inevitable conflicts between a growing aquaculture industry and other economic actors, reduce cumulative impacts caused by many farmers operating in the same area, and help minimize risks associated with climate change.

3. Shift incentives to reward improvements in productivity and environmental performance.

Government initiatives (e.g., regulations, standards, taxation and subsidy policies, market-based mechanisms) and private initiatives (e.g., certification, purchasing standards) can complement landscape-level planning (Recommendation 2) to realign incentives to

encourage and reward sustainable production systems. These incentives should help the aquaculture industry reduce the environmental impacts of its most widely used production systems, and stimulate investment in and deployment of low-impact production systems.

4. Leverage the latest information technology to drive gains in productivity and environmental performance.

Advances in satellite technology, digital mapping technology, ecological modeling, open data, and connectivity mean that global-level monitoring and planning systems that encourage and support sustainable forms of aquaculture development may now be possible. A platform integrating these technologies could help governments improve spatial planning and monitoring, help the industry plan for and demonstrate sustainability of operations, and help civil society report success stories and hold industry and government accountable.

5. Shift fish consumption toward low-trophic farmed species.

Increasing demand for low-trophic farmed fish species (e.g., tilapia, catfish, carp, bivalve mollusks) relative to “business as usual” growth in fish consumption would lead to more efficient use of scarce wild fish resources and could ease fishing pressure on marine and freshwater ecosystems. In industrialized countries, substituting low-trophic farmed species into processed fish products; changing public food procurement policies to favor low-trophic farmed species; and selling the benefits of these species—such as affordability and taste—can all help to alter consumption patterns. In emerging economies, where most aquaculture production and fish consumption is currently of low-trophic species, this strategy could reduce the growth in consumption of high-trophic species that is expected to occur as billions of people enter the global middle class in coming decades.

The global aquaculture industry is dynamic and diverse. National governments, the aquaculture industry, development agencies, international organizations, nongovernmental organizations (NGOs), private foundations, and farmers all have a role to play in implementing these recommendations. One thing is clear: improving the productivity and environmental performance of aquaculture—and ensuring it provides safe, affordable, and nutritious food to millions of people around the world—is an important item on the menu for a sustainable food future.

FISH AND FOOD

Fish—including finfish and shellfish—are an important item in the human food basket.¹ Fish contributed 17 percent of global animal-based protein supply for human consumption in 2010, and are the primary source of animal protein for nearly 1.3 billion people.² More than 75 percent of fish consumption occurs in developing countries.³ Fish 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 that are often deficient in the diets of the poor.⁴ Almost 12 percent of the world’s population depends on fisheries and aquaculture for their livelihoods; more than 90 percent of those employed in these sectors live in developing countries.⁵

However, the global supply of wild-caught fish has long peaked⁶ and is unlikely to rise again unless overexploited stocks are rehabilitated. As world fish consumption continues to grow, aquaculture (fish farming)⁷ has emerged to meet demand. Already, just under half of all fish that people consume come from aquaculture, which is one of the world’s fastest-growing animal food producing sectors.⁸ With the supply of wild-caught fish stagnant, any future increase in world fish consumption will need to be supplied by aquaculture.

According to the Food and Agriculture Organization of the United Nations (FAO),⁹ the world produced 158 million tons (Mt) of fish in 2012. Wild-caught fisheries produced 91 Mt, which provided 69 Mt of fish for people and 22 Mt for animal feed and other nonfood uses. Aquaculture provided another 67 Mt.¹⁰ The world population is projected to reach 9.6 billion by 2050,¹¹ and per capita fish consumption is expected to rise in coming decades because of diet shifts resulting from increasing wealth and urbanization.¹² For global per capita fish consumption to rise from today’s level without further pressure on wild fish stocks, aquaculture production will need to more than double by midcentury.¹³

Doubling aquaculture production could significantly contribute to meeting global animal protein demand in 2050. However, such a high level of growth could also lead to large environmental impacts unless measures are taken to improve the sector’s performance. Furthermore, the aquaculture industry faces looming constraints of land, water, feed, and energy—which may limit its growth potential.

The 2013–14 World Resources Report, *Creating a Sustainable Food Future* (Box 1), explores a menu of solutions to adequately feed 9.6 billion people in 2050 while advancing socioeconomic development and reducing pressure on ecosystems, climate, and freshwater. One menu item that would satisfy these development and environmental criteria (Table 1) is to increase the productivity of aquaculture—the amount of fish produced per unit of land, water, feed, and energy—while at the same time improving aquaculture’s environmental performance, minimizing water pollution, disease, and fish escapes.

What are the possible environmental consequences of more than doubling aquaculture production? What does the world need to do to lift constraints to aquaculture’s growth while also minimizing associated environmental impacts? This working paper addresses these questions.

It begins by examining recent trends in wild fisheries and aquaculture, along with projected aquaculture production growth to 2050. It then details the major sustainability concerns around aquaculture, highlighting the impacts and constraints associated with aquaculture’s use of land, water, feed, and energy. Using a new life cycle assessment by WorldFish and Kasetsart University,¹⁴ the paper assesses the current performance of major aquaculture production systems, and then examines several scenarios of aquaculture production growth to 2050 and associated environmental impacts. By analyzing selected case studies of aquaculture systems from around the world, the paper distills key factors in past improvements in productivity and environmental performance, and the barriers to future improvement. Finally, it offers recommendations for how to address these barriers and ensure that the growth of aquaculture contributes to a sustainable food future.

Box 1 | The World Resources Report: *Creating a Sustainable Food Future*

How can the world adequately feed more than 9 billion people by 2050 in a manner that advances economic development and reduces pressure on the environment? This is one of the paramount questions the world faces over the next four decades.

Answering it requires a “great balancing act” of three needs—each of which must be simultaneously met. First, the world needs to close the gap between the food available today and that needed by 2050. Second, the world needs agriculture to contribute to inclusive economic and social development. Third, the world needs to reduce agriculture’s negative impact on the environment.

The forthcoming 2013–14 World Resources Report, *Creating a Sustainable Food Future*, seeks to answer this question by proposing a menu of solutions that can achieve the great balancing act. “Improving Productivity and Environmental Performance of Aquaculture” profiles one of these solutions or menu items, and is one of a series of working papers leading up to the World Resources Report.

Other menu items that intersect with issues of fisheries and aquaculture production, and which are the subjects of other working papers in the series, include:^a

- *Reducing Food Loss and Waste.* Measured by calories, 24 percent of all fish intended for human consumption was lost or wasted between sea (or farm) and fork in 2009.^b
- *Shifting Diets.* Overconsumption of calories, of animal products in general, and of beef in particular, increases the challenge of sustainably feeding the planet.
- *Achieving Replacement Level Fertility.* If all of the world’s regions achieved replacement level fertility by 2050, the projected growth in food demand would decline modestly in global terms, yet substantially in the world’s hungriest areas—particularly sub-Saharan Africa.^c
- *Reducing Biofuel Demand for Food Crops.* The challenge of feeding the planet gets even harder as crops (and the land used to

grow crops) are used not only for human food and animal feed but also fuel.

- *Sustainably Increasing Productivity of Crops and Livestock.* As with aquaculture, crop and livestock production uses scarce resources (e.g., land, water, energy), and is responsible for environmental impacts such as water pollution and greenhouse gas emissions. Crop and livestock production patterns will therefore also have a bearing on the sustainability of aquaculture. Aquaculture may compete for the same resources as—or be affected by pollution from—other food production sectors.

Since the 1980s, the World Resources Report has provided decision makers from government, business, and civil society with analyses and insights on major issues at the nexus of development and the environment. For more information about the World Resources Report and to access previous installments and editions, visit www.worldresourcesreport.org.

Sources: (a) See Searchinger et al. (2013a) (Table 1) for the full *Creating a Sustainable Food Future* menu. (b) Lipinski et al. (2013). (c) Searchinger et al. (2013b).

Table 1 | **How “Improving Productivity and Environmental Performance of Aquaculture” Performs Against the Sustainable Food Future Criteria** ● = positive ○ = neutral/it depends ⊗ = negative

CRITERIA	DEFINITION	PERFORMANCE	COMMENT
Poverty alleviation	Reduces poverty and advances rural development, while still being cost effective	●	<ul style="list-style-type: none"> ■ Increasing aquaculture productivity can increase profitability and farmer incomes, create on-farm jobs, and create off-farm jobs along fish value chains. Off-farm jobs include building ponds and cages, feed and seed production, manufacturing fish processing equipment, processing, packaging, marketing, and distribution. ■ Aquaculture development can contribute to food and nutrition security at household, community and national levels—either through increases in fish consumption or through increased incomes and thus greater access to food.
Gender	Generates benefits for women and contributes to greater gender equality	●	<ul style="list-style-type: none"> ■ Increasing productivity of aquaculture can provide livelihoods and income to women in the production, processing, and marketing sectors. ■ Fish contain important micronutrients and long-chain omega-3 fatty acids that are essential for maternal health and early childhood development.
Ecosystems	Avoids agricultural expansion into remaining natural terrestrial ecosystems and relieves pressure on aquatic ecosystems	●	<ul style="list-style-type: none"> ■ Increasing productivity of aquaculture leads to greater fish production per unit of land and water, which can reduce pressure to convert natural ecosystems (e.g., mangroves, wetlands), especially if strong policies protect those ecosystems. ■ Aquaculture has the potential to reduce pressure on wild fisheries and terrestrial ecosystems by providing an affordable, nutritious, and efficient source of animal protein to consumers. ■ Increasing productivity of aquaculture leads to greater fish production per unit input of wild fish (as feed or seed), reducing pressure on wild fisheries. ■ Well-managed aquaculture minimizes other pressures on aquatic ecosystems, including fish diseases and escapes of farmed fish into the wild.
Climate	Helps reduce greenhouse gas emissions from agriculture to levels consistent with stabilizing the climate	●	<ul style="list-style-type: none"> ■ Increasing productivity of aquaculture leads to greater fish production per unit of energy. ■ Well-managed aquaculture avoids using areas high in sequestered carbon (e.g., mangroves, seagrass).
Water	Does not deplete or pollute aquifers or surface waters	●	<ul style="list-style-type: none"> ■ Increasing productivity of aquaculture leads to greater fish production per unit of freshwater consumed. ■ Well-managed aquaculture minimizes water pollution through careful waste management. ■ Farming bivalve mollusks and filter-feeding carp can improve water quality.

Sources: Comments are adapted from Bunting (2013), Costa-Pierce et al. (2012), Hall et al. (2011), Soto et al. (2008), Allison (2011).

BEYOND PEAK WILD FISH: THE RISE OF AQUACULTURE

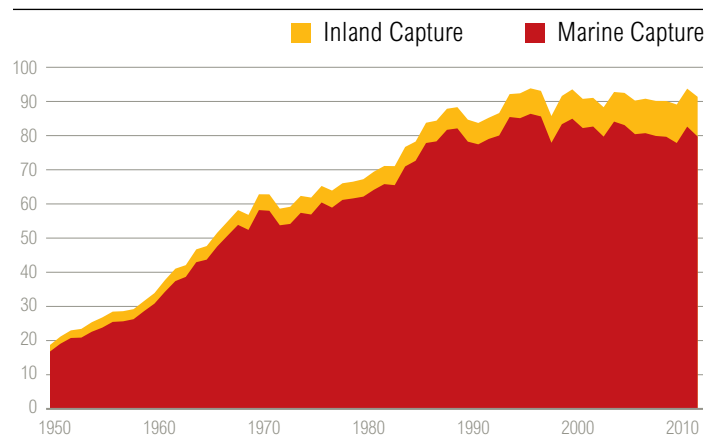
The supply of fish caught in the wild—particularly from the oceans—has stagnated for the past two decades, and future supply is under threat.

According to FAO, the supply of wild fish catch from both marine and inland water bodies grew from 19 Mt in 1950 to a peak of 94 Mt in the mid-1990s. Since that time, however, fish supplies have declined modestly and have hovered around 90 Mt (Figure 1).¹⁵ Even this level of harvest is not sustainable because the percentage of overfished stocks has risen. By 2011, 29 percent of marine fish stocks were overfished, another 61 percent were fully fished, and only 10 percent were fished at less than their full potential (Figure 2).¹⁶ Fisheries exploitation is greatest in the tropics—particularly in Southeast Asia—while stocks appear to be on the rebound along the coasts of a few developed countries such as Australia, New Zealand, Norway, and the United States.¹⁷

The first step toward a sustainable fish supply is to reduce the wild fish catch in the short term to allow depleted stocks to recover (Box 2). The World Bank, FAO, and

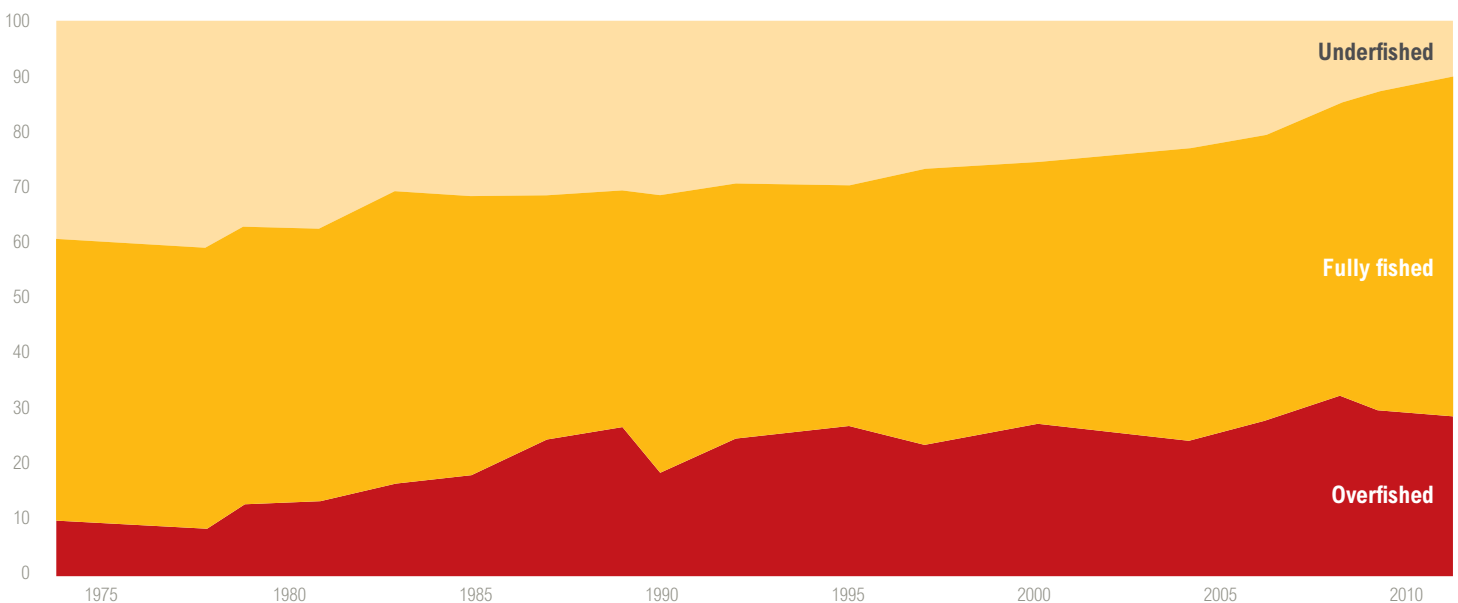
United Nations Environment Programme (UNEP) suggest that world fishing effort¹⁸ needs to decline by up to 50 percent of today’s levels to allow fisheries to rebuild.¹⁹ The result could be annual wild catches that are stable over the long term—one day possibly returning to as high as today’s catches in a best-case scenario.²⁰

Figure 1 | **The wild fish catch has stagnated since the 1990s (million tons)**



Note: “Wild catch” includes finfish, mollusks, crustaceans, and other aquatic animals from marine and freshwater ecosystems. It excludes all aquaculture.
Source: FAO (2014b).

Figure 2 | **Overfishing has risen over the past 40 years (percentage of marine fish stocks assessed)**



Source: FAO (2014b).

Box 2 | An Additional Menu Item: Reduce and Then Stabilize Wild Fish Catch

While the focus of this World Resources Report installment is on aquaculture, an important and complementary menu item for a sustainable food future is to reduce and then stabilize wild fish catch.

Solutions to curb overfishing are well known and documented. They are premised on key principles including (1) limiting the number of fishers to an economically feasible number, (2) limiting fish catch to a level that the fishery can reproduce, and (3) protecting habitat and avoiding harvest in important breeding areas.^a Solutions include establishing total allowable catches based on optimum sustainable yield, gear restrictions, seasonal limits, and closure of breeding areas.

In recent years, some developed countries have achieved some success by limiting the number of fishers and using “individual transferable quotas.” These quotas allocate shares of fish that may be taken among individual fishers, who thereby acquire a long-term stake in the health of the fishery—although this approach can also have disadvantages.^b

In developing countries where oversight, rule of law, and monitoring arrangements are weak, additional approaches are needed. In these governance environments, community-based comanagement systems, combining territorial fishing rights and no-take reserves designed and supported by coastal fishing communities, may prove more effective.^c

Widespread adoption of these solutions is difficult, however, for a number of reasons:^d

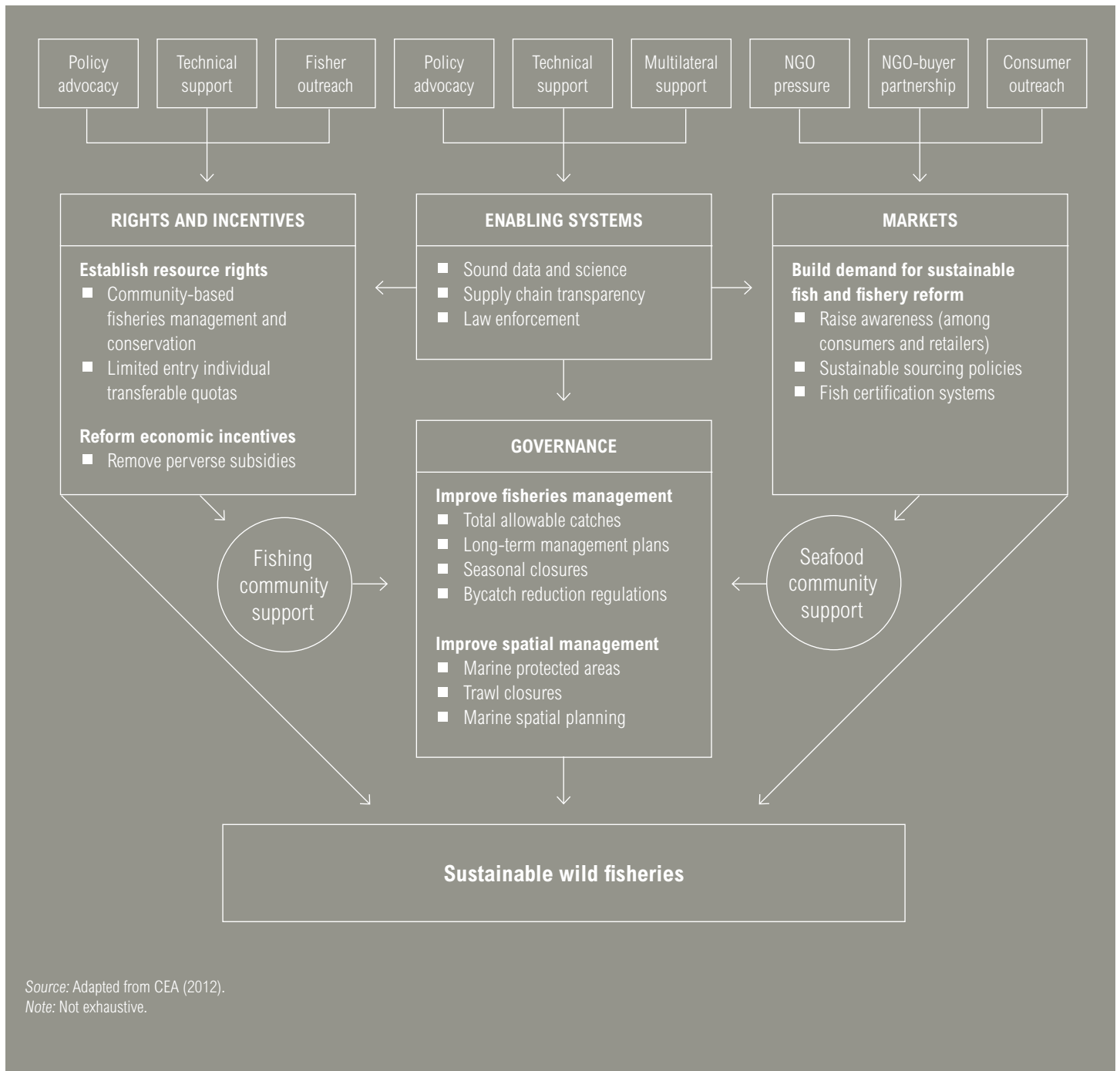
- Restoring a fishery typically involves a decline in fishing activity and landings for some period of time. Consequently, fishers and others in the value chain can experience financial losses over the near- to medium-term; there is no compelling short-term economic reward for acting sustainably.
- There are economic winners and losers in efforts to rebuild stocks, and the potential losers often wield enough power to thwart reform and restoration efforts.
- 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.^e
- Illegal, unregulated, and unreported fishing is a widespread problem, particularly in developing countries. Worldwide, losses from illegal and unreported fishing have been estimated at between \$10 billion and \$23.5 billion per year, representing an additional catch of between 11 Mt and 26 Mt that goes unmanaged.^f
- Fishery restoration requires high-quality data and active management, yet many countries lack the resources to pay for this necessary infrastructure and its operating costs.

- 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 the absence of alternative livelihoods, governments can be hesitant to curtail local fishing operations out of social concerns, even in depleted coastal waters.

Overcoming these barriers requires a number of complementary strategies, adapted to suit specific circumstances (Figure B2.1).^g For example, establishing resource rights and removing perverse subsidies could limit access to fish resources to economically and biologically feasible levels. Adoption of sustainable procurement practices and certification systems by actors in fish value chains could help create demand for sustainably sourced fish. Both the 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. Advocacy, public pressure, technical and financial support, and outreach to major players in fish value chains can all help to put these enabling conditions in place and advance these strategies.

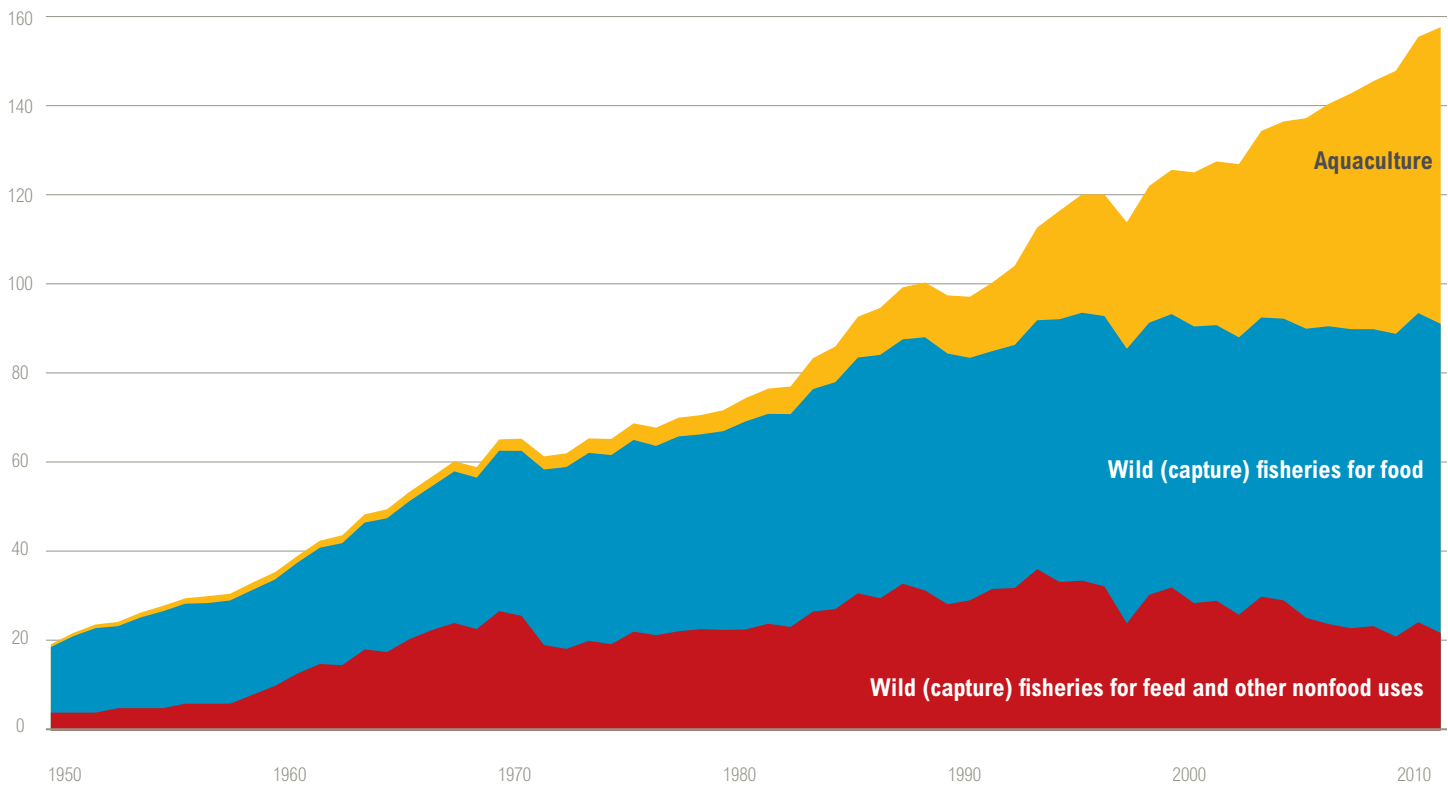
Sources: (a) CEA (2012). (b) Costello et al. (2008), Kura et al. (2004). As with other forms of catch limits, it can be difficult to determine the optimal sustainable yield level of a given fishery, leading to continued overexploitation. Individual transferable quotas (ITQs) can give fishers incentive 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, more well-funded fishing companies at the expense of more vulnerable small-scale fishers. Design of ITQ programs, and overall regulation of fisheries, must be sensitive to the socioeconomic factors of fisher communities that vary considerably among countries. (c) CEA (2012). (d) Summarized from CEA (2012). (e) Worm et al. (2009). (f) Agnew et al. (2009). (g) Summarized from CEA (2012).

Figure B2.1 | A combination of rights, markets, and governance strategies can contribute to sustainable fisheries



Source: Adapted from CEA (2012).
 Note: Not exhaustive.

Figure 3 | Aquaculture production is expanding to meet world fish demand (million tons)

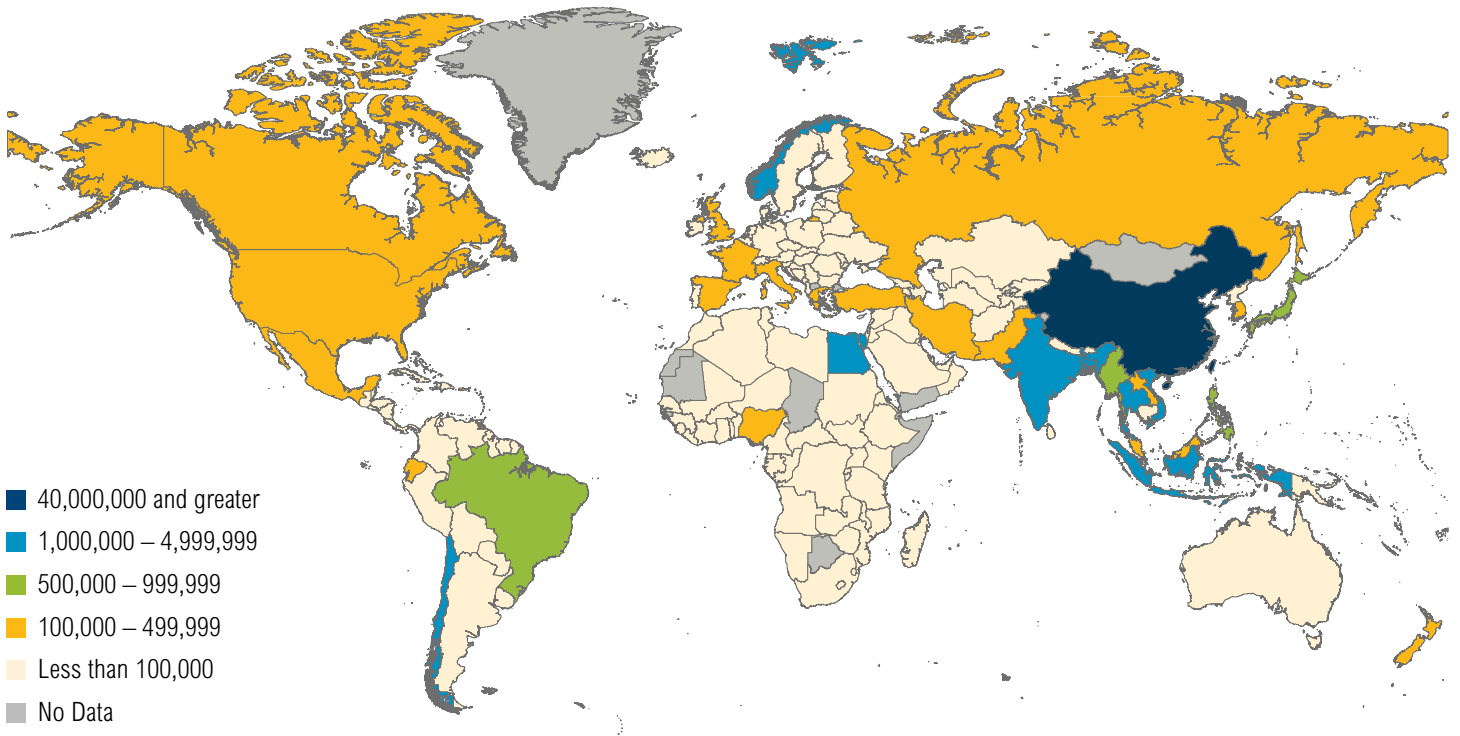


Sources: FAO (2014b), FAO (2013), FAO (2012b), FAO (2012c).

As the wild fish harvest has plateaued, aquaculture has grown to meet the world's demand for fish (Figure 3). Aquaculture is diverse, with more than 500 species grown, and occurs in nearly every country in the world (Figure 4).²¹ Asia accounts for nearly 90 percent of global aquaculture production, and China alone for 62 percent (Figure 5). Sub-Saharan Africa has the fastest growing industry by rate of growth—at more than 20 percent per

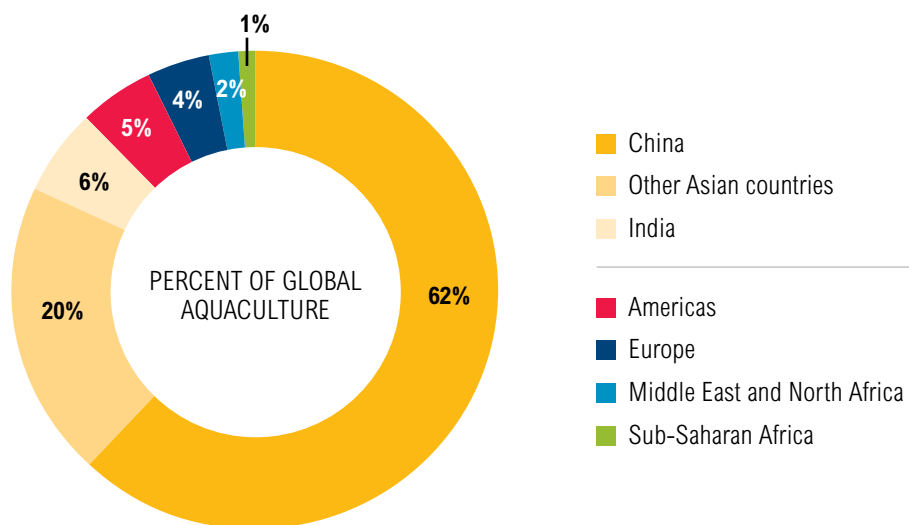
year between 2007 and 2012—but from a low baseline, as the region currently contributes less than 1 percent of global production. From the standpoint of absolute growth in aquaculture production between 2007 and 2012, Asia still dominates, but a diverse set of countries including Norway, Brazil, Egypt, Chile, and Nigeria also experienced strong growth.²²

Figure 4 | Aquaculture production occurs around the world but is concentrated in Asia (tons, 2012)



Source: FAO (2014b).

Figure 5 | Nearly 90 percent of aquaculture production is in Asia (100% = 66.6 million tons)



Source: FAO (2014b).

Notes: Data are for 2012. Production in Oceania (not shown here) is less than 0.5 percent of world total.

Globally, FAO estimates that aquaculture provided almost 19 million on-farm jobs in 2012, 96 percent of which were located in Asia (Table 2).²³ When accounting for secondary sectors such as fish processing and marketing, as well as for workers' families, the number of people reliant on aquaculture for a living rises to more than 100 million.²⁴

Women are actively involved in aquaculture value chains—especially as workers in hatcheries and fish processing plants, and as fish sellers or traders. However, a lack of gender-disaggregated employment data makes it difficult to accurately understand and effectively address gender issues in aquaculture, such as income inequality (Box 3).²⁵

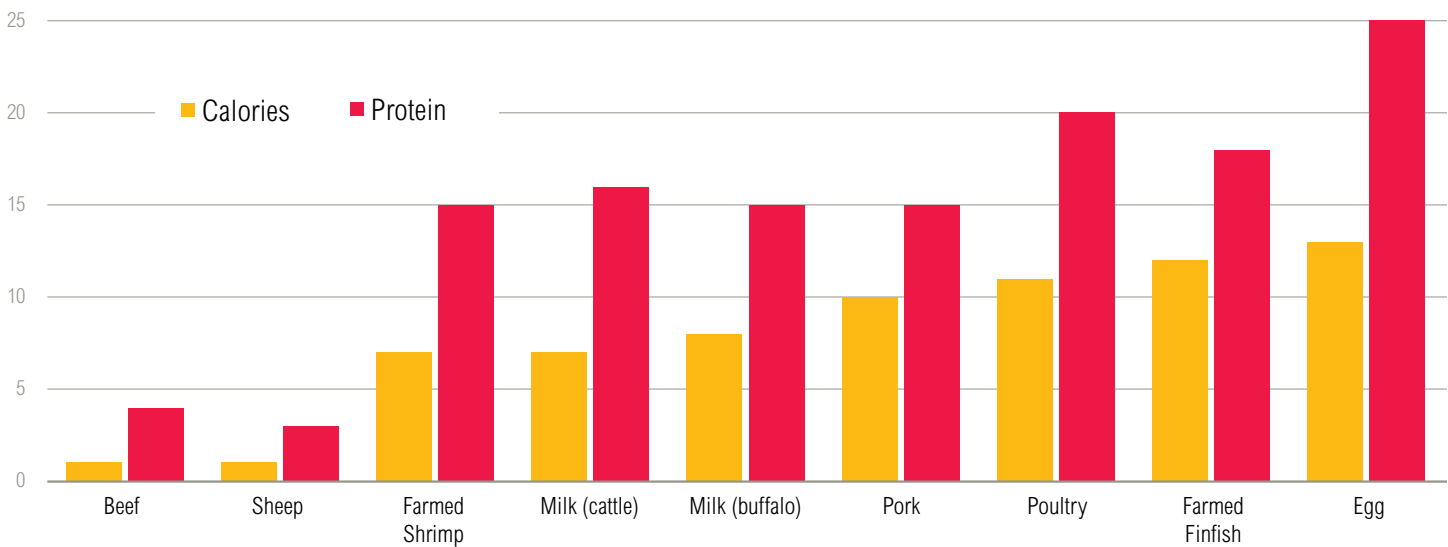
Table 2 | **Aquaculture Employment and Productivity of Aquaculture Labor by Region**

REGION	AQUACULTURE EMPLOYMENT (THOUSANDS OF ON-FARM JOBS)					PRODUCTIVITY, 2012	
	1995	2000	2005	2010	2012	AQUACULTURE PRODUCTION (THOUSAND TONS)	PRODUCTIVITY OF LABOR (TONS OF FISH PER WORKER)
Africa	65	91	140	231	298	1,485	5.1 ^a
Asia	7,762	12,211	14,630	17,915	18,175	58,896	3.2
Europe	56	103	91	102	103	2,880	27.8
Latin America and the Caribbean	155	214	239	248	269	2,594	9.7
North America	6	6	10	9	9	593	59.3
Oceania	4	5	5	5	6	184	32.7
World Total	8,049	12,632	15,115	18,512	18,861	66,633	3.5

Sources: FAO (2014a), Valderrama et al. (2010) (Africa productivity figures).

Notes: Estimates for 1995 were based on data available for a smaller number of countries and, therefore, may not be fully comparable with those for later years. Numbers may not add correctly due to rounding. (a) While FAO (2014a) does not disaggregate aquaculture 2012 labor figures for the African continent, according to Valderrama et al. (2010), labor productivity in North Africa in 2005 was 8.8 tons of fish per worker, versus 0.5 tons of fish per worker in sub-Saharan Africa.

Figure 6 | **Farmed finfish are among the most efficient sources of animal protein (percent or “units of edible output per 100 units of feed input”)**



Sources: Terrestrial animal products: Wirsenius et al. (2010) (extra unpublished tables), Wirsenius (2000).
 Finfish and shrimp: WRI analysis based on USDA (2013), NRC (2011), Tacon and Metian (2008), Wirsenius (2000), and FAO (1989).
 Note: “Edible output” refers to the calorie and protein content of bone-free carcass. All calculations refer to farmed animals.

In a resource-constrained world, aquaculture could be an attractive option for expanding animal protein supply. Because finfish are cold-blooded, excrete waste nitrogen directly as ammonia, and have bodies supported by water, they devote less energy to metabolism and bone structure than terrestrial animals. As a result, most farmed species convert feed into edible meat quite efficiently. Farmed finfish are similar in feed conversion efficiency to poultry (Figure 6), and much more efficient than beef and sheep.²⁶ Furthermore, because aquaculture is relatively young compared with terrestrial livestock production sectors, it

has great scope for technical innovation to further increase its resource efficiency.²⁷

Another group of common aquaculture stock, filter feeders, can be even more efficient. Filter-feeding carp species, clams, mussels, scallops, and oysters obtain all their food from plankton and from dead and decaying organic matter suspended in the surrounding water. Thus, there is no “food-out/terrestrial feed-in” ratio. Furthermore, filter feeders provide the added benefit of removing excess microalgae and nutrient pollution from lakes and coastal waters.²⁸

Box 3 | Enhancing Opportunities for Women in Aquaculture

Women are becoming increasingly involved in aquaculture—probably more so than in the wild fisheries sector. Women benefit from aquaculture through increases in employment opportunities, income, and access to nutritious food. And in developing countries, fish provide essential micronutrients for maternal health that are often lacking in diets.

However, a general lack of gender-disaggregated data—on employment, income, and other benefits from aquaculture—limits understanding of and action on gender equality issues across the aquaculture industry. Still, the fragmented data available begin to paint a picture:

- Men tend to own and operate fish farms. They also tend to be responsible for pond and cage construction and maintenance, stocking, and harvesting. For example, in Africa, women own or manage only 16 percent of fish farms and play a minor role in fish production.
- Women tend to dominate the fish processing and marketing sectors. In Panama, only 7 percent of workers in the production sector are women, but women make up 80 percent of workers in fish processing plants. In Africa, women play a large

role in fish processing and marketing, but much of their labor is unpaid or unreported.

- In places where jobs are dominated by women—like in the fish processing sector—managerial jobs are usually still held by men. Even in countries like Norway and New Zealand, where gender income gaps are relatively low, this pattern persists.
- Education can give women access to a greater range of employment in aquaculture, but even when well educated, women can have less control over resources and decision making than men because of sociocultural and economic factors (e.g., legal rights to assets, cultural norms).
- Data on women's participation in university education in aquaculture (in Asia, Europe, Africa, and the United States) show that while there were very few women studying aquaculture in the 1970s, by 2010 most programs taught classes composed of 30–60 percent women. While data on aquaculture training and vocational programs is even more scattered, the pattern is similar—women's participation is still less than men's, but is on the rise. In many countries, women's participation in training programs may

be low because of competing domestic responsibilities and low literacy levels.

Today, gender remains largely overlooked in aquaculture policy conversations. Development plans, private sector investments, and advocacy programs related to aquaculture rarely mention issues of gender equality. Williams et al. (2012) recommend the following strategies to help integrate gender concerns into conversations around aquaculture development:

- Collect gender-disaggregated data
- Set targets (e.g., participation in training programs, employment in institutions)
- Design aquaculture development plans and programs with gender issues in mind (e.g., cultural norms, resource tenure issues, levels of education, workloads, motivation to participate) to target and remedy drivers of gender inequality
- Train aquaculture policymakers, researchers, and extension agents in gender issues (e.g., drivers of gender inequality and ways to promote equality) so they incorporate them into their work.

Source: Summarized from Williams et al. (2012).

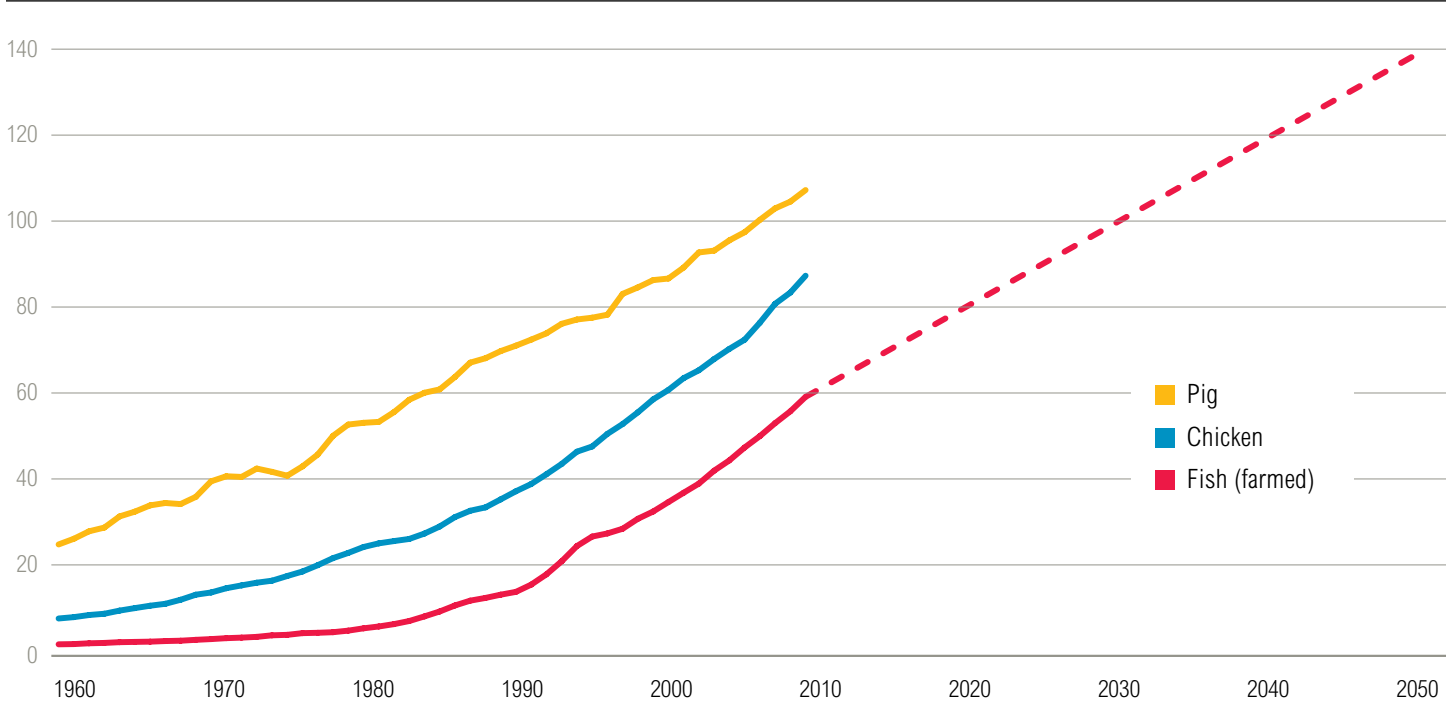
GROWTH OF AQUACULTURE PRODUCTION TO 2050 AND POSSIBLE SOCIOECONOMIC BENEFITS

Published projections of future aquaculture production growth are based on models that forecast fish production as far into the future as 2030, using estimates and assumptions of fish supply and demand, health of wild fisheries, fish prices, population growth, GDP growth, and technological progress.²⁹ Summarizing these studies, and noting that aquaculture growth has always tended to outstrip projections in the past, Hall et al. (2011) estimated that aquaculture production will grow from 60 Mt in 2010 to 100 Mt by 2030.

This projection implies linear growth at 2 Mt per year, similar to the observed recent trends in farmed fish, chicken, and pig production (Figure 7). Assuming that similar drivers of growth (e.g., population growth, income growth, urbanization) will hold to 2050,³⁰ we extended this same 2 Mt per year growth rate from 2030 to 2050 to arrive at an estimated production of 140 Mt of aquaculture production in 2050.

An increase in aquaculture production to 140 Mt in 2050—or 2.3 times its 2010 level—could deliver significant food security and development benefits. This level of growth would add 57 trillion calories to the annual global food supply relative to 2006, enough to close 1 percent of the “gap” between food available in 2006 and that needed

Figure 7 | Aquaculture production could more than double by 2050 (million tons)

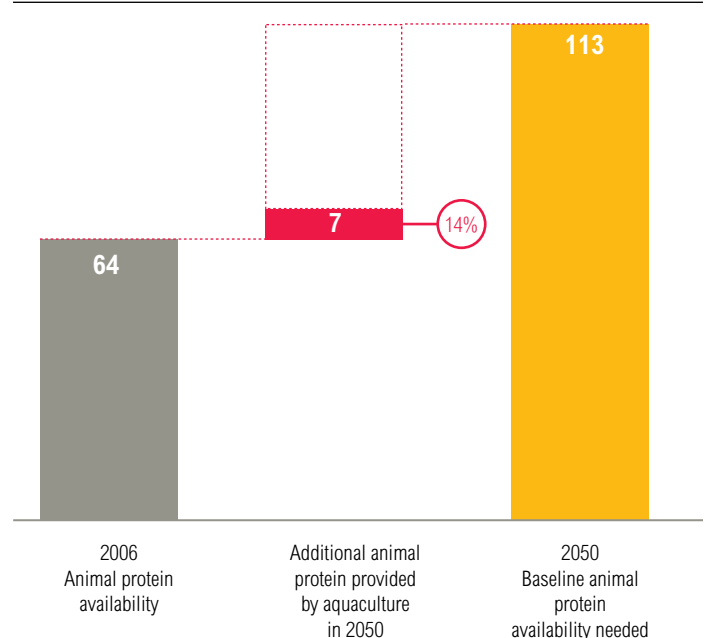


Sources: Production data 1961–2010: FAO (2014b), FAO (2014c). Aquaculture production projections 2011–2050: Authors’ calculations assuming a linear growth rate of 2 Mt per year during this period, from a baseline of 60 Mt in 2010.

in 2050 to adequately feed 9.6 billion people, as described in the interim findings of *Creating a Sustainable Food Future*.³¹ More significantly, this level of growth would boost annual fish protein supply to 16 Mt, or 7 Mt above 2006 levels.³² This increase would meet 14 percent of the necessary increase in global animal protein supply estimated by FAO for 2050 (Figure 8).³³

As for economic development, this level of aquaculture production growth could significantly boost income and employment (Table 3), particularly in developing countries where most aquaculture growth is likely to occur.³⁴ As a comparison, these benefits would far outpace the rate of population growth.³⁵ Income and employment from aquaculture development might also help compensate for projected employment losses in the wild fishing sector—and even help reduce fishing pressure in coastal areas—to the extent that aquaculture could be an alternative livelihood for fishers.³⁶

Figure 8 | Increasing aquaculture production to 140 Mt could close 14 percent of the “animal protein gap” by 2050 (global annual animal protein availability, million tons)



Source: WRI analysis based on Alexandratos and Bruinsma (2012).

Table 3 | Possible Social and Economic Benefits of Aquaculture Production in 2050

SOCIOECONOMIC INDICATOR	2010	2050	GROWTH RATE 2010–50 (PERCENT)	ASSUMPTIONS ABOUT THE 2010–50 PERIOD
Aquaculture production (fish)	60 Mt	140 Mt	133	Wild fish production declines 10 percent, population growth and rising incomes lead to continued strong growth in world fish consumption
Aquaculture value	\$120 billion	\$308 billion	157	Real prices of fish rise (on average) by 10 percent ^a
Aquaculture livelihoods (jobs plus dependents)	100 million	176 million	76	Average family sizes remain constant, aquaculture labor productivity continues to grow at 2000–10 historical rate ^b
World population	7.0 billion	9.6 billion	37	Based on UNDESA (2013), medium fertility scenario

Source: Authors' calculations.

Notes: (a) As a baseline estimate, we multiply farmed fish value in 2010 by 2.33 (140 Mt in 2050 / 60 Mt in 2010) to arrive at \$280 billion. The World Bank, FAO, and IFPRI (2013) project that real prices of all farmed fish will rise between 2010–30, by 5 to 10 percent depending on the species. We therefore believe that a global real price increase of 10 percent by 2050 is reasonable. (b) As a baseline estimate, we multiply aquaculture livelihoods in 2010 by 2.33 to arrive at 233 million people. However, fragmented evidence from across the aquaculture industry suggests that as the industry matures, fewer jobs are created per unit of fish produced because of the economies of scale that come with industry expansion and intensification of production methods. FAO data show that between 2000 and 2010, world aquaculture production grew by 82 percent while aquaculture employment grew by only 47 percent (FAO 2014a, FAO 2014b, see also Table 2). A similar trajectory between 2010 and 2050—where the aquaculture employment growth rate is only 57 percent of the aquaculture production growth rate—would still lead to the industry providing livelihoods for 176 million people by 2050.

SUSTAINABILITY CHALLENGES OF AQUACULTURE

Aquaculture growth could enhance food security and provide development benefits in coming decades. But as aquaculture has emerged as a significant food production system on a global scale, concerns about its environmental and social impacts have emerged as well. As in other animal production sectors, several important aquaculture inputs—land, freshwater, feed, and energy—are associated with significant environmental impacts. At the same time, the availability of these inputs is limited, and will likely become even more limited in the future. Unless the aquaculture industry is able to boost productivity, the limited availability of these inputs may constrain its future growth.³⁷ Furthermore, competition over these increasingly scarce inputs can lead to conflict with other agricultural, industrial, and domestic users.³⁸ Other common environmental and social critiques of aquaculture focus on disease and the effects of escaped farmed fish on wild fish; the use of wild fish for seed;³⁹ and the safety, nutritional value, and affordability of farmed fish.⁴⁰

Fortunately, the aquaculture sector has greatly increased its resource use efficiency and environmental performance in recent years (see Appendix for case studies from several countries). We discuss recent global trends below, focusing especially on land, freshwater, feed, and energy—four important impact (and constraint) categories for which global-level, quantitative data are available.

Land Use

Impacts and constraints: In 2010, global aquaculture occupied an estimated 18.8 million hectares (Mha) of land—an area roughly the size of Syria—including 12.8 Mha of inland (freshwater) areas and 6.0 Mha of coastal (brackish water) ponds. Aquaculture also indirectly used an additional 26.4 Mha that year—an area larger than the United Kingdom—to grow plant-based feeds.⁴¹ Combined, aquaculture occupied about 1 percent of global agricultural land.⁴² An oft-cited concern is that clearing mangroves for shrimp and finfish farms in Asia and Latin America and converting wetlands for aquaculture facilities can lead to loss of habitat and ecosystem services and contribute to climate change.⁴³

Direct land availability is a key constraint for aquaculture growth; in Asia, little land is available for aquaculture (or any agricultural) expansion.⁴⁴ A key challenge, therefore, will be for aquaculture to more than double production by 2050 with no or minimal land expansion—and to limit any needed expansion to economically and environmentally low-value areas.⁴⁵ An additional challenge will be for aquaculture to minimize the indirect land use impacts from plant-based feeds as production grows.

Trends: While the average fish pond on a global basis produces only 2–3 tons of fish per hectare per year (t/ha/yr), intensive (Box 4) carp ponds in China and India now produce 15 t/ha/yr, and intensive catfish ponds in Vietnam now produce more than 100 t/ha/yr.⁴⁶ Intensive production in cages and recirculating systems can be even more efficient—yielding 500 t/ha/yr or more.⁴⁷ Mangrove clearance for shrimp farms has largely stopped, thanks to mangrove protection policies in affected countries and the siting of new, higher-yield farms away from mangrove areas.⁴⁸ And marine aquaculture uses no land at all.⁴⁹

Box 4 | **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) pond farms. Yields from intensive cage, raceway, or recirculating systems can be higher still. In general:

- **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, requiring a higher level of management control and leading to 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.

Because of the strong links between production intensity, resource use, and environmental impacts, production intensity is a recurring theme throughout this paper.

Sources: Hall et al. (2011), Bunting (2013), Dugan et al. (2007).

Water Use and Pollution

Impacts and constraints: In 2010, aquaculture consumed an estimated 201 cubic kilometers (km³) of freshwater, equal to approximately 2 percent of global agricultural water consumption.⁵⁰ 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 feed also consumes water.⁵¹ However, freshwater is becoming increasingly scarce in many aquaculture-producing areas because of upstream dams and diversion of water for agriculture and urban uses.⁵²

Aquaculture not only consumes freshwater, but also can cause 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.⁵³ 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.⁵⁴ Conversely, “upstream” pollution from agriculture or municipal uses can constrain aquaculture production, and individual fish farmers often have little control over the quality of shared water resources.⁵⁵

Trends: Intensification of production and greater recirculation of water are leading to increases in aquaculture’s water use efficiency.⁵⁶ Extensive pond aquaculture can consume more than 10,000 cubic meters of water per ton (m³/t) of fish produced because of the need to drain and fill ponds and replace water lost through seepage and evaporation.⁵⁷ More intensive operations can consume much less (2,000–5,000 m³/t), and cages and recirculating systems consume virtually no freshwater.⁵⁸

Improvements in technology and management are leading to decreases in water pollution from aquaculture. A recent study estimated that while global freshwater finfish aquaculture production grew from 1.2 Mt in 1970 to 32.1 Mt in 2010 (a 27-fold increase), the release of nitrogen from aquaculture systems into the freshwater aquatic environment grew from 0.06 Mt to 1.2 Mt (only a 20-fold increase) and phosphorus release grew from 0.01 to 0.1 Mt (only a 10-fold increase) during that period. Results were similar for marine finfish production.⁵⁹ Researchers attri-

bute much of this pollution reduction to improved feeds and feeding practices, which increased digestibility and decreased wastes.⁶⁰ Improved management practices, such as using settling ponds before releasing wastewater, and advances in production technology, such as recirculating pond or tank systems and biofloc technology⁶¹ (Appendix, Case Study 7) or integrated aquaculture (Appendix, Case Study 8), can also reduce waste production from aquaculture.

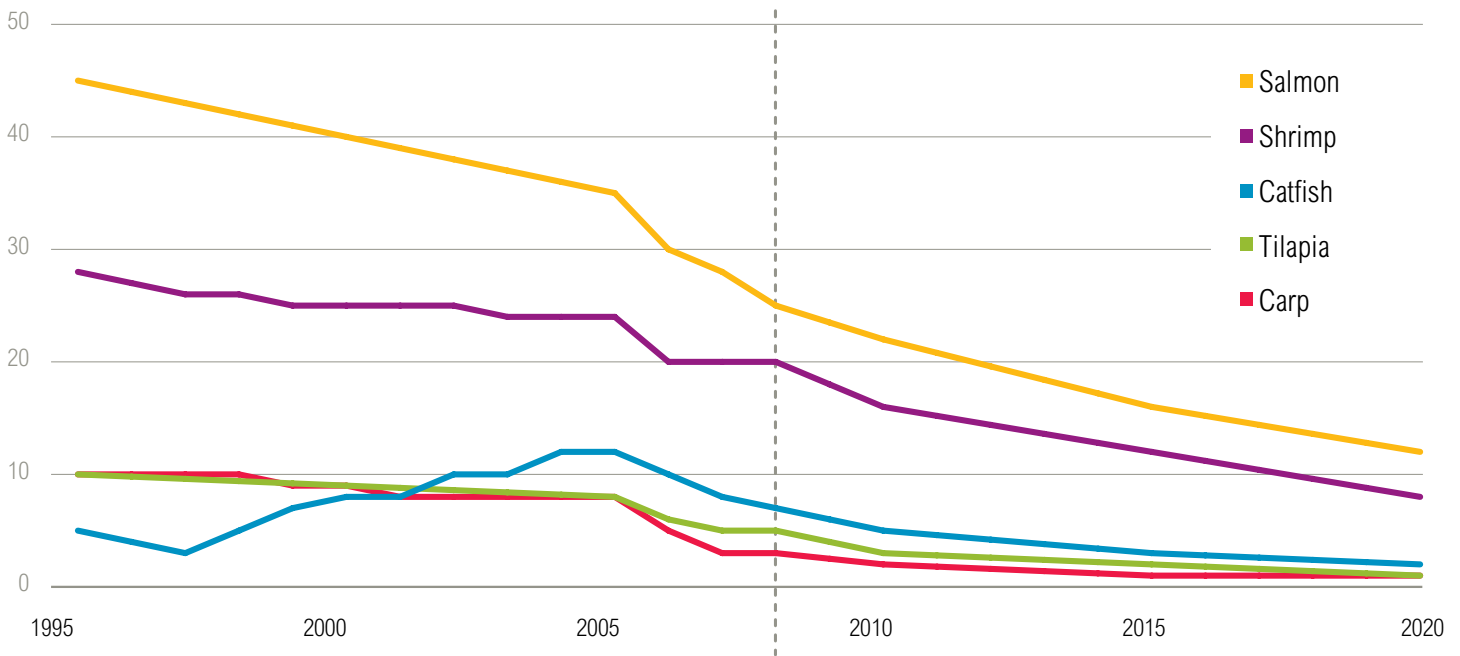
Feed Use

Impacts and constraints: In 2008, at least 60 percent of aquaculture production relied on some form of feed, whether fresh feeds (e.g., crop wastes), feed mixed and processed on the farm, or commercially manufactured feed.⁶² Carnivorous⁶³ species, such as salmon, shrimp, and many other marine finfish, tend to rely on wild-caught fish (in the form of fishmeal and fish oil in commercially man-

ufactured feeds) to receive adequate protein and lipids in their diets.⁶⁴ Conversely, roughly 80 percent of aquaculture production consists of omnivores, herbivores, and filter feeders that consume little to no fish-based ingredients.⁶⁵ Commercial feeds for omnivores and herbivores tend to contain cereals (e.g., maize, wheat, rice, barley), oilseeds (e.g., soy, canola), and pulses (e.g., peas), often in the form of meals and oils.⁶⁶

Aquaculture’s use of wild fish for feed raises two concerns. 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 2012, 16 Mt of wild fish (or roughly one-fifth of the marine catch) was converted to fishmeal and fish oil, most of which was consumed by aquaculture.⁶⁷ Second, the use of wild fish for aquaculture feed may reduce the amount of wild fish

Figure 9 | **The aquaculture industry has reduced the share of fishmeal in farmed fish diets (percent of fishmeal in fish feed)**



Note: Fishmeal use varies within and between countries; the figures presented are global means. Data represent observations between 1995-2008, and projections for 2009-2020.

Sources: FAO (2014b), Tacon and Metian (2008), Tacon et al. (2011).

available for direct human consumption. While there is very limited market demand for direct consumption of the small fish harvested for feed, some believe that the use of bycatch⁶⁸ as aquaculture feed may have led to decreases in food availability in parts of Asia, where bycatch traditionally provided food for the poor near fishing centers.⁶⁹

The fact that the supply of fishmeal and fish oil from wild sources is already near its historical highs and ecological limits represents a clear constraint to aquaculture production growth, particularly of farmed carnivorous fish.⁷⁰ 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.⁷¹

Trends: Faced with a limited supply of fishmeal and fish oil from wild sources, the aquaculture industry has worked hard to reduce its reliance on these ingredients. Globally, the shares of fishmeal and fish oil in farmed fish diets have fallen significantly since 1995, and are projected to further decline by 2020 (Figure 9).⁷² The industry is also working to lift this constraint by using “recycled” fishmeal derived from wild fish processing waste (rather than whole wild fish); in 2012, 35 percent of fishmeal used in aquaculture feeds was derived from fish processing wastes.⁷³ And the proportion of fishmeal derived from farmed fish is growing, with species such as Vietnamese striped catfish—which consume low amounts of fishmeal themselves—becoming net fishmeal producers.⁷⁴ However, as discussed earlier, substitution of fish-based feed ingredients with plant-based ingredients (e.g., soy) tends to increase pressures on land and water.

Energy Use and Greenhouse Gas Emissions

Impacts and constraints: In 2010, aquaculture production contributed about 332 million tons of carbon dioxide equivalent (CO₂e) in greenhouse gas emissions, equal to about 5 percent of emissions from agricultural production and less than 1 percent of total global anthropogenic emissions.⁷⁵ Aquaculture’s emissions arise from on-farm energy use (mainly to pump water to maintain adequate water quality); feed production (e.g., capture and processing of wild fish into fishmeal and oil, crop production, processing of crops into feed ingredients, production of inorganic fertilizers used as aquaculture inputs); transportation, processing and packaging of produce; and disposal of wastes. Aquaculture’s largest energy demands tend to occur on the farm and for feed production.⁷⁶ Untreated pond sediments can lead to methane emissions.⁷⁷

Conversion of land and coastal habitats for aquaculture development—especially carbon-rich ecosystems such as mangroves, seagrass beds, and wetlands—also contributes to climate change. Much aquaculture development, however, occurs in agricultural areas (e.g., former rice paddies) where any net change in carbon sequestration depends on the type of farming being replaced and whether new lands must come under agriculture to replace the lost crop production.⁷⁸

Trends: As the aquaculture industry intensifies production, it is also becoming more energy-intensive. Intensive aquaculture production systems generally have the highest energy needs, as they rely most heavily on pumps to maintain oxygen levels.⁷⁹ Intensive systems are also the most vulnerable to fluctuations in energy prices and interruptions in energy supply.⁸⁰ That said, increased on-farm greenhouse gas emissions from intensive systems may be partially offset by reductions in emissions from reduced land conversion (as has been observed in shrimp production in Thailand—see Appendix, Case Study 3).

Other Sustainability Concerns about Aquaculture

Other concerns about the environmental and social sustainability of aquaculture include:⁸¹

- **Disease and parasites.** Infectious disease has devastated shrimp production in parts of Asia, and Early Mortality Syndrome (first noted in 2009) presents ongoing threats to the shrimp sector. Parasites, such as sea lice, have caused problems to salmon production, most recently in Chile.⁸² Diseases and parasites can also be transferred from farmed to wild fish (and vice versa) in open production systems.⁸³
- **Escapes and genetic contamination.** Farm-raised fish can escape from aquaculture facilities or be intentionally released. These escaped fish can breed with, outcompete, or prey on native fish, altering ecosystem structure and composition.⁸⁴
- **Use of wild fish for seed.** Besides their use in aquaculture feeds, wild fish, especially marine species, are also used for juvenile stock or seed fish for aquaculture. Excessive harvesting of juveniles can adversely affect wild fish populations.

- **Food safety.** Concerns include excessive antibiotic use spreading antibiotic resistance in human pathogens (e.g., *Salmonella*), and the potential for chemical contamination in farmed fish (e.g., persistent organic pollutants, pesticides, heavy metals) which could be harmful to consumers.⁸⁵
- **Human nutrition.** Farmed fish tend to have higher fat content and possibly lower proportions of important long-chain omega-3 fatty acids than wild fish. Nonetheless, one should note that farmed fish are generally as lean and protein-rich as chicken.⁸⁶ Nutrient composition of fish depends on a number of factors including the species, whether the fish is wild or farmed, and the farming methods, particularly feeding.⁸⁷
- **Affordability of farmed fish.** Aquaculture is a business, and profit-driven production may not always use natural resources in the best way for food security. To date, aquaculture has tended to produce relatively large fish targeted at middle-class markets.⁸⁸ That said, in countries like 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.⁸⁹

For aquaculture growth to be sustainable, the sector must improve its productivity while at the same time improving environmental performance—thereby achieving “sustainable intensification.” Specifically, aquaculture must:

- Advance socioeconomic development
- Provide safe, nutritious food
- Increase production of fish relative to the amount of land, water, feed, and energy used
- Minimize water pollution, fish diseases, and escapes.

EVALUATING AQUACULTURE'S PERFORMANCE TODAY

Because the global aquaculture sector is so diverse, we disaggregate it here into a production typology, to better understand the dominant systems and their features. We then conduct a life cycle assessment of the relative environmental impacts of these systems.

Typology of Production Systems

Classifying production systems by certain features allows for performance comparisons:⁹⁰

- **Country.** Production practices can differ widely among and within countries.⁹¹ In 2012, 185 countries reported some aquaculture production, although the top 10 countries (all in Asia, except Norway, Chile, and Egypt) accounted for 88 percent of global production, with China alone accounting for 62 percent of production.⁹²
- **Species.** While hundreds of species are produced worldwide, just six species groups (carps, mollusks, shrimps, tilapias, catfish, and salmonids [salmon and trout]) accounted for 86 percent of global production in 2012.⁹³ The bulk of aquaculture production is of low-trophic-level⁹⁴ fish species. In 2010, 45 percent of fish produced were at trophic levels 2.0–2.5 (filter feeders and herbivores, such as mollusks and carp), 36 percent at trophic levels 2.5–3.0 (omnivores such as tilapia), and 18 percent above trophic level 3.0 (carnivores such as salmon).⁹⁵
- **Habitat/environment.** FAO aquaculture production statistics break down habitat into three categories that describe water salinity as well as geography: freshwater (inland), brackish (coastal), and marine. In 2012, 62 percent of aquaculture production took place in freshwater, with another 30 percent in marine waters and 8 percent in brackish water.⁹⁶

- **Production system.** While there are a wide variety of aquaculture production systems, four are dominant on the world scale: (1) ponds in inland (freshwater) or coastal (brackish) areas, (2) cages and pens suspended in marine or inland waters, (3) bottom culture in coastal and marine areas (e.g., oyster beds), and (4) off-bottom culture in coastal and marine areas (e.g., shellfish suspended from long lines and rafts). In 2008, approximately 64 percent of aquaculture production took place in ponds (with 56 percent of global production in freshwater ponds and 8 percent in coastal ponds), 16 percent in off-bottom culture, 12 percent in cages or pens (split relatively evenly between marine and inland waters), and 8 percent in bottom culture.⁹⁷
- **Feed.** Feed is often a key determinant of the environmental impact of aquaculture systems, and usually makes up the majority of production costs. There are at least five feed regimes:
 - **filter-feeding or extractive**, which requires no human-managed feed inputs
 - **natural**, which relies on natural productivity, but is often supplemented by locally-available crop wastes—a characteristic of extensive pond aquaculture
 - **trash**, where small or low-value fish, such as by-catch, are fed directly into aquaculture systems
 - **mash**, farm-made feed characteristic of semi-intensive aquaculture—often a mixture of ingredients available on the farm and purchased ingredients
 - **pellet**, industrially manufactured feed that fulfills all nutritional requirements and is used in intensive operations.

- **Intensity.** Intensity of production is generally split into three categories: (1) extensive, (2) semi-intensive, and (3) intensive (Box 4). In 2008, based on harvested fish weight, roughly 39 percent of aquaculture production was extensive, with another 42 percent semi-intensive and 20 percent intensive.⁹⁸

Evaluating Aquaculture’s Environmental Performance through Life Cycle Assessment

WorldFish’s *Blue Frontiers* report (2011)⁹⁹ used the life cycle assessment (LCA) method to examine, quantify and compare the environmental performance of major aquaculture production systems around the world.¹⁰⁰ This particular LCA compiled data on inputs (e.g., land, water, feed, energy) and environmental releases (e.g., waste nitrogen and phosphorus), and evaluated the potential environmental impacts associated with each.

The *Blue Frontiers* report analyzed environmental impacts of 75 major aquaculture production systems that accounted for 82 percent of total world aquaculture production in 2008.¹⁰¹ For this working paper, WorldFish and Kasetsart University updated the *Blue Frontiers* data to assess the environmental performance of aquaculture in 2010.¹⁰²

In Table 4, we accompany these results with socioeconomic data to rate major aquaculture production systems against the *Creating a Sustainable Food Future* criteria. The result is a mixed picture. We also include data to compare the environmental performance of aquaculture with that of terrestrial animal meat production.

Table 4 | **Social, Economic, and Environmental Performance of Aquaculture (~2010)**

SPECIES GROUP	DEVELOPMENT AND FOOD SECURITY						
	PRODUCTION (MILLION TONS, HARVESTED WEIGHT)		FARM GATE VALUE (US\$ BILLIONS)		FARM GATE PRICE (US\$ / kg)	EDIBLE PROTEIN CONTENT (THOUSAND TONS)	
Carps	25.4	38.1%	36.8	26.6%	1.45	2,751	46.7%
Mollusks	15.2	22.8%	16.1	11.7%	1.06	470	8.0%
Shrimps	4.8	7.2%	22.1	16.0%	4.57	405	6.9%
Tilapias	4.5	6.8%	7.7	5.5%	1.70	488	8.3%
Catfish	3.9	5.8%	6.1	4.4%	1.57	422	7.2%
Salmonids	3.2	4.8%	15.3	11.1%	4.73	350	5.9%
All six species groups	57.1	85.6%	104.0	75.3%		4,886	82.9%
World aquaculture	66.7	100.0%	138.0	100.0%	2.07	5,895	100.0%
TERRESTRIAL LIVESTOCK							
Pork	108.5		164.8		1.54	11,355	
Chicken	92.7		132.1		1.43	11,676	
Beef	62.7		169.5		2.70	8,592	

Table 4 | **Social, Economic, and Environmental Performance of Aquaculture (~2010) (continued)**

SPECIES GROUP	ECOSYSTEMS			WATER			CLIMATE
	HABITAT ^a	LAND USE (ha / t EDIBLE PROTEIN) ^b	USE OF WILD FISH IN FEED (FISH-IN / FISH-OUT RATIO)	FRESHWATER CONSUMPTION (m ³ / kg EDIBLE PROTEIN)	WATER POLLUTION (kg P / t EDIBLE PROTEIN)	WATER POLLUTION (kg N / t EDIBLE PROTEIN)	GREENHOUSE GAS INTENSITY (t CO ₂ e / t EDIBLE PROTEIN)
Carps	F	12.0	0.2	61.4	97	329	47.2
Mollusks	M	0.0	0.0	0.0	-148	-136	11.1
Shrimps	B, F, M	16.4	0.8	4.4	104	422	161.7
Tilapias	F, B	7.5	0.7	15.9	82	349	40.7
Catfish	F	9.5	0.4	52.2	97	234	134.8
Salmonids	M, F	2.4	1.9	0.0	48	182	9.8
All six species groups							
World aquaculture	F, M, B	9.1	0.3	40.4	76	273	66.8
TERRESTRIAL LIVESTOCK							
Pork	T	2.0	N/A ^c	56.5	120	800	57.6
Chicken	T	3.0	N/A ^c	34.3	40	300	42.3
Beef	T	50.0–145.0	N/A ^c	112.5	180	1200	337.2

Sources: FAO (2014b), FAO (2014c), Mungkung et al. (2014) (unpublished data) (aquaculture environmental indicators), Herrero et al. (2013) (terrestrial animal land use), Mekonnen and Hoekstra (2012) (terrestrial animal water consumption), Gerber et al. (2013) (terrestrial animal greenhouse gas intensity), Flachowsky (2002) and Postrk (2003) in Hall et al. (2011) (terrestrial animal nitrogen and phosphorus emissions). Authors converted tons of harvested animal products to tons of edible protein using the global average edible protein contents of harvested animal products as reported in FAO (2012a).

Notes: Numbers may not add correctly due to rounding. Data are for the most recent years available (development and food security indicators are for 2012, aquaculture environmental indicators are for 2010, terrestrial environmental indicators are from 1997–2012). Because of the variety of studies used to compare environmental performance of terrestrial livestock production to aquaculture, and differences in methods and assumptions among studies, numbers may not be perfectly comparable; nevertheless, the authors believe that the overall conclusions are reasonable. (a) F = Freshwater, M = Marine, B = Brackish, T = Terrestrial. (b) Includes land for direct production and land used to grow feeds. Estimates for pork and chicken are global averages; estimates for beef are for mixed grazing and crop-based systems in humid and temperate zones. The beef calculation assumes, in addition to cropland, the devotion of 615 million hectares of grazing land to ruminant livestock production in mixed humid and temperate systems. (c) Although pigs and chicken do consume a small amount of fishmeal as part of their diets, the ratio is so small that a “Fish-in/livestock-out” ratio is not very meaningful.

Table 4 provides further evidence that aquaculture compares well against other sources of animal protein in terms of productivity and environmental performance. As in Figure 6, farmed fish on the whole are roughly as efficient as chicken and pork across a range of indicators, and markedly more efficient than beef.¹⁰³ Table 4 also indicates that within aquaculture, species groups differ widely in terms of their environmental and socioeconomic performance. For instance:

- The majority of species groups—carp, mollusks, tilapia, and catfish—consume feeds low in fish-based ingredients and command relatively low prices. These groups equal 74 percent of global production by weight but only 48 percent of global farm gate value.
- Carp account for 38 percent of all aquaculture (by weight) and provide nearly half of all edible protein that comes from aquaculture—more than five times the amount of protein provided by the next-highest group (tilapia).¹⁰⁴
- Lesser-produced, but higher-priced species groups—shrimp and salmon—consume feeds higher in fish-based ingredients (fishmeal and fish oil). These groups equal 12 percent of global production but 27 percent of global farm gate value.
- There are environmental tradeoffs among species groups. For instance, salmon (which feed high on the food chain in the wild) have until recently relied on wild fish-based ingredients, but their land use per unit of protein produced is low since they are farmed in pens at sea and the share of plant-based feeds in their diet is relatively low (although growing). Conversely, carp (which feed lower on the food chain) require little to no fish as feed, but use a relatively large amount of land per unit of protein produced—directly for ponds and indirectly for plant-based feeds.

- Of all species groups—including all fish and terrestrial livestock—only bivalve mollusks (e.g., clams, mussels, oysters, scallops) perform well across all environmental categories. They use no land or freshwater, require no human-managed feeds, and can reduce water pollution.¹⁰⁵

The global-level, averaged data in Table 4—while important for comparative purposes—mask important ranges in environmental performance of aquaculture among and within countries. For example, although water pollution impacts vary only moderately across most species groups at the global level, actual waste outputs from aquaculture production vary enormously depending on country, production system (e.g., ponds versus recirculating systems) and farm management (e.g., use of best management practices). Hall et al. (2011) found that environmental impacts (including those related to land, water, feed, and energy) per ton of fish produced—within a single species group—varied by 50 percent or more among producer countries. This finding suggests that there are large efficiency “gaps” in environmental performance among and within countries, indicating great potential for improvements in efficiency.¹⁰⁶

Even within a single country and species group, environmental impacts can vary by level of production intensity. Intensification tends to pull impact indicators in two directions. To date, intensification has led to a decrease in the use of land and freshwater per unit of farmed fish protein. However, intensification has also led to an increase in the use of energy and of fish-based feed ingredients, as well as an increase in water pollution, per unit of farmed fish protein (Table 5).¹⁰⁷ In intensive systems, the risk of disease also rises.¹⁰⁸ These types of natural resource tradeoffs suggest that “sustainable intensification” is easier said than done—and that more intensive aquaculture systems must be managed to be as efficient as possible across all indicators of environmental performance.¹⁰⁹

Table 5 | Effects of Aquaculture Production Intensity on Productivity and Environmental Performance (2010)

CATEGORY	INTENSITY	FEED TYPE	ECOSYSTEMS					WATER			CLIMATE
			DIRECT LAND USE (ha / t EDIBLE PROTEIN)	INDIRECT LAND USE (ha / t EDIBLE PROTEIN)	TOTAL LAND USE (ha / t EDIBLE PROTEIN)	USE OF WILD FISH IN FEEDS (FISH-IN / FISH- OUT RATIO)	DISEASE RISK	WATER USE (m ³ / kg EDIBLE PROTEIN)	WATER POLLUTION (kg P / t EDIBLE PROTEIN)	WATER POLLUTION (kg N / t EDIBLE PROTEIN)	GREENHOUSE GAS INTENSITY (t CO ₂ e / t EDIBLE PROTEIN)
Bivalve mollusks	Extensive	None	0.0	0.0	0.0	0.0	Low	0.0	-148	-136	11.1
Finfish and crustaceans	Extensive	Natural	13.4	10.7	24.1	0.1	Low	77.2	90	129	13.6
Finfish and crustaceans	Semi-Intensive	Mash, Pellet	2.0	4.4	6.4	0.5	Med	36.0	101	367	71.8
Finfish and crustaceans	Intensive	Pellet	0.8	4.7	5.5	0.8	High	33.5	94	337	128.1
World aquaculture			3.8	5.3	9.1	0.3	N/A	40.4	76	273	66.8

Sources: Authors' calculations from Mungkung et al. (2014) (unpublished data), FAO (2014e) (disease risk).

Note: Data are global-level averages and mask significant variations among and within countries. Greenhouse gas emissions figures do not include emissions from land-use change.

SCENARIOS OF AQUACULTURE'S GROWTH AND ENVIRONMENTAL IMPACTS IN 2050

If aquaculture production were to grow to 140 Mt in 2050 using current practices, there would be significant environmental impacts and resource constraints. For this working paper, WorldFish and Kasetsart University (Mungkung et al. 2014) built on the global LCA in *Blue Frontiers*, and with the authors of this paper, developed a baseline production scenario for 2050 and seven alternative scenarios. Environmental impacts associated with each of the 75 major production systems, in each of the scenarios, were modeled using LCA.¹¹⁰ As in *Blue Frontiers*, the scope of analysis was from cradle to farm gate, covering raw material production (crops, fishmeal and fish oil), feed production, aquaculture production (farming), and water emissions (nitrogen and phosphorus).¹¹¹ The LCA did not cover infrastructure, seed production, land-use change, packaging and processing of produce, transport of feed and produce, or waste disposal.

The future scenarios for global aquaculture production of 140 Mt in 2050 include:

- **Baseline scenario (business as usual):** Proportions of species cultivated and production systems used (e.g., composition of feeds, intensity level of production, input efficiency) remain unchanged between 2010 and 2050. All other scenarios are variations of this baseline scenario.
- **Scenario 1: Improved efficiency in input use.** Increasing resource scarcity leads to market forces that advance technology and improve farm management. Farmers improve their production efficiency, and in each production system the same amount of farmed fish is produced with 10 percent less inputs (e.g., water, feed, energy, fertilizers) and 10 percent less nitrogen and phosphorus emissions.¹¹²

- **Scenario 2: Significant intensification.** Pond farming—the current dominant production system on the world scale—becomes significantly more intensive. Fifty percent of all farms classified as “extensive” in 2010 shift to “semi-intensive” in 2050, and 50 percent of “semi-intensive” farms shift to “intensive.” Assumptions of 2010 environmental impacts at each level of intensity (e.g., land, water, feed, energy use per ton of fish produced) remain constant.
- **Scenario 3: Shifting energy supply.** Energy resources for electricity production in 2050 reflect the current direction of energy policy in each major aquaculture producer country, resulting in a larger share of renewable sources in the global energy mix in 2050 relative to 2010.
- **Scenario 4: Adoption of current best practice.** Feed and feeding practices are a major contributor to environmental impacts of aquaculture, as they influence the demand for crops, fishmeal, and fish oil for feed—and also the amounts of aquaculture waste discharged into the surrounding environment.¹¹³ Using feed conversion ratio (FCR) as a proxy indicator of farming efficiency, all farmers in 2050 achieve the efficiency of the best farmers in 2010 in each species group and level of production intensity (e.g., all semi-intensive carp ponds in 2050 in all countries have an FCR equal to the most efficient semi-intensive carp ponds in 2010).
- **Scenario 5: Shifting species mix.** Freshwater finfish farming (e.g., tilapia, catfish, carp) becomes more prevalent relative to farming of marine species.¹¹⁴ The share in overall global production from freshwater systems rises by 20 percent in 2050 relative to 2010, with a proportional decreased share of marine species produced.
- **Scenario 6: Replacement of fishmeal and fish oil with crop-based ingredients.** Salmon and trout require high protein diets, using high levels of fishmeal and fish oil relative to other species. In this scenario, fishmeal and fish oil in salmonid diets are completely replaced by a nutritionally complete mix of crop-based ingredients (e.g., soy and other alternative protein and oil sources) by 2050.
- **Scenario 7: Combined effect of Scenarios 1, 3, 4, and 6.** This scenario investigates the environmental impact of improving efficiency (Scenario 1), shifting the energy supply (Scenario 3), adopting best practice in terms of feed conversion ratio (Scenario 4), and replacing fishmeal and fish oil with crop-based ingredients for salmon and trout production (Scenario 6). The assumptions for these four scenarios are reflected in Scenario 7.

Table 6 summarizes the results from these LCA scenarios, showing changes in overall environmental impacts (land occupation, wild fish use or “biotic depletion,” water consumption, eutrophication potential, and climate change).¹¹⁵ For each scenario, it also shows how much higher each impact is in 2050 relative to 2010. In the “business as usual” scenario, all impacts are 2.3 times higher than in 2010, reflecting the fact that productivity and relative environmental performance remain unchanged.

Table 6 | Projected Change in Environmental Impacts of Aquaculture (2010–50) in Eight Scenarios of Aquaculture Growth

 CHANGE IN PRODUCTIVITY OR PERFORMANCE
RELATIVE TO BUSINESS AS USUAL IN 2050

INCREASE NO CHANGE DECREASE

SCENARIO	PRODUCTION (Mt)	ECOSYSTEMS			WATER			CLIMATE
		DIRECT LAND OCCUPATION FOR FARMS (Mha) ^c	INDIRECT LAND OCCUPATION FOR FEEDS (Mha)	WILD FISH USED FOR FEEDS - BIOTIC DEPLETION (Mt)	FRESHWATER CONSUMPTION (km ³)	FRESHWATER EUTROPHICATION POTENTIAL ('000 t P eq)	MARINE EUTROPHICATION POTENTIAL ('000 t N eq)	CLIMATE CHANGE — GREENHOUSE GAS EMISSIONS (Mt CO ₂ e)
2010								
Baseline^a	60.0	18.8	26.4	20.2	200.9	380.6	1,360.1	332.3
2050								
Business as usual	140.0	44.0	61.6	47.2	469.0	888.5	3,175.3	775.8
x higher ^b	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
1. Improved efficiency in input use	140.0	44.0	55.6	42.9	426.3	800.1	2,879.7	705.6
x higher	2.3	2.3	2.1	2.1	2.1	2.1	2.1	2.1
2. Significant intensification	140.0	29.5	56.3	53.0	391.7	886.7	3,524.1	979.1
x higher	2.3	1.6	2.1	2.6	2.0	2.3	2.6	3.0
3. Shifting energy supply	140.0	44.0	59.4	47.2	468.1	805.0	3,119.7	343.6
x higher	2.3	2.3	2.3	2.3	2.3	2.1	2.3	1.0
4. Adoption of current best practice	140.0	44.0	54.8	35.3	456.3	870.4	2,886.6	737.4
x higher	2.3	2.3	2.1	1.8	2.3	2.3	2.1	2.2
5. Shifting species mix	140.0	46.9	70.3	45.0	535.7	988.8	3,480.3	786.3
x higher	2.3	2.5	2.7	2.2	2.7	2.6	2.6	2.4
6. Replacing fish-based ingredients with crop-based ingredients^d	2.1	0.0	0.1	0.0	5.5	10.9	55.9	1.8
x higher	2.6	N/A	3.9	0.0	2.3	2.7	3.6	2.2
7. Combined effect of Scenarios 1, 3, 4, and 6	140.0	44.0	49.0	29.4	414.1	723.2	2,577.8	276.7
x higher	2.3	2.3	1.9	1.5	2.1	1.9	1.9	0.8

Source: Mungkung et al. (2014).

Notes: (a) 2010 baseline includes total estimated impacts from the 75 production systems modeled by Mungkung et al. (2014) which represented 90 percent of world aquaculture production in 2010, divided by 90 percent to estimate complete global impact. (b) "x higher" refers to the level of production in a given 2050 scenario versus the 2010 baseline of total aquaculture production. For instance, production in 2050 (business as usual) was 2.3 times higher than in 2010. (c) Direct land occupation figures do not include sea area occupation (this applies to bivalve mollusks, salmonids, and other coastal cage/pen/off-bottom culture systems). (d) explores only salmonid production, not all aquaculture.

The results in Table 6 demonstrate plausible potential impacts associated with increasing aquaculture production from 60 Mt in 2010 to 140 Mt in 2050 in various scenarios based on the spread of best practices, shifting of energy resources or farmed species, and improvements in technology. These environmental impacts are estimated from combinations of inputs and outputs required throughout the life cycle production activities at the farm level. As a result, the environmental impact levels should not be taken as “absolute” predictions; nevertheless, they are useful to broadly show the range of potential impacts, and highlight measures to mitigate impacts and/or lift resource constraints.

The data in Table 6 yield several interesting insights:

- Holding aquaculture’s environmental impacts to 2010 levels—let alone reducing them—will be a real challenge given the sector’s projected rapid growth to 2050.¹¹⁶ All environmental impacts increase under all scenarios relative to 2010 levels—except Scenario 7, where greenhouse gas emissions slightly decrease from 2010 levels.
- Under most scenarios, most impacts roughly double between 2010 and 2050, although impacts range from slightly decreasing (e.g., greenhouse gas emissions under Scenario 7) to tripling (e.g., greenhouse gas emissions under significant intensification, Scenario 2).
- The increasing cost of inputs will likely drive changes in management practices and some increase in efficiency (Scenario 1), but policies will be necessary to further mitigate environmental impacts.
- Improved efficiency in input use (Scenario 1), shifting energy supplies (Scenario 3), and lowering feed conversion ratios (FCRs) in line with the best performers (Scenario 4) all seem to reduce environmental impacts relative to the “business as usual” scenario with no impacts worsening under these scenarios. However, even under these scenarios, many impacts will double from 2010.
- In several scenarios, the effects on impacts relative to “business as usual” are mixed. Encouraging intensification of pond systems (Scenario 2), shifting the species mix toward freshwater species (Scenario 5), and replacing fish-based feed ingredients with crop-based ones (Scenario 6) offer mixed results and tradeoffs across the impact categories. For instance, relative to “business as usual,” a shift toward freshwater species would reduce demand for wild fish as feed but increase land and water use, water pollution, and greenhouse gas emissions. A deeper analysis of the tradeoffs under different scenarios, with more detailed data, is needed to provide insights at finer scales (e.g., national level).
- Because significant intensification will likely occur (Scenario 2) because of land and freshwater constraints, solutions to make intensification sustainable must be aimed at mitigating its negative impacts (the rise in wild fish use, energy use, and water pollution)—and lifting resource constraints.¹¹⁷ As an example of an important constraint, Scenario 2 estimates a demand in excess of 50 Mt of wild fish for feed in 2050, but the wild fish catch (for nonfood purposes) is not likely to rise much beyond the current level of 22 Mt. Furthermore, Scenario 2 estimates that greenhouse gas emissions would rise to nearly 1 Gt CO₂e by 2050—a level equal to roughly one-sixth of global emissions from all direct food production in 2010.¹¹⁸ In a world where agriculture will need to reduce greenhouse gas emissions between 2010 and 2050 in order to contribute to stabilizing the global climate, this high level of emissions from aquaculture would make such a goal more difficult.¹¹⁹
- Some analysts believe that land and water scarcity will cause the proportion of farmed marine fish species to actually increase relative to freshwater species between now and 2050. Such a scenario would essentially entail a reversal of the assumptions and impacts in Scenario 5. Therefore, relative to “business as usual,” an increase in the proportion of marine species produced (holding all other factors constant) would likely raise demand for fish-based feeds, but reduce land and water use, water pollution, and greenhouse gas emissions. Such a scenario would again highlight the need to further reduce use of fish-based ingredients in the culture of marine fish species, lifting the “wild fish” constraint.
- Combining approaches represented by multiple scenarios, as seen in Scenario 7, has the potential to further reduce impacts and in some cases hold impacts at or below 2010 levels. Therefore, to substantially reduce aquaculture’s environmental impacts relative to “business as usual,” a variety of solutions must be implemented at the same time.

CASE STUDIES: LEARNING FROM THE PAST

What factors caused past improvements in productivity and environmental performance, and what barriers stand in the way of future improvements? Table 7 lists the eight case studies of aquaculture systems detailed in the Appendix, showing which cases address the key environmental impacts and constraints discussed above. These case studies include a mix of major production systems that have improved productivity and environmental performance in recent years (e.g., carp in China, shrimp in Thailand, salmon in Norway), as well as low-impact production systems that already exhibit high productivity and performance but do not yet produce a globally significant amount of fish (e.g., recirculating aquaculture systems).

Factors Encouraging Improvements in Productivity and Performance

The eight cases in Table 7, detailed further in the Appendix, span a variety of species and production systems across many countries. However, despite this diversity, common factors associated with improvements in productivity and environmental performance emerge. Four categories of factors stand out: (1) technological innovation and adoption, (2) market forces, (3) public policy, and (4) private initiatives.

Technological innovation and adoption

Aquaculture is a young industry, and the role of technological improvement will be central to improving its productivity and environmental performance. In all eight case studies, technological innovation across the aquaculture value chain enabled improvements. For example:

Table 7 | **Case Studies of Improved Productivity and Environmental Performance**

SPECIES GROUP OR PRODUCTION SYSTEM	COUNTRY	ECOSYSTEMS			WATER		CLIMATE
		LAND USE	WILD FISH USE	FISH DISEASES, ESCAPES	WATER USE	WATER POLLUTION	ENERGY USE, GREENHOUSE GAS EMISSIONS
1. Carps	China	●	●				
2. Bivalve mollusks	United States	●	●	●	●	●	●
3. Shrimps	Thailand	●	●		●	●	●
4. Catfish	Vietnam	●	●				
5. Tilapias and catfish	Ghana, Nigeria, Zimbabwe	●	●				
6. Salmonids	Norway	●	●	●	●	●	
7. Closed systems (recirculating aquaculture systems and biofloc technology)	Various	●	●	●	●	●	
8. Integrated systems	China, Canada	●	●		●	●	●

Notes: ● = aspect is addressed in the case study. See Appendix for full details of each case study.

- A long history of farmer innovation in Asia and partnerships between farmers and researchers have allowed farmers to adapt new technologies to local conditions, blending traditional and scientific knowledge. Innovative and entrepreneurial farmers have also been instrumental in the growth of aquaculture in Nigeria and other African countries.¹²⁰
- Improved breeding and hatchery technology allowed rises in carp production in China beginning in the 1960s, shrimp farming in Thailand in the 1970s, and striped catfish farming in Vietnam in the 2000s.
- Improved feeds have led to shares of fishmeal and fish oil in Norwegian salmon diets to fall by half between 1995 and 2010, with potential for further efficiency gains. The development of local feed production in Vietnam was another enabling factor in the catfish industry boom.
- Production systems have continuously improved. Two especially exciting systems with potential for fish production at low environmental cost include recirculating systems and biofloc technology (Appendix, Case Study 7).
- New approaches to combat disease have reduced incidences of disease and reliance on chemicals. In Norway, development of vaccines and improvement of biosecurity (control and containment of diseases) has greatly reduced the need for antibiotics in salmon production. In Asian countries, better management of farms has helped control shrimp diseases, but diseases remain a problem in shrimp production.

Market forces

Scarcity of land, water, feed, and energy has increased the costs to producers and led them to increase their efficiency out of self-interest. The trend of increased resource scarcity driving efficiency and intensification is likely to continue between now and 2050. Resource scarcity has also driven private sector investment in research and innovation, ultimately resulting in efficiency improvements. For example:

- Scarce land has caused Chinese and Vietnamese fish farmers to greatly intensify production in ponds, with yields per hectare five or more times higher than the global average.

- A limited supply of fishmeal and fish oil, and competition from other sectors for these resources (e.g., the nutraceutical industry that produces fish oil pills), has driven producers of salmon in Norway and shrimp in Thailand to reduce their dependence on feed ingredients derived from wild fisheries.

Additionally, high fish prices have led farmers to intensify production, with increased profits per hectare justifying the higher production costs associated with intensification. The World Bank, FAO, and IFPRI (2013) predict that real prices of farmed fish species will continue to rise in coming decades. However, increased profit per hectare can also promote expansion of aquaculture into new areas—as has been observed with terrestrial agriculture (crops and livestock)—if complementary policies do not limit expansion.¹²¹

Public policy

Changes in public policy played a role in improving productivity and performance in every case study. Policy changes have helped to correct market failures, and have helped to stimulate technology innovation and adoption, curb pollution, direct aquaculture development onto appropriate sites, ensure food safety, and ensure the economic viability of the aquaculture sector. For example:

- Strong regulation of the salmon farming industry in Norway has driven technological innovation, reducing production costs and environmental impacts.¹²² Norway's Aquaculture Act of 2005 requires that all fish farmers have licenses to operate, guides the siting of new farms, and mandates environmental monitoring.¹²³ Almost all European countries have environmental impact assessment as a prerequisite for establishing aquaculture operations.
- Spatial planning and zoning helped establish resource use rights, protect vulnerable and valuable ecosystems, and encourage more sustainable aquaculture development in Thailand (away from mangrove areas), Norway (away from wild salmon areas), and the United States (downstream from protected “buffer zones” to maintain coastal water quality).

- Land-use policies in China designed to combat cropland loss, as well as those that constrain farmers' rights to buy and sell land, have halted expansion of aquaculture farms and forced farmers to further intensify production.
- Many governments now have fish quality (food safety) standards in place, to protect domestic consumers or provide producers access to international markets where consumers' demands are transmitted through retail chains.¹²⁴
- Fiscal incentives—such as tax holidays for domestic (including small-scale) or foreign investors, subsidized loans, or price stabilization policies—have helped establish new farms, protect farmers from price fluctuations, and stimulate local supplies of feed and seed in many countries.¹²⁵
- Publicly-funded research, extension, and training encouraged the development and spread of improved technology and production practices in China, Vietnam, Thailand, Europe,¹²⁶ and the United States.
- Development of landscape- and seascape-level planning, modeling, and monitoring systems has allowed the Norwegian government to ensure that existing and new aquaculture sites stay within the surrounding ecosystems' carrying capacity.

Private initiatives

Aquaculture industry associations have encouraged increases in environmental performance through development of standards, certification programs, and codes of conduct—such as those for responsible shrimp farming in Thailand—in response to economic and reputational risks and to open up market opportunities (especially for exports to industrialized countries, where demand for sustainably produced fish is growing, see Box 5). Industry associations, companies, nongovernmental organizations (NGOs), and universities have helped the aquaculture sector improve farm management, productivity, and performance through research, advocacy, and service delivery.

Box 5 | What Is the Role for Certification in Sustainable Aquaculture?

One response to the environmental and social issues associated with aquaculture has been the rise of private sustainability standards and certification, especially in places where state regulation has been ineffective. Since the 1990s, “best management practice” guidelines, industry standards, certification schemes, seafood guides, and codes of conduct have proliferated with the intent to create market incentives to move the aquaculture sector toward sustainability.

The greatest demand for certified aquaculture products comes from North America and Europe, where large supermarket and restaurant chains are committing to sell certified sustainable fish. Global and regional buyers are turning to certified fish in response to NGO campaigns that threaten their brands by associating them with harmful environmental and labor practices. As of 2010, there were more than 30 private and nonprofit certification standards and “seafood sustainability” information schemes.

But has certification led to greater sustainability in aquaculture? The answer is not immediately clear:

- **Certification's reach may be limited.** Private schemes currently certify less than 5 percent of global production. Furthermore, the majority of the world's “potentially certifiable” farmed fish is produced and sold in countries (e.g., China) with little consumer demand for sustainability certification.
- **Certification in aquaculture takes an enterprise-level approach.** As in agriculture certification, only farms or value chains can be certified. Therefore, the cumulative impacts of multiple farms in a particular location, or the impact of farms on surrounding ecosystems or land uses, are rarely considered. Still, some standards include indicators (e.g., benthic diversity, wastewater quality) that may be proxies for cumulative impacts.
- **Certification can be complex and expensive.** Compliance is easier for larger-scale farmers who can afford the transaction and monitoring costs, while these costs can be prohibitively expensive for smallholders.

Although private sustainability certification partly arose out of fear of underregulation by states, the assumption that developing countries are incapable of regulating aquaculture no longer holds true everywhere. Countries that have dealt with mandatory international food safety and traceability requirements, such as Thailand, demonstrate a capacity to effectively deal with sustainability issues in aquaculture. Going forward, successful certification schemes may be those that build on what states are already doing—thereby drawing on the strengths of states and the private sector.

Source: Summarized from Bush et al. (2013).

Barriers to Further Gains in Production, Productivity, and Performance

This working paper has shown that the aquaculture sector faces important resource constraints to continued production growth, including land, water, feed, and energy. Yet even if the sector is able to ease those constraints, barriers remain to increasing aquaculture production, productivity, and environmental performance at the scale necessary to sustainably meet the demand for fish in 2050.

Analysis of the case studies listed in Table 7, and further detailed in the Appendix, showed at least seven common, interconnected barriers to improvements in production, productivity, and performance: (1) off-farm externalities, (2) weak resource tenure rights, (3) economic constraints for value-chain actors, (4) limited access to information, (5) competition for resources and markets, (6) climate change, and (7) other factors outside of aquaculture.

Off-farm externalities

Aquaculture producers are likely to deal swiftly with water pollution, fish diseases, and fish escapes if their own operations are threatened. However, the cost of these environmental impacts is often borne by those outside the farm. Absent mechanisms to internalize these costs, these impacts will likely continue to occur, especially where governance is weak and producers operate with only a slim profit margin. An important challenge will be to internalize costs without significantly compromising levels of production and/or increasing producers' economic vulnerability.

In addition, most government regulations and private certification schemes tend to focus on improving farm-level management and therefore can still fail to ensure ecosystem-level or global-level sustainability. For example, many small farms clustered in a watershed can pollute a river and cause eutrophication downstream—even if each individual farmer is using “responsible” practices in line with local regulations or a certification scheme.¹²⁷

Weak resource tenure rights

In coastal and marine areas—and many inland aquatic areas—resource rights are often poorly defined or held by multiple state agencies. In these cases, it can be especially difficult to establish, grow, or improve aquaculture operations, no matter how potentially efficient or sustainable these operations may be.¹²⁸

Economic constraints for aquaculture producers and other value-chain actors

Intensification and improvement of aquaculture operations often carry added production costs. In some cases, these improvements raise the price of the consumer product enough to offset the added costs, but when they do not, the producer has no economic incentive to improve. And even if farmers might eventually receive a high enough price to justify these improvements, they might not have the capital to make the necessary initial investments in technological innovation or adoption—a particular problem for smallholders who operate with small profit margins and cannot access credit.¹²⁹ When these sustainability improvements are mandated by public regulations or private certification schemes, smallholder farmers may not be able to adapt and may be forced out of a market or out of aquaculture altogether.

Limited access to information

In addition to economic constraints and tenure issues, lack of access to information has been a major constraint to technology development and transfer in developing countries. Both a lack of skilled and experienced aquaculture extension services, as well as limited access to educational materials and newer information technologies, hamper farmer innovation and uptake of new technologies and best management practices.¹³⁰ Additionally, lack of monitoring capacity has made it difficult for countries to ensure compliance with laws and regulations designed to improve aquaculture's environmental performance.¹³¹

Competition for resources and markets

Aquaculture must compete with other economic activities for access to resources and markets—and its expansion can be seen as a threat to groups with a stake in those resources and markets. Environmentalists, the wild fishing industry, protectionists within local aquaculture industries, and coastal real estate developers have campaigned against aquaculture—sometimes justifiably, but often based on hearsay—to draw attention to aquaculture's problems and deter investment.¹³²

For example, in industrialized countries, groups opposed to aquaculture often cite examples of harmful practices (e.g., mangrove clearing for shrimp farms, high use of wild fish in salmon feed) that the aquaculture industry has

greatly mitigated over the past 20 years (Appendix, Case Study 3; Figure 9). The wild fishing industry and developed-country aquaculture industries have also questioned the safety and sustainability of farmed fish imported from developing countries—such as Vietnamese catfish (Appendix, Case Study 4). Scientifically inaccurate and outdated accusations can cause undue hardship to producers in developing countries and threaten stability of fish supplies in developed countries.¹³³

Climate change

Climate change could affect all aquaculture production—particularly through changes in the availability of resources (e.g., land, water, feed).¹³⁴ Farms in delta, 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.¹³⁵ Ocean acidification also threatens the long-term viability of shellfish aquaculture.¹³⁶ Still, climate change may also open up new production opportunities in certain areas, such as higher-latitude areas that are currently too cold for aquaculture, or coastal land areas that become too saline for agriculture but could accommodate aquaculture.¹³⁷

Other factors outside of aquaculture

A number of broader factors influence aquaculture's development and capacity to grow sustainably. For example, Table 6, Scenario 3 shows that energy policies in producer countries have the potential to greatly influence the amount of greenhouse gas emissions from the aquaculture sector. Industrialization and urbanization, governance and corruption, trade laws and flows, and infrastructure (e.g., roads, electricity, refrigeration) all provide additional constraints to (and opportunities for) sustainable aquaculture growth.¹³⁸

RECOMMENDATIONS

Resource scarcity will intensify between now and 2050, and price signals will continue to provide some incentive for producers to improve productivity and environmental performance. But the life cycle assessment summarized in Table 6 shows that the scale of projected aquaculture production growth will likely offset gains achieved from market forces alone. How can the world accelerate the necessary technological breakthroughs that will lead to further gains in productivity and performance, help farmers adopt technologies and best practices at scale, and ensure that the growth of aquaculture contributes to a sustainable food future? We offer five recommendations aimed at addressing the barriers identified in the previous section and catalyzing transformational change in the aquaculture sector.

Recommendation 1. Increase investment in technological innovation and transfer

Relative to terrestrial agriculture, aquaculture is a young industry. There is still room for science to complement traditional knowledge and help the industry become more efficient. Furthermore, increasing intensification (driven by land and water scarcity) could lead to new challenges with disease, feed availability, energy use, and economic viability (Table 6, Scenario 2). Technological advances, by scientists, researchers, and innovative farmers—and widespread uptake of improved technologies—will be necessary to allow aquaculture to grow and intensify rapidly with minimal environmental impacts. These advances will also help aquaculture adapt to a changing climate.¹³⁹

Technological advances will be needed in four interrelated areas: (1) breeding and genetics, (2) disease control, (3) nutrition and feeds, and (4) low-impact production systems.

Breeding and genetics

Fish bred for faster growth rates¹⁴⁰ could lead to more efficient use of land and sea area, water, feed, and labor.¹⁴¹ Selective breeding also could reduce disease problems, enable increased use of plant-based ingredients in feed, reduce production costs, and lead to the eventual development of truly domesticated fish that do not survive or breed in the wild, lessening problems of escapes.

However, aquaculture lags far behind crop and livestock agriculture in using selective breeding to enhance production efficiency. In 2010, less than 10 percent of world aquaculture production was based on genetically improved stocks.¹⁴² 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-produced aquaculture species group.¹⁴³

Establishing or expanding selective breeding efforts aimed at the countries and species with the highest levels of production (and absolute environmental impact)—such as carp species in China—could bring substantial efficiency gains.¹⁴⁴ And establishing national and regional domestication and breeding programs in areas of low productivity and growing fish demand—such as sub-Saharan Africa—could help meet both food security and sustainability goals and increase productivity of indigenous farmed fish species.¹⁴⁵ Recent advances in genomics (DNA analysis) also hold promise for accelerating selective breeding.¹⁴⁶

Disease control

Disease outbreaks continue to constrain aquaculture production. New technologies (e.g., advanced diagnostic technologies, vaccines, dietary supplements) and wider application of best management practices (e.g., reducing water exchange in ponds or tanks, reducing water seepage in ponds, improving feed and feeding practices, improving sanitation) will be essential to lessen risk from disease.¹⁴⁷

Nutrition, feeds, and feeding management

Feed (whether plant- or fish-based) is usually a fish farmer's largest operational cost, often accounting for 50 percent or more of all production costs.¹⁴⁸ Further research on suitable alternatives to fishmeal and fish oil in feed remains a high priority in aquaculture (Box 6). In particular, microalgae production could provide a viable fish oil substitute that uses a fraction of the land and water required for plant-based oil crops,¹⁴⁹ but further investments in research and development will be necessary to bring costs of algae-based oils below fish oil prices.

More research is also necessary to improve understanding of fish digestion and the nutritional requirements of important aquaculture species, to develop low-carbon feed ingredients with sufficient nutrient levels for farmed fish, and to optimize feeding practices to maximize efficiency and minimize waste and production costs.¹⁵⁰

Low-impact production systems

Recirculating aquaculture systems, biofloc technology, and integrated systems (see Appendix, Case Studies 7 and 8) perform well across most indicators of productivity and environmental performance. Offshore marine aquaculture, which would avoid problems of competition for space in coastal areas by locating farms in the open sea, is still in its infancy.¹⁵¹ Additional research is necessary to understand and manage tradeoffs (e.g., high energy use and greenhouse gas emissions in recirculating systems). Life cycle assessment is a particularly useful tool to investigate possible impacts of a given production system or value chain. Widespread commercial implementation of these systems will likely require a drop in production costs.

The development of new low-impact production systems will require research, and perhaps combining innovations in the areas mentioned above (e.g., breeding, feed) in ways that ease multiple resource constraints and resolve tradeoffs. Examples include combining marine finfish production with crop- or algae-based diets, or combining recirculating systems with low-carbon energy sources.

Box 6 | Alternatives to Fishmeal and Fish Oil in Aquaculture Feed

Fishmeal and fish oil are important ingredients in aquaculture feed—particularly for farmed salmon, trout, other marine finfish, and brackish-water shrimp. For the past 20 years, global fishmeal and fish oil production has been fairly stable, and given the stagnation in the global wild fish catch, this production is not expected to rise.^a Over the same time period, aquaculture production has grown significantly, and as of 2008, consumed 61 percent of all global fishmeal and 74 percent of all global fish oil.^b Therefore, alternatives for fishmeal and fish oil are essential for future sustainable aquaculture growth.

Fish (both wild and farmed) that eat other fish constitute the main source of long-chain omega-3 fatty acids to humans. 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 long-chain and are naturally present in fish, marine algae, marine mammals, krill, and human milk. Daily intake of 250 mg of EPA and DHA has been shown to benefit eye, brain, and heart health.^c However, there are currently no cost-effective alternatives to fish oil that are rich in long-chain omega-3 fatty acids, meaning that fully replacing fish oil in aquaculture feed with other animal- or plant-based oils would reduce the nutritional benefit of the farmed fish to the consumer. A first step is to more effectively ration scarce fish oil resources by using them only as “finishing feed” just prior to harvesting, thereby restoring levels of omega-3 fatty acids in the farmed fish to meet recommended dietary allowances.

Omega-3 fatty acids in fish oil have their origin in microalgae and are gradually accumulated along the food chain. Fish oil alternatives are based on the ability of microalgae to produce omega-3 fatty acids, either by direct production of microalgae or by transferring their biochemical capability to other organisms such as yeast or oilseed plants through genetic engineering (Table B6.1). However, currently available microalgal- and yeast-based omega-3 products are still more expensive than fish oil. Although it remains to be seen which technologies ultimately prove to be economically viable and socially accepted, it appears that several fish oil alternatives will be available on the market within the next few years.

Sources: (a) Naylor et al. (2009). (b) Tacon et al. (2011). (c) EFSA (2010), EFSA (2011).

Table B6.1 | Fish Oil Alternatives

PRODUCT	COMPANY	OMEGA-3 TYPE	ORIGIN	GMO ^a	PRODUCTION ^b	SCALEABLE?	AVAILABLE ON MARKET?
Fish oil	Various	EPA, DHA	Marine Fish	No	Fishery	No	Yes
Fish byproducts	Various	EPA, DHA	Marine Fish	No	Fish Processing	Limited	Yes
DHAgold	DSM	DHA	Microalgae	No	Heterotrophic	Yes	Yes
Verlasso	DuPont	EPA	Yeast	Yes	Heterotrophic	Yes	Yes
A2 EPA Pure™	Aurora Algae	EPA	Microalgae	No	Photoautotrophic	Yes	Samples
ReNew	Cellana	EPA, DHA	Microalgae	No	Photoautotrophic	Yes	Samples
Soybean oil	Monsanto	SDA ^c	Soybean	Yes	Photoautotrophic	Yes	2014–16
Canola oil	BASF	EPA, DHA	Canola	Yes	Photoautotrophic	Yes	2020
Camelina oil	Publicly funded research (UK)	EPA, DHA	Camelina	Yes	Photoautotrophic	Yes	Samples

Sources: Aurora Algae (2013), Cargill (2013), Cellana (2013), DSM (2013), DuPont (2013), Monsanto (2013), Newton and Little (2013), Naylor et al. (2009), Ruiz-Lopez et al. (2014).

Notes: (a) GMO=genetically modified organism. (b) Heterotrophic production requires starch or sugar as energy source, photoautotrophic production requires light and carbon dioxide. (c) SDA (stearidonic acid) is another omega-3 fatty acid that the human body converts relatively efficiently to EPA (Monsanto 2013).

While there are numerous initiatives directed at technological innovation and transfer, their present scale is insufficient to achieve transformational 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 smallholders in developing countries access and adopt improved technologies. 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.¹⁵²

Ratcheting up aquaculture research, development, technical support, training, and extension will require additional investments. National governments, development agencies, the aquaculture industry, international 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 private equity investment—will also be needed.¹⁵³

Where should investments in technology development and transfer be targeted? Research from Asia and Africa shows that investment in commercially-focused small- and medium-scale (SME) producers is perhaps the most cost-effective way to boost aquaculture production and employment opportunities at a large scale in developing countries.¹⁵⁴ Brummett et al. (2008) therefore suggest that national governments, development agencies, and other donors should:¹⁵⁵

- Target research, extension, and training at the growth of an SME aquaculture subsector that can maximize the number of additional off-farm economic opportunities created through the aquaculture value chain.
- Help make credit available to SME producers (e.g., through loan guarantees).
- Include NGOs and farmers’ organizations as partners in the delivery of key services such as marketing, feed, and seed supply.
- Engage larger-scale farms to participate actively in the development of the sector and help create opportunities for small-scale investors.
- Invest in marketing infrastructure including roads, retailing facilities, and ice plants.

Recommendation 2. Use spatial planning and zoning to guide aquaculture growth at the landscape and seascape level

Much of aquaculture growth to this point has been “organic” or “opportunistic” and led by a dynamic private sector. 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 future aquaculture growth must be more strategic.

Spatial planning and zoning¹⁵⁶—particularly if participatory—can lessen the inevitable conflicts among a growing aquaculture industry and other economic actors (including other agricultural production sectors) competing for the same resources (e.g., land). Planning focused at the landscape and seascape level can reduce the cumulative impacts of many individual aquaculture operations, and can help minimize risks associated with future climate change. Landscape- and seascape-level planning can also identify areas especially well-suited for aquaculture (e.g., those with access to markets and production infrastructure, deep water, fast currents, protection from storms, good water quality).¹⁵⁷

In Norway, for example, zoning ensures that new aquaculture sites stay within the surrounding ecosystem’s carrying capacity, reducing disease risk. 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). Beyond the case studies analyzed in this paper, integrated coastal zone management has helped to lessen conflict between aquaculture and other coastal resource users in Australia, Belize, Chile, the European Union, the Philippines, and Namibia.¹⁵⁸ And in China, following a severe algal bloom in 2007, the government launched the Lake Tai Master Plan, which includes provisions to remove fish cages from the lake, and to build artificial wetlands to filter runoff from upstream fish ponds.¹⁵⁹

A number of wider initiatives are already in place that promote participation in aquaculture planning and take landscape- and seascape-level concerns into account, including:

- FAO/World Bank Ecosystem Approach to Aquaculture¹⁶⁰
- Assessment of Sustainable Development of Aquaculture (EVAD) initiative, led by the French National Research Agency¹⁶¹

- Regional initiatives, such as:
 - 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
 - The European Aquaculture Technology and Innovation Platform¹⁶²
- National initiatives (e.g., Strategic Frameworks for Aquaculture Development in sub-Saharan African countries)
- Local, private sector-led initiatives linking producers and fish processors in an area to solve collective sustainability issues (e.g., fish diseases, feed supply, water quality)
- Global Aquaculture Alliance initiative on best aquaculture practices for zone management

This recommendation alone—to use spatial planning and zoning to guide aquaculture growth at the landscape and seascape level—would help tackle nearly every barrier identified in the previous section. But additional effort is necessary to accelerate the initiatives listed above, as well as similar collaborative planning efforts. In particular:

- National and subnational governments should establish legal frameworks for spatial planning, create aquaculture development plans that link to wider development plans, and invest in monitoring and enforcement to ensure plan implementation.
- Development agencies and international organizations should invest in capacity building and technology transfer in developing countries, to enable better planning, monitoring and enforcement.
- The aquaculture sector, NGOs, and communities hosting production facilities should be engaged in planning to the maximum extent possible to reduce conflicts, increase likelihood of compliance, and ensure social sustainability.

Recommendation 3. Shift incentives to reward improvements in productivity and environmental performance

Where costs are externalized—whether in the form of water pollution, interactions between farmed and wild fish, habitat destruction, or greenhouse gas emissions—realigning incentives can help internalize these costs and reward sustainable production practices. Government initiatives (e.g., regulations, standards, taxation and subsidy policies, market-based mechanisms) and private-sector led initiatives (e.g., certification, purchasing standards) can complement landscape-level planning (Recommendation 2) to realign incentives to encourage and reward sustainable production systems. These incentives should help the aquaculture industry reduce the environmental impacts of its widely used production systems, and stimulate investment in and deployment of low-impact production systems.

Shifting incentives played a role in nearly every case analyzed in this working paper, as well as others. Many countries have used regulations, including licensing, environmental impact assessment and monitoring, and wastewater discharge standards to promote more sustainable aquaculture development. For example, in Denmark, stringent wastewater standards have encouraged investment in recirculating aquaculture systems.¹⁶³ A clearly designated “lead agency” (e.g., the Ministry of Fisheries and Coastal Affairs in Norway) that coordinates aquaculture regulation can streamline processing of new licenses and monitoring of existing operations, and help to reconcile legislation that affects the aquaculture sector.¹⁶⁴ Private certification schemes and standards (Box 5) may complement state regulations, encouraging further improvements in environmental performance.

Ensuring that the design of regulations and standards—both public and private—is as participatory as possible can help ensure compliance, and reduce barriers to investment in low-impact production systems. For instance, in Canada, researchers and industry groups met with regulatory agencies and other stakeholders in 2004 to discuss the challenges associated with regulating integrated multi-trophic aquaculture (IMTA). In 2008, the Canadian Shellfish Sanitation Program was amended to recognize IMTA and provide a procedure for registration and management of IMTA sites.¹⁶⁵

A variety of fiscal incentives have reduced financial barriers to improvements in productivity and environmental performance, in both developed and developing countries. For example, tax exemptions can encourage domestic and foreign investment in aquaculture production and increase supply of necessary inputs that might otherwise be a constraint on production (such as feed or seed). Government grants and guaranteed or subsidized loans can make credit more affordable to small-scale farmers and allow them to invest in improved practices. Of course, these policies can lead to increased government expenditures and/or reductions in tax revenues, and can also create perverse incentives (e.g., growth of unsustainable forms of aquaculture) if not carefully designed and managed.¹⁶⁶ Redirecting harmful wild fisheries subsidies—subsidies that enhance fishing capacity and contribute to overfishing, which totaled roughly \$16 billion globally in 2003—to low-impact, high-productivity forms of aquaculture could contribute to reforming both wild fisheries and aquaculture without increasing strains on public budgets.¹⁶⁷

Finally, market-based mechanisms, such as programs to pay producers for ecosystem services not currently sold in the market (e.g., water quality improvement by bivalves or seaweed, carbon sequestration by mangroves) can offer direct economic incentives to reward sustainable aquaculture production. In Sweden, several communities are establishing mussel farms in a pilot “nutrient trading scheme” to reduce coastal pollution.¹⁶⁸ However, such schemes are in their infancy and have yet to be proven at a large scale.

Recommendation 4. Leverage the latest information technology to drive gains in productivity and environmental performance

Advances in information and communication technology are helping fish farmers and other aquaculture stakeholders make better decisions. These advances range from high-tech modeling and monitoring systems used to improve the environmental and economic performance of salmon farming, to systems improving traceability of farmed fish products, to increased information and learning resources for small-scale fish farmers in developing countries.¹⁶⁹

As aquaculture’s contribution to the global food supply continues to increase, debate on its merits compared with other forms of food production—as well as other possible land and water uses—will likely continue. How will

the world be able to verify if aquaculture is growing in a sustainable way?

Advances in satellite technology, digital mapping technology, ecological modeling, open data, and the spread of mobile phones and Internet access mean that global-level monitoring and planning systems that could encourage and support more sustainable forms of aquaculture development may now be possible. A 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). For example:

- 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 receive 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 (Recommendation 2), detect illegally sited operations, and target monitoring and law enforcement efforts.
- NGOs and communities could report stories of improvements in productivity and environmental performance that could serve as inspiration 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 oftentimes polarized debates around aquaculture and build coalitions in favor of sustainable aquaculture growth.

Recommendation 5. Shift fish consumption toward low-trophic farmed species

Shifting consumer preferences toward farmed fish—particularly species which sit low on the food chain and do not require large amounts of fishmeal and fish oil in their diets—would help ease pressures on wild fish stocks and marine and freshwater ecosystems.

The current global wild fish harvest is not sustainable (Figure 2), and it will be necessary to reduce wild fish catch in the short term (Box 2). Low-trophic farmed fish species, such as tilapia, catfish, and carp, use very low shares of fish-based ingredients in their diets, and filter-feeding mollusks and carp use no feed at all (Table 4, Figure 9). Increased demand for low-trophic fish species relative to “business as usual” aquaculture growth would thus lead to more efficient use of scarce fishmeal and fish oil resources.¹⁷⁰

Many experts believe that overfishing of high-trophic-level species and the rapid growth of farming of these species—which command the highest farm gate prices of all aquaculture products (Table 4)—are largely driven by market demand in industrialized countries.¹⁷¹ Looking ahead, however, at least 3 billion more people are expected to enter the global middle class by 2030, with 85 percent of this growth coming in Asia.¹⁷² If past is prologue, the new middle class members will consume more resource-intensive foods, shifting from more plant-oriented diets to more animal-intensive diets, and within fish consumption, from low-trophic to high-trophic species. In China, this trend is already occurring, as wealthier urban consumers are shifting from purchasing live fish products farmed near the point of consumption (e.g., carp) to purchasing frozen and processed fish products, such as imported salmon.¹⁷³ Therefore, the challenge will be two-pronged: (1) to shift existing fish preferences in industrialized countries toward low-trophic farmed fish species, and (2) to reduce the growth in consumption of high-trophic fish species in emerging economies. This recommendation is not relevant in regions, such as sub-Saharan Africa, where consumption of high-trophic fish species is likely to still be low in 2050.

Shifting diet preferences—which requires changing human behavior—is not easy. Food choices are influenced by a variety of interacting factors including age, gender,

health, prices, income, geography, culture, marketing, and media.¹⁷⁴ Although most efforts to shift diets have focused on educating consumers, examples from around the world show that four mutually reinforcing approaches can build on consumer education to influence food choices:¹⁷⁵

- **Disguise the diet shift.** One effective approach to changing consumers’ diets is to minimize perceived differences between the “old” and “new” food options. For example, highly-processed fish products made from white fish, such as breaded fish fillets or fish sticks, may be indistinguishable whether they are made from a wild-caught, high-trophic species (such as cod) or from a farmed, low-trophic species (such as tilapia or catfish).
- **Sell a compelling benefit.** When marketing low-trophic farmed fish species to consumers, it is most effective to highlight attributes such as affordability, convenience, taste, and health benefits (rather than environmental sustainability). The Asian tilapia and catfish industries, which have greatly increased exports to Europe and the United States in recent years, commonly cite these benefits in marketing materials.¹⁷⁶ There are also likely lessons to be learned from countries like Fiji, where farmed tilapia is increasingly accepted by consumers despite strong cultural ties to wild reef fish.¹⁷⁷
- **Maximize availability and visibility.** The more opportunities consumers have to see and buy a product, the greater chance they will notice and consider it. Positioning low-trophic farmed species more prominently in fish markets relative to high-trophic species could influence consumers’ choices. Likewise, changing public food procurement policies (e.g., in schools, hospitals, and government offices) to favor low-trophic farmed species can alter the food choices of large numbers of people, and also stimulate market demand signals for these low-trophic species.
- **Reprogram repertoires.** Promoting recipes that include low-trophic farmed fish species, using celebrity chefs to promote consumption of low-trophic species, and making consumption of high-trophic wild fish species (especially those caught in unsustainably managed fisheries) socially unacceptable can help change cultural norms.

A CALL TO ACTION

Aquaculture is poised to play a large role in satisfying demand for animal protein and contributing to food and nutrition security in 2050. If planned and managed well, a growth in aquaculture production could provide food and employment to millions more people than today at relatively low environmental cost. However, other aquaculture development pathways could lead to a doubling or more of environmental impacts—or could inhibit the sector from growing, as it bumps up against resource constraints.

Our recommendations are ambitious and wide ranging, but also feasible and necessary. In this rapidly growing and maturing industry, adaptive management will be important to ensuring economic, social, and environmental sustainability.

One thing is clear: improving the productivity and environmental performance of aquaculture—and ensuring it provides safe, affordable, and nutritious food to millions of people around the world—is an important item on the menu for a sustainable food future.

APPENDIX: CASE STUDIES OF IMPROVEMENTS IN AQUACULTURE PRODUCTIVITY AND ENVIRONMENTAL PERFORMANCE

Case Study 1: Carp Farming in China—A Diverse, Evolving Set of Practices

Carp farming (of species from the family *Cyprinidae*) is responsible for 27 percent of value, 38 percent of production (by wet weight), and nearly 50 percent of production (by edible protein weight) of all of world aquaculture. In China, the world's top aquaculture producer, carp species (grass carp, silver carp, bighead carp, common carp, crucian carp) occupy the top five spots in finfish production. In China, carp have been farmed for more than 2,000 years, traditionally in the Yangtze River and Pearl River deltas—although production is more widespread today. Today, carp remains the most popular fish consumed in China, and nearly all carp produced in China is consumed domestically.

Mirroring global trends, over the past two decades, overall aquaculture productivity has increased in China, from 1.7 tons per hectare per year (t/ha/yr) in 1990 to 4 t/ha/yr in 2000. By 2010, the productivity of Chinese carp ponds varied from 0.5 t/ha/yr in extensive systems to 12.5 t/ha/yr in semi-intensive systems and 15 t/ha/yr or more in intensive systems.

As examined in Case Study 8, as farmers intensify production, they tend to move away from traditional polycultures (i.e., several carp species in the same pond with each species occupying a different spatial and feeding niche) toward more of a monoculture system. (However, even in intensive systems, farmers tend to keep a small number of filter-feeding carp in ponds to improve water quality and fish health.)

Several factors have encouraged the growth and intensification of carp farming in China, including:

- **Advances in breeding.** Although carp have been farmed in China for more than 2,000 years, it was only after breakthroughs in the artificial breeding of silver carp, bighead carp, grass carp, and black carp in the late 1950s that carp production really began to take off. The government has invested around 1.6 billion yuan (\$250 million) in improving “seed” quality
- of a range of aquaculture species (not only carp) and encouraging farmers’ use of improved seed.
- **Price deregulation, market liberalization, and land reforms.** Beginning in 1979, these open-market economic reforms gradually allowed producers and others along the aquaculture value chain to make production, marketing, and distribution decisions.
- **Shift in emphasis from wild fisheries to aquaculture.** Also beginning in 1979, in response to declines in wild fish stocks, the government started increasingly promoting aquaculture production while trying to curb fishing in inland and nearshore areas. By 1985, aquaculture production already surpassed wild fisheries production, and has continued to grow ever since while wild fisheries production has leveled off.
- **Land scarcity and related government land policy.** Rapid urbanization and industrialization has led to a loss of cropland in China, and the country’s Twelfth Five Year Plan (2011–15) contains a target to maintain the current total agricultural area of 120 million hectares. Until recently, there was some conversion of agricultural land (e.g., rice) to fish ponds because aquaculture was more profitable, but agricultural land policy in the current Five Year Plan, as well as policies that constrain farmers’ rights to buy and sell land, have effectively prohibited new pond construction and led to intensification within existing ponds.
- **Advances in feed.** A greater use of commercially formulated feed has allowed Chinese carp farmers to intensify production. A recent survey showed that 95 percent of carp farmers in the country’s major carp farming area now use manufactured feed (Chiu et al. 2013). Today, carp are the biggest consumers of aquaculture feed in China because of their sheer volume of production, even though they depend less on feed inputs than carnivorous fish species.

Water, land, and feed constraints mean that carp production is likely to continue to intensify in coming decades. However, nutrient pollution from carp farming (and other aquaculture) remains an issue, especially in farms that do not treat or recycle their waste. (Still, aquaculture is responsible for only 3–5 percent of China’s total agricultural nitrogen and phosphorus loads in waterways.) Furthermore, land laws often prevent farmers from buying or selling land, and property rights are often not clearly defined—constraining investment in the aquaculture sector that could lead to improvements in performance.

Going forward, carp production will remain important in China, but trends in consumption and market demand—both from within China and from foreign countries—are leading to a shift away from carp toward more omnivorous and carnivorous species. Chinese consumers (whether in rural or urban areas) still greatly prefer to purchase live fish, which generally results in fish production being located near areas of consumption. But wealthier consumers in coastal urban areas are increasingly purchasing processed, frozen fish such as tilapia and salmon fillets in supermarkets—and consumption of frozen, higher-value fish is expected to rise rapidly in China in coming decades.

Sources: Chiu et al. (2013); Edwards (2008); FAO (2014b); Garnett and Wilkes (2014); Hishamunda and Subasinghe (2003); Li (2003); Mungkung et al. (2014) (unpublished data).

Case Study 2: Clam Aquaculture Supports Sustainable Livelihoods in the United States

Farming bivalve mollusks, such as the hard clam (*Mercentaria mercenaria*), requires no feed, fertilizers, herbicides, chemicals, drugs, or antibiotics. Bivalves can also help decrease nutrient loads in waterways, making them a very efficient and sustainable food production system. In Cedar Key, Florida, commercial oystermen and fishermen were forced out of business after the state imposed a fishing net ban and closed productive oyster grounds in 1994. But a government job-retraining program to support a transition in livelihoods from fishing to clam farming gave birth to a new, sustainable industry.

During the 1990s, more than 200 people were trained in clam farming. The state government established roughly 500 hectares of new clam aquaculture zones—the first on Florida’s Gulf Coast—and leased them to program graduates. Federal and state agencies have also protected more than 35,000 hectares of land around Cedar Key, to act as a natural buffer zone to protect the local clam industry, which relies on clean coastal waters to ensure the clams are safe to eat. The aquaculture zones are located roughly a kilometer offshore—far enough from population centers to have low pollution risk—and are temporarily closed to harvesting after periods of heavy rainfall until bacteria levels meet national water quality standards. Because of the area’s high water quality, waters are only closed to harvesting for an average of five days per year.

Today, Cedar Key is a leading producer of farm-raised clams in the United States. More than 75 percent of the clams grown in Cedar Key are sold outside the region, bringing new money into the community. The clam indus-

try generated an economic impact of nearly \$45 million in 2008 and has created more than 500 new jobs.

How replicable is the Cedar Key experience to other coastal waters of the United States—or other countries? While similar projects are underway in Massachusetts, Alaska, and North Carolina, unfortunately Cedar Key’s story is not yet common. In many coastal areas, heavy use of nearshore waters by other sectors (e.g., tourism and recreation, fishing, shipping, residential), and high levels of water pollution (e.g., from stormwater or industrial sources), constrain opportunities for expansion of bivalve farming. Coastal areas are often publicly owned and governed by multiple agencies (with sometimes conflicting laws), making it difficult to establish use rights for bivalve farming and constraining investment in farming operations. And looking to the future, climate change threatens bivalve aquaculture through increased ocean temperatures, which can cause harmful algal blooms—and through ocean acidification, which will inhibit shell growth.

Although nearshore use conflicts are an important constraint to expansion of bivalve farming, bivalve farmers—and aquaculture development project designers—can reduce political opposition to establishment of aquaculture leases by engaging constructively with local communities early in planning processes and designing their operations to minimize conflict with established uses of the coast.

Sources: Adams (2012); NRC (2010); Shumway (2012); Sturmer (pers. comm.); Sturmer and Colson (2012); Weeks and Sturmer (1994).

Case Study 3: Thai Shrimp Sector Improves as it Matures, but Disease Issues Remain

While traditional coastal shrimp farming has been practiced for centuries in Southeast Asia, it began to take off as a major industry and source of employment in Thailand in the 1970s following breakthroughs in breeding (induced spawning) of giant tiger shrimp (*Penaeus monodon*). The industry grew at a rate of more than 20 percent per year during the 1970s and 1980s, thanks to high profitability and strong growth in demand from affluent customers in Japan, Europe, and the United States. Thailand is currently the world’s second-highest producer of shrimp at nearly 600,000 tons in 2012, and it has been the world’s leading exporter of farmed shrimp since the mid-1990s. The country’s shrimp farming sector is dominated by relatively small-scale farmers, with an average farm size of 1.6 hectares.

However, by the 1990s, Thai shrimp farming was heavily criticized for its links to mangrove clearing. And outbreaks of disease, caused by “self pollution” with too many farms crowded into production areas, were leading to devastating economic losses for shrimp farmers and the abandonment of ponds.

Today, mangrove clearing for aquaculture has largely stopped in Thailand. Farms are no longer as susceptible to disease, although new emerging diseases continue to challenge the sector. What caused the turnaround?

- **Zoning for mangrove conservation and economic development.** The government of Thailand introduced a zoning plan for the country’s mangroves in 1987, setting aside more than 40,000 hectares of mangroves for conservation and designating about 300,000 hectares for “sustainable management” and regulated economic activity. Although enforcement of the zones was difficult if mangroves had already been converted to shrimp farms before the zoning plan took effect, the plan has helped control the siting and registration of new shrimp farms. As an added incentive, the government has provided farmers operating legally in aquaculture zones access to free training, quality control of farmed fish to ensure food safety, water supply, wastewater treatment facilities, and market advice.
- **Intensification of production.** Much of the mangrove area converted to shrimp ponds in Thailand was for large extensive ponds constructed in the 1980s, where farmers operating with little capital would compensate for low yields by constructing larger ponds. Improvements in pond productivity have greatly reduced pressure to clear new land, and nearly all farms are now semi-intensive or intensive. Furthermore, the best locations for intensive farms are above the high water mark—where ponds can be easily dried and drained between growing seasons—not in low-lying mangrove areas, where soils are highly organic and acidic.
- **Technological improvements.** Beyond the breeding technology that unlocked the first shrimp boom of the 1970s and 1980s, a number of improvements have helped Thai farmers increase productivity. “Backyard hatcheries” that allow farmers access to a constant supply of juvenile shrimp have become common in shrimp-producing areas. In the early 2000s, when diseases continued to plague *P. monodon* farming—and expanding use of antibiotics and other chemicals to control disease led to an European Union ban on Thai

shrimp imports—farmers switched to growing whiteleg shrimp (*Penaeus vannamei*). By 2006, the switch to whiteleg shrimp had led to reductions in disease as well as production costs, higher production levels, and higher productivity (Table A1). However, the production boom lowered shrimp prices, benefiting consumers but causing challenges for small-scale farmers.

- **Networking, social organization, and information exchange.** Lead farmers—the innovators or “early adopters” of new technology—are able to rapidly transfer technology to their counterparts. Local shrimp farming clubs and national shrimp farming and industry associations help farmers exchange ideas and information, improve planning and development, coordinate with the government, and negotiate with importers. Mobile technologies help spread information in rural areas.
- **Other supportive public policies.** The Department of Fisheries provides free technical assistance to small-scale shrimp farmers. Price stabilization policies have helped small-scale shrimp farmers sell their products at guaranteed prices, the country’s Agricultural Bank provides loans to small-scale farmers at low interest rates, and the government provides income tax exemptions for small-scale farmers who have low net profits.
- **Improvements in rural infrastructure** (roads, electricity, water) have all helped the shrimp aquaculture industry grow.

The Thai shrimp farming industry still faces important constraints that will affect its sustainability. The most immediate threat is the outbreak of Early Mortality Syndrome—first reported in China in 2009 and subsequently in Vietnam, Malaysia, and Thailand—which has caused Thai shrimp production to fall by about 40 percent, with some farmers losing 70 percent of their harvests or more. Although the worst effects may have passed, Thailand’s shrimp production has yet to return to 2010 levels. Looking ahead, increasing fuel costs (for pumping, aeration, and transport) will raise operating costs. Increasingly stringent international rules and agreements—for food safety, traceability, and other standards set by importing countries—also increase production costs for smallholders. Finally, climate change—with warmer waters and increased frequency and intensity of storms—poses a longer-term threat to this coastal industry.

Sources: FAO (2014b); Hongkeo and Davy (2010); Lebel et al. (2010); Lewis et al. (2002); Macintosh et al. (2002); Martin (2013).

Table A1 | **Amount of Main Inputs for Producing 1 Ton of Farmed Shrimp in Thailand**

	GIANT TIGER SHRIMP (<i>P. monodon</i>)	WHITELEG SHRIMP (<i>P. vannamei</i>)
Land (m ²)	5,130	580
Water (m ³)	9,240	2,540
Energy (kWh)	8,100	4,610
Feed (kg)	2,420	1,620

Source: Lebel et al. (2010).

Case Study 4: Catfish Farming in Vietnam—Unprecedented Productivity Growth

In Vietnam’s upper Mekong Delta region, farming of the native striped catfish (*Pangasius hypophthalmus*) in backyard ponds was an old tradition. Farmers caught wild seed from the Mekong River and grew the fish in ponds and cages. A confluence of forces catapulted Vietnamese catfish production from less than 50,000 tons in 2000 to more than 1 million tons in 2010—a more than 20-fold increase in a decade. During that time, striped catfish farming areas only roughly doubled from 2,300 hectares to 5,500 hectares—indicating a very rapid period of intensification. Striped catfish yields now average nearly 200 tons per hectare per year across the Mekong Delta, and some ponds attain yields in excess of 300 tons per hectare per year—a level of intensity unprecedented in pond aquaculture.

Roughly 95 percent of all striped catfish production is exported, with exports of 622,000 tons in 2010 bringing in \$1.4 billion in foreign exchange. And this rapid increase in catfish production has led to the development of other sectors along the value chain, including hatchery production, fillet processing, and production of feed, drugs, and chemicals. This development has created nearly 180,000 new jobs in the Mekong Delta, the majority of which are performed by rural women in the processing sector.

Several factors led to the productivity increases and the emergence of Vietnamese striped catfish on the world stage in just a decade’s time:

- **Environmental setting.** Ponds divert water from the Mekong River and allow it to return to the river, allowing a large amount of pond water to be flushed daily with minimal pumping costs. This high water availability also allows ponds to be dug much more deeply than is common—more than 4 meters deep—allowing a very high stocking density per hectare and producing very high yields.
- **Technological improvements.** Traditionally, farmers caught wild seed from the Mekong River. The development of artificial propagation of striped catfish in hatcheries around the year 2000 was the key innovation that allowed seed production to be carried out on a much larger scale, unlocking the boom in catfish production. Improvements in farming techniques, and farmers’ adoption of higher-quality pelleted feed, complemented the hatchery breakthrough.
- **Globalization.** Increased trade liberalization through the 1990s, coupled with a decline of European and American wild fisheries of “white fish” such as cod, allowed Vietnamese striped catfish to satisfy a growing white fish demand in these countries with an affordable substitute. When the United States imposed trade restrictions in 2002, the Vietnamese government responded by targeting other markets, and by 2010 Vietnam exported striped catfish fillets to more than 130 countries. However, this export-oriented industry is vulnerable to continued criticism and protectionism in importing countries. In 2010, for example, a Member of the European Parliament attacked the industry’s environmental, social, and food safety credentials—leading to negative media attention. Although the Member of Parliament recanted his criticism after visiting Vietnam in 2011, future protectionism could undermine the economic sustainability of the catfish industry.
- **Supportive government policies.** Technical trainings and extension programs, bank loans for producers and processors, international trade promotion programs, and research programs (e.g., in seed quality improvement, disease control, and environmental monitoring) have also helped to grow the catfish industry.

The Vietnamese striped catfish farming sector is distinctive within aquaculture in that it is export-oriented but also dominated by smallholder producers who own and operate their farms. As such, perhaps the biggest short-term risk to the sustainability of the sector is the con-

tinued economic viability of farm operations. Although catfish farming can generate high economic returns per hectare because of very high yields, profits per kilogram of fish produced are quite low, thus many smallholders operate quite close to the margin. And production costs, notably that of feed—which makes up 70 percent of producers’ operating costs—are rising over time.

Three important environmental risks and constraints loom: fish diseases, availability of feed, and water (quantity and quality). A recent life cycle assessment of striped catfish farming in the Mekong Delta (Bosma et al. 2009) showed that the sector’s biggest environmental impacts were related to the production and transport of feed, and to local pollution from pond discharge into the river. The analysis noted that the pond discharges, however, had hardly changed the river’s water quality since before the industry boom, that pollution from ponds (only 2 percent of total nitrogen discharges and 3 percent of total phosphorus discharges) was equal to or smaller than other food production sectors in the 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.

Sources: Bosma et al. (2009); De Silva and Phuong (2011); Little et al. (2012); Phan et al. (2011); Phuong and Oanh (2010); Phuong (2011).

Case Study 5: Sub-Saharan Africa—Poised for an Aquaculture Take-Off?

Of all the world’s regions, the need for growth in aquaculture production is most pronounced in sub-Saharan Africa. Africans are second only to Asians in the importance of fish in the diet, with 19 percent of the region’s animal protein intake in the form of fish. Fourteen countries in the region rely on fish for more than 30 percent of their animal protein. However, across the continent, wild fisheries are exploited to their maximum. And fish supply has not kept up with population growth, with per capita fish supply in Africa down to 8.1 kg per person per year since a peak of more than 9 kg per person per year in the 1980s.

Despite decades of research and development, hundreds of millions of dollars of investment, and high biophysical potential, aquaculture has not yet significantly contributed to national food supplies or economic growth in Africa.

International development agencies largely targeted their aquaculture investments in the 1970s through the 1990s at the subsistence farming sector, in the hopes that low-external-input aquaculture operations would evolve into commercial enterprises. However, most positive impacts were short-lived and ended within a few years after external support was withdrawn. By 2012, the continent still accounted for less than 1 percent of world aquaculture production.

Still, Africa may be poised for aquaculture “take-off,” with high production growth rates in countries such as Nigeria, Ghana, and Zimbabwe. In all three countries, growth has been driven by the private sector—specifically, a few successful investors who relied on locally available inputs, fish species (particularly tilapia [*Oreochromis niloticus*] and African sharp-tooth catfish [*Clarias gariepinus*]), technology, and markets to show the way for secondary adopters.

However, significant constraints to aquaculture development in Africa remain. Many constraints are similar to those facing other commercial enterprises on the continent, such as poor infrastructure and high transportation costs, political instability, and policies that impede expansion by emphasizing central planning over private sector initiative. Specific constraints related to aquaculture include a lack of good quality seed, feed, and technical and marketing information—and increasing competition from cheaper imported farmed fish products (e.g., Chinese tilapia).

Because of rising incomes and urbanization, fish consumption continues to grow in sub-Saharan Africa, and commercial enterprises—especially in peri-urban areas close to large markets—have exhibited higher productivity and profitability relative to their rural counterparts. There will always be a role for aquaculture to help subsistence farmers diversify output, store water during droughts, and ensure family food security. But recent research suggests that enabling the growth of profitable commercial aquaculture—particularly by small- and medium-scale producers—is the surest path to increasing productivity and fish supply, with the potential to ultimately bring fish prices down to the point where quality fresh fish is accessible to all African consumers.

Sources: Brummett et al. (2008); Brummett et al. (2011); FAO (2012a); FAO (2014b); Moehl et al. (2006).

Case Study 6: Norway Leads the Way in Salmon Sustainability

Norway is far and away the world leader in Atlantic salmon (*Salmo salar*) production, producing more than 1.2 million tons in 2012 and providing 4,500 direct jobs in the country, mostly in rural coastal areas.

Intensive salmon farming, which takes place in cages submerged offshore in Norway's fjords, uses no freshwater and very little land (for feed). But it has been criticized in the past for its high use of fishmeal and fish oil, and use of chemicals and antibiotics. And even though the environmental setting is generally favorable—with ocean currents that disperse pollution from wastes, leaving minimal impacts on surrounding ecosystems—high-density farming areas have had problems with fish diseases. Concerns remain about the possibility that these diseases could affect wild fish, as well as about the genetic interactions between escaped farmed salmon and wild salmon.

Still, the Norwegian farmed salmon industry has made dramatic sustainability gains over the past 30 years, including:

- A reduction in share of fishmeal and fish oil in salmon diets from 45 percent and 25 percent respectively in 1995, to 25 percent and 15 percent respectively by 2010, by replacing the fish-based ingredients with soybean meal, canola oil, and other plant-based ingredients
- A 98 percent reduction in the use of antibiotics between 1987 and 2004
- A reduction in fish escapes from 553,000 in 2004 to 100,000 in 2008

Productivity growth has also helped both the production cost and export price of Norwegian salmon to fall by about 75 percent between the mid-1980s and 2007.

Several factors have helped Norway improve the productivity and environmental performance of its salmon industry:

- **Technological improvements**, stimulated by high levels of public and private investment in research and development, have been at the core. Development of vaccines and improvement of biosecurity (control and containment of diseases) have greatly reduced the need for antibiotics. Selective breeding has led to con-

tinuous improvements in fish production traits such as feed conversion ratios from generation to generation, increasing production efficiency. And research on feed formulation and feeding practices has helped the industry reduce its reliance on wild fish for feed.

- **Industry consolidation and vertical integration.** The Norwegian (and global) farmed salmon industry has become greatly consolidated and vertically integrated over the past two decades, with the number of companies producing 80 percent of Norwegian farmed salmon falling from 70 in 1997 to 22 in 2012. A similar trend has happened in the salmon feed industry. Well-capitalized companies have been able to make significant investments in research and development, increasing efficiency of production and driving down production costs.
- The Norwegian government has **invested heavily in planning and monitoring systems** to manage the environmental performance of its salmon industry. The government has created a system for environmental monitoring of current aquaculture sites and spatial planning/zoning of new aquaculture sites. The system uses a combination of monitoring and ecological modeling to look at ecosystem effects of new aquaculture sites, determine whether existing and new sites are staying within ecosystem carrying capacity, and minimize local pollution.
- **Public policy** has created an enabling environment for sustainable development. Norway's Aquaculture Act, which came into force in 2006, mandates permits for fish farms that take environmental and coastal zoning issues into account, aiming to lessen conflicts with other users of the coastal zone. The government also established protected areas for wild salmon in rivers and fjords in 2007 to decrease interaction between farmed and wild salmon.

How applicable is the Norwegian experience to other countries and farmed species? Zoning, monitoring, ecological modeling, and enforcement of regulations all require a certain level of public and private investment and capacity, which may be difficult to replicate in developing countries where most aquaculture is located. Still, the technical innovations and gains in productivity offer lessons for the rest of the aquaculture industry.

Sources: Asche (2008); FAO (2014b); Marine Harvest (2012); Tacon et al. (2011); Torgersen et al. (2010).

Case Study 7: Closed Systems— Ready for Prime Time?

The dominant forms of aquaculture production are in “open” systems—in ponds or cages where wastes are released into the environment (often directly into water bodies), and where problems of disease and interactions with wild fish must be carefully managed. Open systems are also vulnerable to storms (especially on the coast) and to water pollution from other resource users. In contrast, two “closed” systems—recirculating aquaculture systems and biofloc technology—rectify many of the problems associated with open systems and satisfy the environmental sustainability criteria mentioned in Table 1. But these closed systems are just emerging on a commercial scale, and it remains to be seen whether they will produce a significant amount of fish by 2050.

Recirculating aquaculture systems

Land-based recirculating aquaculture systems (RAS) have been promoted (and continuously improved) since the 1970s. These tank systems that filter and reuse water can grow freshwater or marine species at high densities and allow nearly complete control over the production process. As such, they are extremely efficient; use very little land, water, and feed; and have almost no local environmental impact (eliminating issues of disease, escapes, antibiotics, and chemicals). RAS technology can be combined with vegetable farming in an integrated “aquaponic” system where the nitrogen waste from aquaculture fertilizes vegetables and herbs. RAS waste can also be transported for use as a fertilizer or soil conditioner on (terrestrial) farms. In urban areas, RAS have the potential to contribute to local food production and employment. Today, RAS are commonly used in hatchery production.

However, RAS technology is expensive compared with dominant open systems, requiring high up-front investments and with higher operating costs. Losordo, Masser and Rakocy (2001) estimated that RAS capital costs ranged from \$2,250 to \$8,800 per ton of annual production, as compared with average costs of \$2,000 per ton in more conventional pond or flow-through systems. Energy used to maintain pond water quality leads to relatively high operating costs. And higher levels of management and monitoring—while costly—are necessary to decrease the risk of system failure. Because of the high cost, commercial examples of RAS for “grow-out” (i.e., for growing fish for harvest and sale, rather than the hatchery stage) are still rare, although several companies in the United

States, Canada, and Europe are using the technology to farm high-value fish species destined for niche markets. And there is a significant environmental tradeoff—while RAS minimize local environmental impacts, their high electricity use make them more energy-intensive (and thus greenhouse gas-intensive) than most open systems.

Use of low-carbon energy sources could significantly mitigate greenhouse gas emissions from RAS. Policies to regulate pollution and other externalities associated with open systems—along with rising fish prices—could make RAS production more economically competitive. It remains to be seen whether RAS can be scaled up to produce a significant amount of fish—and in particular, more affordable fish, in a wider range of countries for a wider range of consumers.

Because pond culture is the dominant aquaculture production system globally, a more flexible option than self-contained RAS may be “pond-based recirculating systems,” where pumps are added to “traditional” pond systems to improve water quality. However, while pond-based recirculating systems do lead to more efficient water use and reductions in water pollution, land use remains relatively unchanged.

Biofloc technology

Under this approach, which is usually practiced in ponds, farmers grow not only fish but also microorganisms (“biofloc” or floating clumps of bacteria, algae, and other particulate organic matter) that both maintain water quality within the farm and also provide additional protein-rich nutrition to the farmed fish. Biofloc technology thus eliminates the need for water exchange to maintain pond water quality—greatly reducing water use and pollution, disease, and escape risks—and reduces feed costs and demand for wild fish as feed.

Biofloc technology was first developed in the 1970s, and interest in biofloc research and development has been mainly driven by concerns about shrimp disease (and efforts to minimize water exchange, a main pathway for introduction of disease), as well as scarcity of water, land, and feed. Early adopters of the technology in French Polynesia and Belize demonstrated that biofloc shrimp farming could be commercially viable. Commercial-scale biofloc-based shrimp ponds now operate in Asia and Latin America, and there are smaller-scale operations in those regions, Europe, and the United States.

Until now, biofloc technology has been mostly accessible to large-scale farmers who can invest in the necessary monitoring and management, as the need to closely monitor biofloc and water quality levels increases the complexity and operating costs of fish farming. Furthermore, only certain fish species—such as shrimp and tilapia—are amenable to biofloc technology because they can tolerate the high concentrations of solids in the pond water. Nevertheless, research and development in biofloc technology continues to increase, and the technology holds promise for improving aquaculture’s productivity and environmental performance over the coming decades.

Sources: Bunting (2013); Emerenciano et al. (2013); Hambrey et al. (2008); Lazur and Britt (1997); Losordo, Masser and Rakocy (2001); Ocean Foundation (n.d.).

Case Study 8: Integrated Aquaculture—Wave of the Future or Relic of the Past?

Traditional inland aquaculture, practiced in Asia for thousands of years, is integrated with other agricultural activities (e.g., crops and livestock). Wastes from other activities (e.g., crop residues, livestock manure) provide the sources of nutrition for the fish, and fish wastes are recycled back into the system to fertilize crops (e.g., rice). Integrated aquaculture can be a highly efficient system producing negligible amounts of waste, optimizing use of scarce land and water, and imitating ecosystem functions. Examples of traditional integrated aquaculture include:

- Integrated agriculture-aquaculture systems (e.g., rice-fish, livestock-fish). Rice and fish may be raised together, or alternated in a rotation. In 2011, there were an estimated 1.2 million hectares of land under rice-fish cultivation in China (compared with 29 million hectares in rice only and 5 million hectares in fish only).
- Polyculture of fish (e.g., multiple species of carp in one pond) that occupy different spatial and feeding niches in a pond. Semi-intensive carp polyculture contributed an estimated 50–58 percent of total inland aquaculture production in China in 2005. Polyculture is also common in Bangladesh, as well as in India, where the majority of Indian carp production relies on polyculture of the “Indian major carps.”
- Wastewater-fed integrated peri-urban aquaculture systems (fed from human sewage or industrial effluents). However, these systems are in decline as people’s social and economic status improves.

While these traditional practices make optimal use of scarce resources, they are currently declining in China. Intensification of both rice and fish farming in China—and resultant rises in profits—have led farmers to abandon rice-fish farming and move toward more intensive monoculture systems. Increasingly, farmers are also converting their rice fields to fish ponds. And as carp farmers’ access to industrially formulated feed grows, they are also shifting away from polyculture in favor of intensive monoculture, although as noted in Case Study 1, even these farmers tend to keep some filter-feeding carp in ponds to improve water quality and fish health.

Some researchers promote integrated aquaculture as a way to combine traditional practices with industrial-scale production, thereby mitigating the negative effects of modern monocultures, and increasing long-term sustainability and profitability. For instance, Canadian researchers are working to develop “integrated multi-trophic aquaculture” (IMTA) systems that combine salmon cage farming with the farming of mussels and seaweeds in close proximity. Mussels are grown to help absorb particulate organic matter, and kelp (seaweed) is grown to take up dissolved inorganic nutrients—thereby producing more marketable aquatic products with less pollution. Monitoring of all farmed species ensures that concentrations of contaminants (e.g., medicines, pesticides, heavy metals) are kept well below regulatory limits, ensuring food safety.

Although commercial-scale applications are still rare, IMTA has been shown to increase overall output and profitability of farms, reduce risks through diversification, and increase social acceptability of salmon farming. Salmon grown in IMTA systems (such as WiseSource™ Salmon in Canada) can also command a higher market price. Similar work is underway in Norway, and there are also large-scale IMTA initiatives in China and Korea. However, current aquaculture legislation and fish purchasing standards (e.g., for Canadian salmon retailers) are often geared toward the dominant monoculture systems—making it difficult for IMTA farmers to obtain permits to establish new integrated farms or sell their harvest. Policy reform initiatives are underway in North America and Europe.

In an era of increasing resource scarcity, integrated aquaculture systems have a role to play. Some farmers are using integrated aquaculture and polyculture as a resilience strategy—such as shrimp farmers in Thailand who grow rice and shrimp, switching between them depending on prices

and rainfall. Other farmers may have incentive to revert to integrated aquaculture of lower-value, lower-risk species as prices for feed and fertilizers rise along with energy costs in coming years. However, the biggest problem in scaling up these types of systems is that they are very knowledge intensive and difficult to manage as businesses because adding species and production systems greatly increases the complexity of an enterprise.

Sources: Barrington et al. (2009); Chopin (2011); Edwards (2009); Garnett and Wilkes (2014); Ridler et al. (2007).

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ENDNOTES

1. Throughout this paper, "fish" refers to both finfish and shellfish. More precise definitions of these terms, and others used throughout this paper, 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; *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 (2012a) and FAO (2014a). Nearly 1.3 billion people live in countries where the level of animal protein consumption from fish exceeds 25 percent. Figures include both wild-caught and farmed fish.
3. Authors' calculations from FAO (2012a). In 2009, 78 percent of fish consumption occurred outside of North America, Europe, and other OECD countries.
4. Allison (2011).
5. FAO (2012b), FAO (2014a).
6. FAO (2014b), Sea Around Us Project (2011).
7. Aquaculture is commonly defined as the farming of aquatic organisms, which include both animals and plants (FAO 2008). Because the focus of this paper 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 paper, "aquaculture" is used to mean "the farming of aquatic animals."
8. FAO (2014b) and FAO (2014c). 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 (see Figure 7).
9. Many figures in this paper are based on statistics from the FAO FishStat global database of wild fisheries and aquaculture production (FAO 2014b). 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, and collection of aquaculture data remains relatively new. Furthermore, the fact that one country—China—is responsible for more than 60 percent of global aquaculture production means that global aquaculture production data are heavily influenced by the quality of data from China. Nevertheless, the FAO data remain the best available source of data for global fisheries and aquaculture production. See Kura et al. (2004) (Annex B), Campbell and Pauly (2013), and CEA (2012) for further discussion of FAO fisheries and aquaculture data, limitations and caveats.
10. FAO (2014b), FAO (2013).
11. UNDESA (2013).
12. Hall et al. (2011).
13. Authors' calculations. According to FAO (2013), people consumed 136 Mt of fish (69 Mt from wild fisheries and 67 Mt from aquaculture) in 2012. In

- order to maintain the 2012 per capita fish consumption level in 2050, total fish consumption will need to rise by 35 percent (9.6 billion people in 2050 / 7.1 billion people in 2012), to 184 Mt. Assuming a 10 percent decline in the amount of food fish from wild fisheries between 2012 and 2050 (to 62 Mt in 2050), aquaculture would need to provide the remaining gap of 122 Mt—or an 82 percent increase over the 2012 aquaculture production level. If per capita fish consumption were to increase by 10 percent from its 2012 level, total fish consumption in 2050 would be 202 Mt, and aquaculture production would need to rise to 140 Mt—more than doubling from the 2012 level and in line with the growth projection in Figure 7.
14. Mungkung et al. (2014).
 15. FAO (2014b). While the FAO capture (wild) 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 of significant importance when it comes 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).
 16. FAO (2014a). Data are from periodic FAO fish stock assessments. According to FAO (2012b), *overfished* stocks produce lower yields than their biological and ecological potential, *fully fished* stocks produce catches that are very near their maximum sustainable production, and *non-fully fished* stocks are under relatively low fishing pressure and have some potential to increase their production.
 17. Examples summarized in CEA (2012) and Worm et al. (2009).
 18. As defined by the World Bank and FAO (2009), fishing effort is “a composite indicator of fishing activity. It includes the number, type, and power of fishing vessels and the type and amount of fishing gear. It captures the contribution of navigation and fish-finding equipment, as well as the skill of the skipper and fishing crew.”
 19. World Bank and FAO (2009), UNEP (2011), Costello et al. (2012).
 20. See, for instance, World Bank and FAO (2009), UNEP (2011), Costello et al. (2012), Srinivathan et al. (2010), NEAA (2010). Note also that climate change adds a new dimension of uncertainty in forecasting future marine catches.
 21. FAO (2014b).
 22. Authors’ calculations from FAO (2014b). Sub-Saharan Africa saw an average annual (compounding) growth rate in aquaculture production of 20.5 percent between 2007 and 2012, by far the highest growth rate of any region. Still, the growth in absolute production in sub-Saharan Africa was only 276,000 tons (from 179,000 tons in 2007 to 455,000 tons in 2012), far behind absolute growth in many other regions that started from a much higher 2007 production baseline.
 23. FAO (2014a).
 24. FAO (2012b), Valderrama et al. (2010).
 25. Williams et al. (2012).
 26. Costa-Pierce et al. (2012). However, while the feed efficiency figures in Figure 6 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.
 27. Volpe et al. (2010), Asche (2008).
 28. Hall et al. (2011). 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. These issues are further explored in Appendix, Case Study 2.
 29. See, for example, Hall et al. (2011) and World Bank, FAO, and IFPRI (2013). Studies summarized in Hall et al. (2011) include: Ye (1999), Wijkström (2003), Delgado et al. (2003), and Brugère and Ridler (2004). Other expert assessments, such as EATIP (2012a), come to similar conclusions: global aquaculture production will likely rise by at least 50 percent, and probably more, by 2030.
 30. See, for example, UNDESA (2013).
 31. Searchinger et al. (2013a). Source of aquaculture’s contribution to the food gap: authors’ calculations. Searchinger et al. (2013a) built on the work of Alexandratos and Bruinsma (2012) to estimate the amount of food—measured in calories (kcal)—necessary to feed a population of 9.6 billion people by 2050, given projected trends in food consumption patterns. They estimated that the amount of food available directly for human consumption, on an annual basis, would need to rise from 6,300 trillion kcal in 2006 to 10,500 trillion kcal in 2050—a “gap” of 4,200 trillion kcal or roughly 65 percent (Searchinger et al. (2013a), unpublished data). In 2006, people consumed roughly 72 trillion kcal of fish per year on a global basis. If aquaculture production rises to 140 Mt per year by 2050, and capture fisheries production decreases by 10 percent relative to 2006 levels, total fish consumption would rise to roughly 195 Mt per year, equivalent to 129 trillion kcal per year. This additional consumption of 57 trillion kcal of fish per year, relative to the 2006 baseline, would close roughly 1 percent of the 4,200 trillion kcal “food gap.” These calculations also assume the same ratio of fish calories to total fish weight in 2050 will be unchanged from 2006 (implying the same mix of fish species), and that all aquaculture production in 2050 will feed humans. Note also that this “food gap” is different than the 69 percent “food gap” emphasized in Searchinger et al. (2013a), which counts the total increase in calories from crop production (including all crops intended for direct human consumption, animal feed, industrial uses, seeds, and biofuels). Each approach to counting the food gap has its merits and is further discussed in Searchinger et al. (2013a), Box 3. We choose the 65 percent “food gap” for comparison because it is the most appropriate for this paper’s subject: the farming of fish for direct human consumption.
 32. Authors’ calculations based on a growth in aquaculture production to 140 Mt, the same ratio of fish protein weight to total fish weight as in 2006 (implying the same mix of fish species), assumes that all aquaculture production will feed humans, and assumes a 10 percent decrease in wild fish capture for food.
 33. Authors’ calculations. Building off of FAO projections (Alexandratos and Bruinsma 2012) and the FAO Food Balance Sheets (FAO 2012a), we predicted an increase of 48.7 million tons in consumption of animal protein between 2006 (63.9 million tons) and 2050 (112.6 million tons). This would imply that an increase in animal protein provided by aquaculture of 6.9 million tons over that period would be equal to 14.3 percent of the total increase in animal protein consumption over that period.
 34. See Hall et al. (2011) and World Bank, FAO, and IFPRI (2013) for a discussions predicting the geographic distribution of aquaculture growth to 2030.
 35. However, the links between aquaculture’s growth and its contribution to food security and poverty reduction are not automatic. Even if most aquaculture growth in coming decades occurs in developing countries, aquaculture growth will not have meaningfully contributed to alleviating

- poverty and hunger if relatively few jobs are created or farmed fish are only consumed by wealthy urban or foreign consumers (Allison 2011).
36. Case Study 2 (Appendix) offers an example of a successful transition from wild fishing to marine aquaculture. However, wild fishing and farming (aquaculture) are two very different activities, so one cannot assume that such transitions will be easy or even feasible in a given location.
 37. Costa-Pierce et al. (2012).
 38. Costa-Pierce et al. (2012).
 39. Aquaculture “seed” can refer to eggs, spawn, offspring, progeny or brood of a farmed aquatic organism—also referred to as fry, larvae, postlarvae, spat, and fingerlings. Aquaculture seed may originate from captive breeding programs or be caught from the wild (FAO 2008).
 40. Tacon et al. (2010), Kura et al. (2004), Costa-Pierce et al. (2012), Bunting (2013).
 41. Authors’ calculations from 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.
 42. Authors’ calculations. FAO (2011) estimated total agricultural land at 4,921 Mha.
 43. Conversion of seagrass beds can also lead to loss of habitat and ecosystem services, although it is not land use change *per se*.
 44. FAO (2007).
 45. Croplands that have become too saline for rice cultivation are an example of such lands with low economic and environmental value.
 46. Mungkung et al. (2014) (unpublished raw data). Counts only direct land use.
 47. Dugan et al. (2007), Hall et al. (2011). In aquaculture, it is also common to express yields in terms of kg/m³ because of its three-dimensional nature.
 48. Lewis et al. (2002).
 49. However, marine aquaculture may use land indirectly for plant-based feeds.
 50. Authors’ calculations. Aquaculture water consumption given in Mungkung et al. (2014), global agricultural water consumption of 8,363 km³ per year (not counting aquaculture) given in Mekonnen and Hoekstra (2012).
 51. Beveridge and Brummett (2012).
 52. Costa-Pierce et al. (2012).
 53. Bouwman et al. (2013).
 54. Kura et al. (2004).
 55. Tisdell et al. (2012).
 56. Brummett (2007).
 57. Hall et al. (2011).
 58. Hall et al. (2011) (unpublished raw data), Brummett (2007).
 59. Bouwman et al. (2013).
 60. Bouwman et al. (2013).
 61. *Biofloc technology* is an aquaculture production system where farmers grow not only fish but also microorganisms (“biofloc” or floating clumps of bacteria, algae, and particulate organic matter) that both maintain water quality within the farm and also provide added protein-rich nutrition to the farmed fish. See Appendix, Case Study 7 for more details.
 62. Tacon et al. (2011). As a low-bound estimate, “fed aquaculture production” consisted of at least 31.5 Mt tons of fish (out of 52.9 Mt of total aquaculture production in 2008, 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 60 percent of all production.
 63. 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 percent fishmeal and 14 percent 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.
 64. Tacon et al. (2011).
 65. Authors’ calculations from FAO (2014b); see also discussion below about aquaculture production by species and trophic level, and Table 4.
 66. Tacon et al. (2011).
 67. FAO (2012b).
 68. “Bycatch” refers to part of a wild fish catch taken incidentally in addition to the target species toward which fishing effort is directed (FAO 2014d).
 69. Wijkström (2012).
 70. Naylor et al. (2009).
 71. Tacon et al. (2011).
 72. Tacon and Metian (2008), Tacon et al. (2011).
 73. FAO (2014a).
 74. Newton and Little (2013). Tacon and Metian (2008) note that “it is important to ensure that the fishmeals and fish oils derived from aquaculture process wastes are not fed back to the same species (intra species recycling) so as to prevent the possibility for the spread of diseases and/or recycling of unwanted environmental and/or dietary contaminants.”
 75. Mungkung et al. (2014). Figures do not include emissions from land-use change associated with aquaculture or agriculture. In 2010, Searchinger et al. (2013a), based on UNEP (2012), FAO (2012c), EIA (2012), IEA (2012), and Houghton (2008), give figures of 6.4 gigatons of CO₂e from agricultural production and 49.1 gigatons CO₂e from all anthropogenic emissions.
 76. Hall et al. (2011).
 77. Bunting and Pretty (2007).
 78. Bunting and Pretty (2007).
 79. Authors’ calculations from Mungkung et al. (2014) (unpublished data); see also Table 5.

80. Bunting and Pretty (2007).
81. The list below, unless otherwise cited, is from Tacon et al. (2010), Kura et al. (2004), Costa-Pierce et al. (2012), and Bunting (2013). Note that, conversely, aquaculture can have positive ecosystem effects; for example, providing seed for restocking overexploited fish populations, or providing wastes that can be used to fertilize terrestrial crops (Soto et al. 2008, 16).
82. Bravo (2003).
83. Looking beyond issues of disease, some groups have raised concerns about the welfare of farmed fish—especially those raised in intensive systems. These concerns are similar to animal welfare concerns related to intensive livestock farming, including overcrowding, feeding and handling, transport, and stunning and slaughter methods (HSUS n.d.).
84. Lorenzen et al. (2012).
85. Hine et al. (2012).
86. USDA (2013).
87. Beveridge et al. (2013), 10.
88. Cai et al. (2012).
89. Beveridge et al. (2013), Belton et al. (2012).
90. Descriptions are drawn from Hall et al. (2011) and Bunting (2013).
91. Tacon and Metian (2008).
92. Authors' calculations from FAO (2014b). In this list, "aquaculture production" is measured by tons of fish produced.
93. Authors' calculations from FAO (2014b). The six species groups listed are in descending order of production level (by weight).
94. Trophic levels are steps in the food chain of an ecosystem. Trophic level 1 contains green plants, level 2 contains herbivores, level 3 contains primary carnivores, level 4 contains secondary carnivores, and so on (Encyclopaedia Britannica 2014). However, as discussed in note 63, distinctions between "carnivores" and other groups of fish can be misleading in aquaculture, because fish diets can be altered.
95. Authors' calculations from FAO (2014b) and Froese and Pauly (2014). Percentages do not total to 100 due to rounding.
96. Authors' calculations from FAO (2014b).
97. Hall et al. (2011). Data for 75 production systems that represented 82 percent of world aquaculture production in 2008. Data exclude seaweeds.
98. Hall et al. (2011). Data for 75 production systems that represented 82 percent of world aquaculture production in 2008. Data exclude seaweeds.
99. Hall et al. (2011). Data are for 2008.
100. Life cycle assessment (LCA) is a technique used by many industries and businesses to assess environmental impacts associated with a product, process, or service. Its results can be used to select products, processes, or services with minimal environmental impacts (U. S. EPA 2006).
101. Hall et al. (2011).
102. Mungkung et al. (2014).
103. Of course, this does not mean to imply that there is infinite substitutability between animal protein sources in human diets, but simply to illustrate the relative efficiency of these protein sources in the context of the challenge of sustainably feeding a growing population.
104. Therefore, because of carp's outsized contribution to world aquaculture production, their *absolute* environmental impacts are the highest of any species group across all categories (although absolute impacts are not shown in Table 4).
105. Farmed seaweeds (aquatic plants) also exhibit a similar pattern of extremely low (or benign) environmental impacts, but are outside the scope of this paper.
106. The variation in indicators of environmental performance among and within countries also probably reflects the variation in suitability of different countries and sites to aquaculture.
107. Authors' calculations from Mungkung et al. (2014) (unpublished data). Regarding greenhouse gas emissions, it is important to note that Mungkung et al. (2014) did not assess emissions from land-use change, which would decline under intensification, partially offsetting the increases in greenhouse gas emissions from intensive aquaculture production.
108. FAO (2014e).
109. Three additional concerns with "sustainable intensification" include: (1) Intensification generally increases investment and production costs—potentially forcing out smallholder farmers with little capital (Beveridge et al. 2013); (2) Fish produced in more intensive systems—those reliant on pelleted feeds—often have higher fat levels and lower levels of omega-3 fatty acids, reducing the nutritional benefits to consumers (Beveridge et al. 2013); and (3) As noted below, intensification can lead to increased profit per hectare, possibly promoting expansion of aquaculture into new areas if policies do not limit expansion (Ceddia et al. 2013).
110. See ISO (2006a) and ISO (2006b) for more on the internationally standardized life cycle assessment approach for environmental management (ISO 14040 and ISO 14044).
111. See Hall et al. (2011), chapter 2, and Mungkung et al. (2014) for further technical details on assessment methods and assumptions. As Hall et al. (2011) note, "previous [aquaculture LCA] studies suggest that setting [these LCA boundaries]... is defensible because the bulk of environmental resources and environmental emissions lies within these bounds... the biggest energy demands for aquaculture production systems occur on farm, for processing feed, for reduction of wild fish into fishmeal and fish oil and in the capture of wild fish to feed into the production process."
112. Direct land use was not adjusted based on the premise that farms will not reduce in size once established.
113. Hall et al. (2011), Mungkung et al. (2014).
114. World Bank, FAO, and IFPRI (2013) project that of all aquaculture species groups, tilapia, carp, and catfish production will grow most quickly between 2008 and 2030.
115. One limitation of life cycle assessment is that it traditionally does not consider social and economic variables—only environmental ones. A modified life cycle approach, which does include social and economic variables, would provide additional insight on how to make aquaculture growth as sustainable as possible, but was beyond the scope of this paper.
116. Of course, these results should also be interpreted in the broader context of growth in demand for animal products to 2050. As shown in Figure 6 and Table 4, high growth in resource-inefficient animal production—particularly beef—would have even larger environmental impacts.
117. It is also interesting to explore the inverse of Scenario 2—a world in which low-intensity aquaculture is encouraged. In this case, our results suggest that a shift to lower-intensity aquaculture would reduce energy use, water pollution, and wild fish use, but increase land and freshwater use. Tuomisto et al. (2012), when comparing conventional agriculture to organic

- agriculture in Europe, came a similar conclusion: organic farming systems had lower energy use but higher land use per unit of crop product than conventional, higher-intensity farming systems.
118. Searchinger et al. (2013a), based on UNEP (2012), FAO (2012c), EIA (2012), IEA (2012), and Houghton (2008). Does not include emissions from land-use change.
 119. However, this high level of emissions growth would be partially offset by a reduction in land-use change emissions under intensification.
 120. Nandeeshha et al. (2012).
 121. Ceddia et al. (2013).
 122. Hall et al. (2011).
 123. Ministry of Fisheries and Coastal Affairs (2005).
 124. Hishamunda et al. (2012).
 125. Hishamunda et al. (2012).
 126. EATIP (2012b).
 127. Brummett (2013), Bush et al. (2013).
 128. Hishamunda et al. (2012), NRC (2010).
 129. Nandeeshha et al. (2012).
 130. Nandeeshha et al. (2012).
 131. Hishamunda et al. (2012).
 132. Little et al. (2012).
 133. Little et al. (2012).
 134. De Silva and Soto (2009).
 135. De Silva and Soto (2009).
 136. Watson et al. (2012).
 137. Hall et al. (2011), De Silva and Soto (2009).
 138. Belton and Little (2011).
 139. De Silva and Soto (2009).
 140. This section focuses on “conventional” selective breeding (as opposed to genetic modification).
 141. Gjedrem et al. (2012).
 142. 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.
 143. Gjedrem et al. (2012).
 144. Gjedrem et al. (2012).
 145. FAO (2014e), Brummett et al. (2008).
 146. Liu (2007).
 147. Browdy et al. (2012).
 148. Garnett and Wilkes (2014).
 149. Smith et al. (2010).
 150. Browdy et al. (2012).
 151. Kapetsky et al. (2013).
 152. Umesh et al. (2010).
 153. Fort (2013).
 154. Brummett et al. (2008), Brummett et al. (2011), Belton and Little (2011). This is not to say, however, that donors and countries should abandon support to small-scale subsistence producers, who with small subsidies can help ensure local food security and livelihoods (Allison 2011).
 155. Brummett et al. (2008).
 156. Here, “spatial planning and zoning” encompasses processes and tools such as land-use planning, water-use planning, ecosystem modeling, marine spatial planning, integrated coastal zone management, and integrated watershed management.
 157. Brummett (2013).
 158. Hishamunda et al. (2012).
 159. NDRC (2008).
 160. Soto et al. (2008), Brummett (2013).
 161. Rey-Valette et al. (2008).
 162. EATIP (2012b).
 163. Heldbo and Klee (2014).
 164. Hishamunda et al. (2012).
 165. Chopin (2008).
 166. Hishamunda et al. (2012).
 167. Sumaila et al. (2010).
 168. DEFRA (2013). While the mussels have been able to reduce nutrient pollution more cheaply than conventional sewage treatment, the scheme has not yet proven economic sustainability. Although the farms were supposed to obtain revenue from both the community government (to reduce pollution) and from consumers of the mussels as food, lack of market demand for the produced mussels led to the bankruptcy of one pilot farm in 2011.
 169. Browdy et al. (2012), Nandeeshha et al. (2012).
 170. However, other environmental impacts, such as land and water use, could rise. Table 4 shows, for instance, that fish produced in inland ponds (e.g., tilapia, catfish, carp) require more land and freshwater per unit of fish protein produced than salmonids. Investments in technological innovation and transfer (Recommendation 1), targeted at low-trophic species, could help ease some of these resource constraints.
 171. Tacon et al. (2010).
 172. “Middle class” is defined by OECD as having per capita income of \$3,650 to \$36,500 per year or \$10 to \$100 per day in purchasing power parity terms. “Middle class” data from Kharas (2010).
 173. Garnett and Wilkes (2014).
 174. Keats and Wiggins (2014).
 175. Summarized and adapted from WRI (forthcoming).
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 177. Pickering (2009), Fijian Government (2010).

ABOUT THE AUTHORS

Richard Waite (Associate, World Resources Institute)

Contact: rwaite@wri.org

Malcolm Beveridge (Director [retired] of Aquaculture and Genetics, WorldFish)

Randall Brummett (Senior Aquaculture Specialist, World Bank)

Sarah Castine (Post-Doctoral Fellow, WorldFish)

Nuttapon Chaiyawannakarn (Researcher, Centre of Excellence on Environmental strategy for GREEN business, Faculty of Environment, Kasetsart University)

Sadasivam Kaushik (Director of Research, Institut National de la Recherche Agronomique [INRA])

Rattanawan Mungkung (Director, Centre of Excellence on Environmental strategy for GREEN business, Faculty of Environment, Kasetsart University)

Supawat Nawapakpilai (Researcher, Centre of Excellence on Environmental strategy for GREEN business, Faculty of Environment, Kasetsart University)

Michael Phillips (Director, Aquaculture and Genetic Improvement, WorldFish)

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ABOUT WRI

WRI is a global research organization that works closely with leaders to turn big ideas into action to sustain a healthy environment—the foundation of economic opportunity and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.



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