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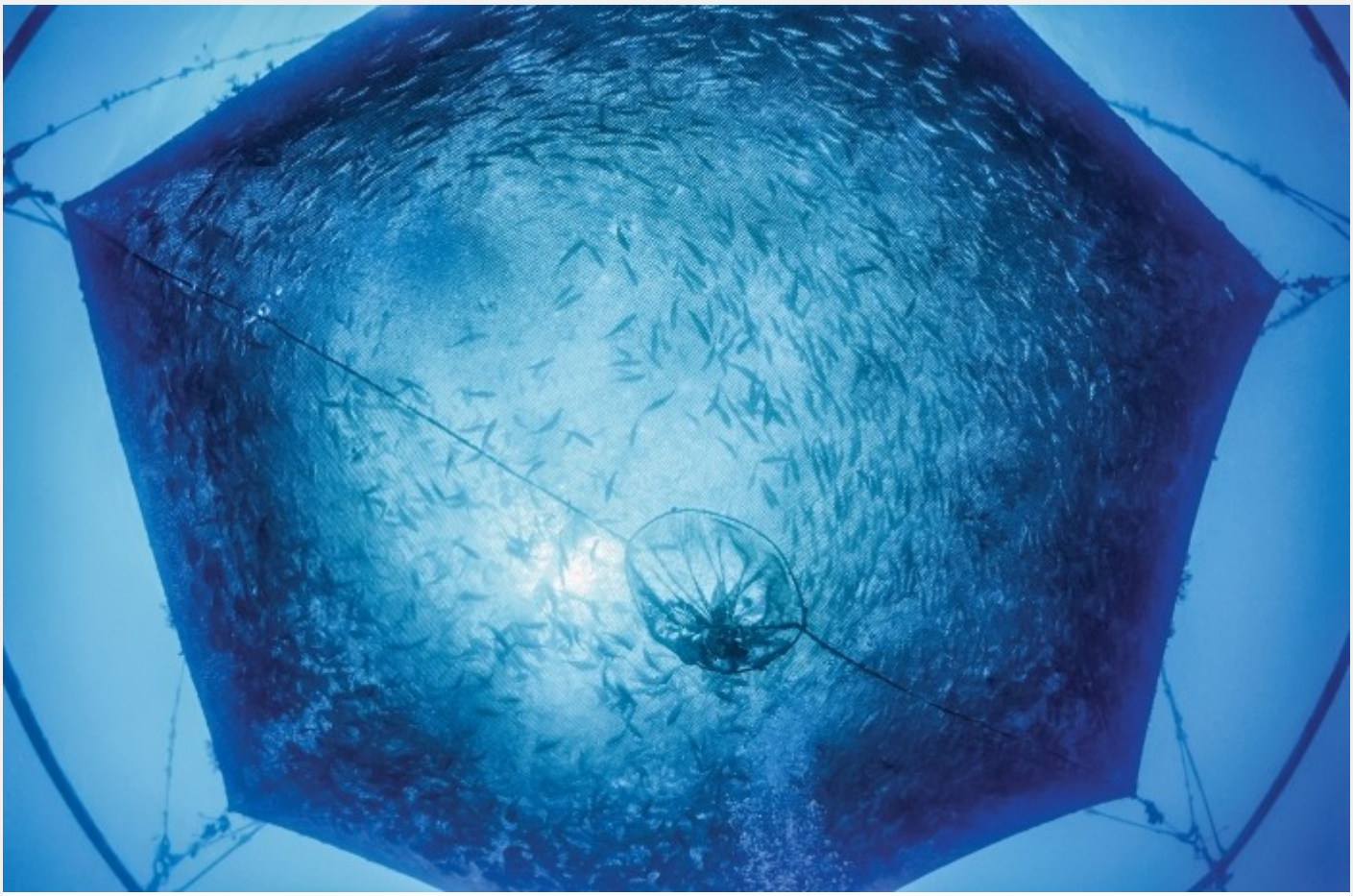
COVER STORY

Sustaining the aquaculture revolution

Fish farmers face feed and ecosystem constraints as they supply a growing portion of the world's protein

By ***Melody M. Bomgardner***



Fish farmers raise seabream in net cages in the Mediterranean off the coast of Southern Italy.

Credit: Shutterstock

In brief

Half of the world's seafood now comes from aquaculture, and a growing middle class means more demand for farmed fish. But farming practices are changing as the industry faces limits on its feed supplies and

Travelers crossing southern Idaho may barely register a flash of green piercing the brown, sagebrush-strewn high desert as they zoom along Interstate 84. But those who take a detour west of Twin Falls will see a verdant landscape formed by man and nature.

questions about its impact on the environment. The amount of wild-caught fish available as food is decreasing, forcing feed producers to look for alternative sources of protein and of essential fatty acids. Farmers also must ensure the health of their fish as farms become larger and denser. Meanwhile, researchers are examining the ways that fish farms impact the environment, and consumers are voting with their wallets for seafood that is sustainable. In the pages that follow, C&EN examines how feed firms, chemical companies, animal health experts, and start-ups are helping aquaculture meet these challenges.

The area, known locally as the Magic Valley, is like a wide canyon—steep on one side, hilly on the other. At the bottom winds the Snake River. The area boasts lush pastures thanks to abundant groundwater and gushing springs that burst from the steep cliffs. The cliffs are part of a huge formation of porous volcanic rock and soil that shuttles melted snow from as far away as Yellowstone National Park.

Idaho's agriculture industry may be best known for potatoes, but the Magic Valley is all about trout. About 80% of trout consumed in the U.S. comes from southern Idaho fish farms.

In a stretch of land less than 50 km long, farmers raise more than 18 million kg of fish per year, according to Leo Ray, owner of **Fish Breeders of Idaho <https://www.fishbreedersofidaho.com>** , a trout farm in Hagerman. "The spring water is a constant 58 °F (14.4 °C) year-round, saturated in oxygen, and perfect for raising rainbow trout."

Mother Nature is no doubt generous to Ray and the other trout farmers in the Magic Valley. But the local industry is part of a global aquaculture business that includes everything from giant salmon operations in Norway to family shrimp farms in Southeast Asia.

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An aural aquaculture primer

Listen to Leo Ray of Fish Breeders of Idaho explain his approach to sustainable fish farming in the Magic Valley.

Credit: Melody Bomgardner (reporting)/Matt Davenport (editing)/Will Ludwig (mixing)/C&EN

As fish farm output rises to meet growing global demand for seafood, farmers are confronting a stagnant supply of wild caught fish used for feed. They constantly battle diseases and parasites. And their customers increasingly demand assurance that fish farms are safe for the environment and for wild fish populations.

The aquaculture industry is served by companies of all sizes: giant multinational agriculture corporations, specialty chemical and nutrition firms, and even small start-ups. They are developing alternative feed sources, new health-promoting additives, and improved vaccines to help fish ward off disease.

Still, firms that provide nutritional inputs do not have ready answers for all the issues facing fish farmers. Researchers continue to question the sustainability of aquaculture. Add to that changing consumer preferences and new trends in fish farming, and it becomes clear that aquaculture will need to evolve further.

Feeding the fish that feed the world

A quiet revolution is happening in seafood. Output from aquaculture now equals that from wild fisheries, and it's growing at a faster rate. Although fish have been farmed for thousands of years, only since the late 1970s has farmed fish played a notable role in the global seafood trade.

For the past 20 years, the world's fisheries have struggled to increase their catch as stocks deplete from overfishing. But demand for seafood continues to increase, and most of the additional supply is coming from fish farms. About 80% of farmed fish now come from Asia, most of that raised in China.

Wild fisheries also supply the fish meal consumed by several types of farmed fish, particularly popular species such as salmon, shrimp, and trout. Some ambitious farmers have plans to raise tuna and halibut, which also prefer to dine on other fish.

Fish meal is made primarily from wild-caught menhaden, herring, sardines, anchovies, and increasingly, squid. It has quadrupled in price over the past two decades to more than $2,000 per metric ton, according to market data firm Quandl.

As a result, much of the protein and lipids in feed now come from plant sources, commonly soybeans. Salmon diets contain as little as 12% fish meal, down from 40% only a few years ago. But going still lower will require a wholesale revamping of feed ingredients and formulations, experts say.

For example, a diet with too much soy protein is hard for fish to digest because it contains what feed experts call antinutritional factors—compounds that inhibit protein-digesting enzymes. That can slow growth and increase the amount of feed needed. Feed producers are responding with new forms of affordable, digestible protein.

Last year, the agribusiness giant Archer Daniels Midland (ADM) introduced a protein ingredient made of dried *Saccharomyces* yeast obtained from corn ethanol operations. “The protein is palatable and supplies highly digestible amino acids,” says Hong Yang, Asia director for ADM Animal Nutrition. ADM is already seeing early adopter customers placing orders, Yang says.

The potential for single-cell organisms in aquaculture feed has created an opening for biotech firms as well. Last November, ADM rival Cargill and the start-up Calysta announced plans to scale up production of FeedKind, a protein source made of methane-fermenting bacteria. They plan to make the protein in Memphis in what they say will be the world’s largest gas fermentation facility.

Cold water fish eat smaller fish that get the omega-3s from algae. Firms want to bypass the middle fish and supplement diets directly with algal oil.

“Our product is extremely high value because of its low fiber content,” says Alan Shaw, Calysta’s chief executive officer. He says Calysta used directed genome evolution to develop

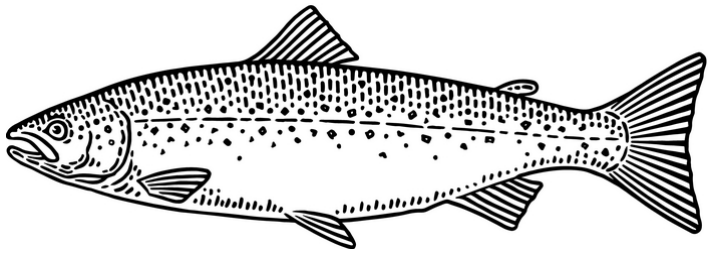
tailor protein's amino acid profile to precisely meet the nutritional needs of fish, specifically salmon.

Now, Shaw says, the partners are working to drive down the cost of producing the protein. His goal is to quickly enter the market so that FeedKind will be the market standard. "We believe if you build the road, the cars will come," he says.

Meanwhile, Lowell, Mass.-based start-up KnipBio is **developing a protein <http://dx.doi.org/10.7717/peerj.3170>** based on the microbe *Methylobacterium extorquens*. As the name implies, it's a bacterium that can live on methanol. KnipBio worked with university researchers to test its protein on white shrimp, smallmouth grunt, and Atlantic salmon. They also conducted taste tests of the protein-fed fish with consumers.

Other start-ups are looking at insects and insect larvae as an alternative protein. The idea should be familiar to fish, many of which eat insects in the wild.

AgriProtein, based in South Africa, has raised venture funds to build facilities where black soldier fly larvae will be fed food waste and then processed into a protein meal. "Trials show MagMeal performs similarly to fish meal in diets, but we also see improvements in animal health," says Cobus Kotze, AgriProtein's director of business development.



The company is working to quantify those improvements under real-world farming conditions with trout producers in South Africa and prawn producers in Southeast Asia. "Feed producers have been very positive," Kotze says, "and they are excited to finally have a viable alternative protein source to fish meal."

Similarly, the French start-up Ynsect is in the process of raising $35 million to build a facility for growing mealworms. CEO Antoine Hubert says the insect protein has a positive impact on fish weight and can boost disease resistance. And insect production is not affected by the changes in seasons and ocean currents that can create price swings for fish meal.

Cold water species such as salmon and trout require diets that contain the omega-3 fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), heart-healthy oils that

give those fish a good reputation with consumers. In the wild, these fish eat smaller fish that in turn get the omega-3s from algae.

Now, a number of firms want to bypass the middle fish and supplement salmon and trout diets directly with omega-3-rich algal oil. Veramaris, a joint venture between Evonik Industries and DSM, plans to spend $200 million to build a U.S. facility to make the oil. It's already distributing test quantities of algal oil from a pilot plant.

The algae will be fed sugar and grown in tanks without sunlight, in a process similar to those used with common fermentation microbes such as *Escherichia coli*. "But algae are a different organism, so we need to develop the right fermentation conditions," points out Christoph Kobler, head of sustainable healthy nutrition at Evonik. "You need to mimic the salt water of the ocean."

And the partners developed a "totally new approach" to extract the oil, which Kobler says is more valuable than whole algae because it has less of an impact on the overall feed formulation.

They will have competition. Last year, ADM introduced an algal oil with 17–20% DHA derived from its own proprietary strain. Cargill has taken a different path. It inserted algal fatty acid genes into canola plants so the crop can supply both DHA and EPA. But the canola won't reach the market until after 2020.

Such products hold the promise of creating fish food that performs more like fish meal than today's plant-derived inputs. "Over the years the amount of fish meal in fish diets has been reduced. Normally, growth slows down," says Ray, the Idaho trout farmer. "There's no argument—the best food for a fish is another fish."

Fine-tuning fish health

Fish Story

Aquaculture provides more than half of the world's seafood.

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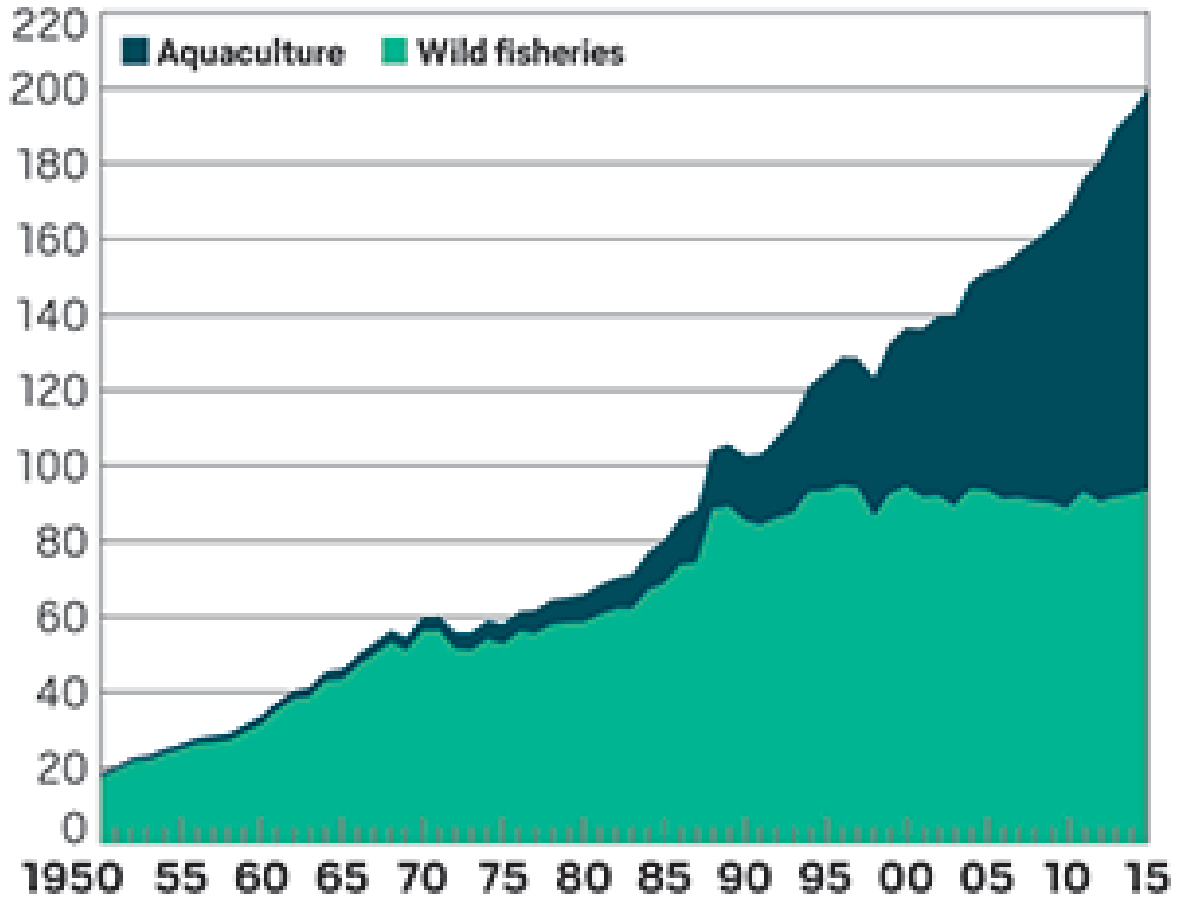
Seafood production, million metric tons

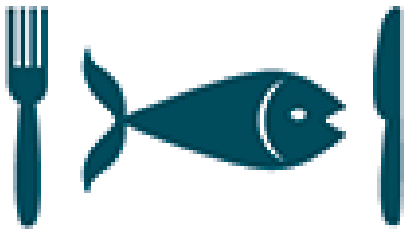


1.2%

Annual growth rate of wild fisheries' production

5.8%

Annual growth rate of aquaculture production



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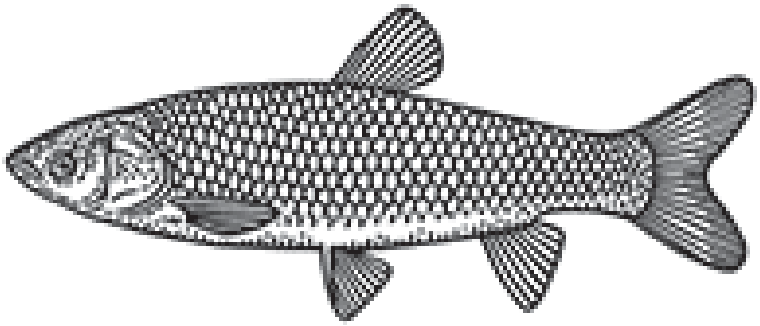
20 kg

Amount of fish consumed per capita worldwide in 2014

31%

Share of global fish stocks that are overfished



Grass carp

(Ctenopharyngodon idellus) is the world's most common farm-raised fish

Credit: Will Ludwig/C&EN/Shutterstock

To produce 1 kg of ...

... beef requires **8.7 kg** of feed

... pork requires **5.9 kg** of feed

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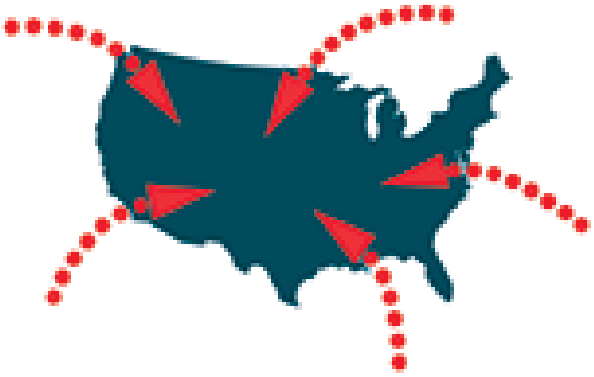
... chicken requires **1.9 kg** of feed

... salmon requires **1.2 kg** of feed

In the U.S.

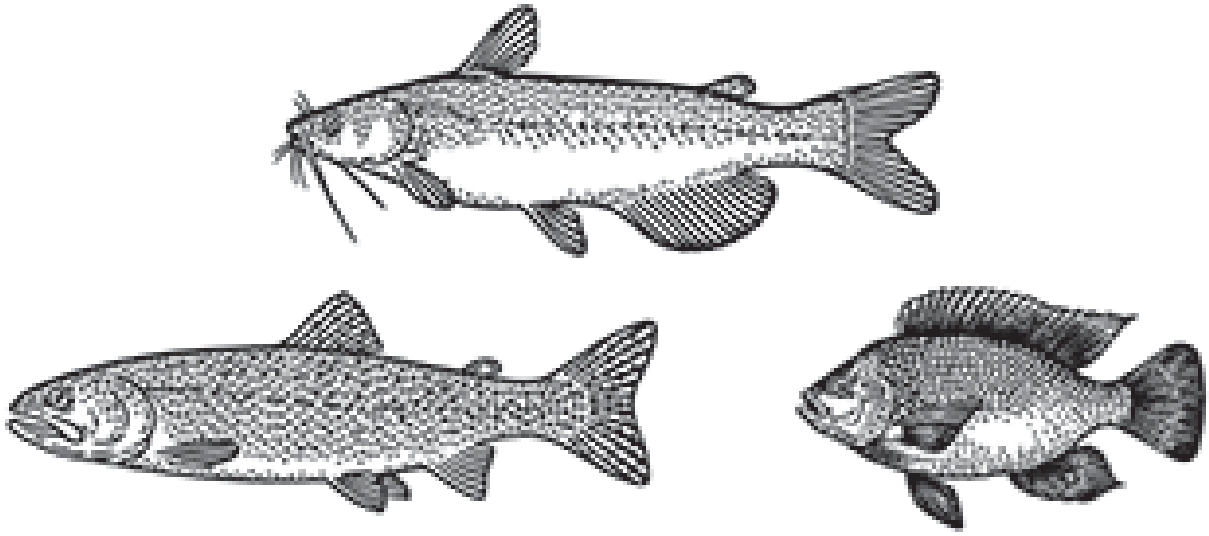


$1.1 billion

Annual value of the farmed fish industry

91%

Share of seafood that is imported



Catfish, trout, and tilapia

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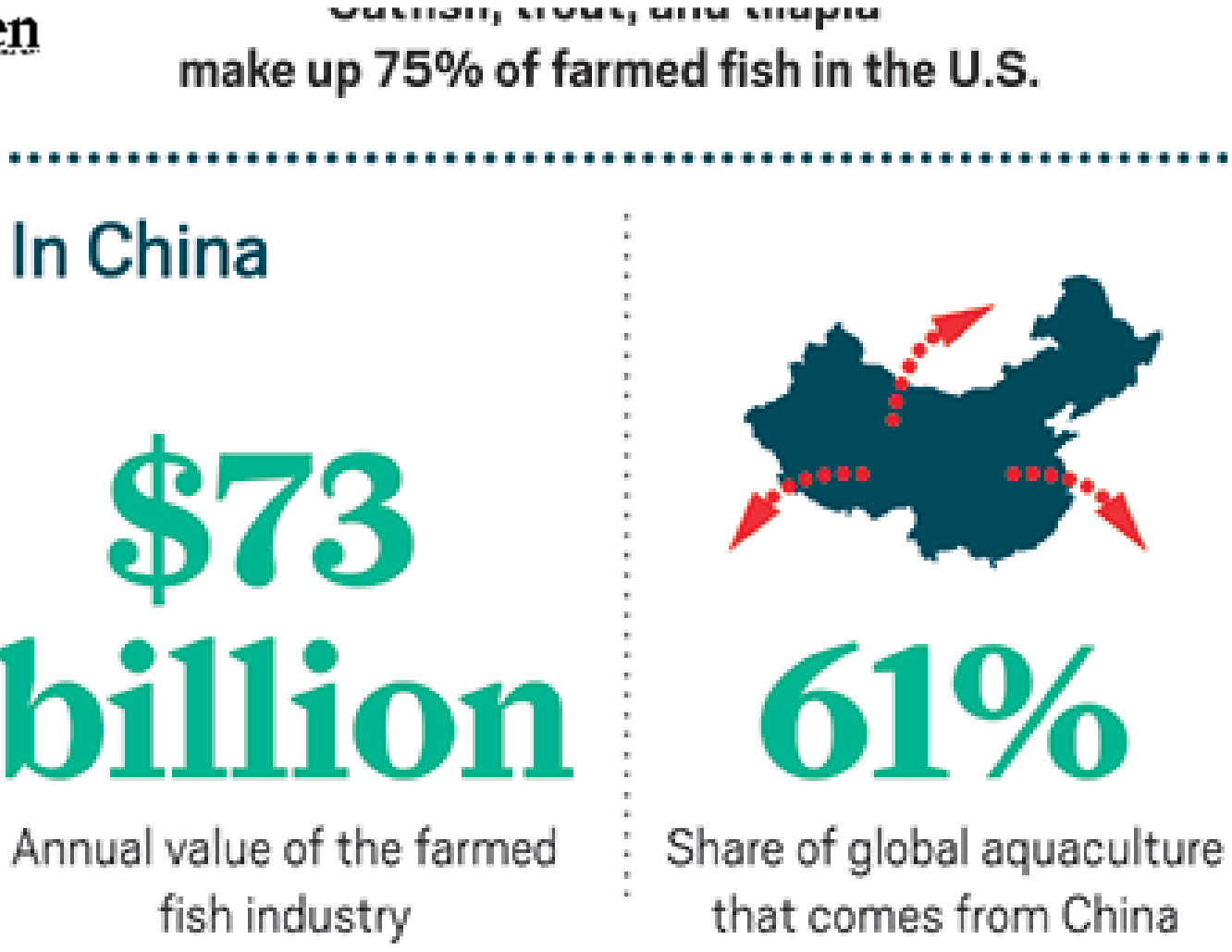


Sources: United Nations Food & Agriculture Organization, National Oceanic & Atmospheric Administration

Credit: Will Ludwig/C&EN/Shutterstock

“You are what you eat” and “Let food be your medicine” are diet tropes that are as true for fish as they are for humans. The connection between nutrition and fish health is quite direct, experts say. For one thing, there is the issue of poop.

In a fish farm environment, whether it’s a large net in the ocean, a concrete raceway-style channel, or a brackish pond, the presence of fish feces—along with any uneaten food pellets—alters the fish’s surroundings.

“If you produce too much feces, then nitrogen, ammonia, and phosphate lead to eutrophication of the water. You are in a bad spiral that is an ideal atmosphere for pathogens,” Evonik’s Kobler explains. Microbes and other small creatures that grow on the nutrients can also metabolize a lot of the oxygen in the water. Diseases that thrive in this environment and low oxygen levels stress out the fish and weaken their immune systems.

In shrimp farms, the problem was historically addressed with large amounts of antibiotics. Salmon farmers have to let sea cages lie fallow for months to let the collected residue break down.

A newer approach is more efficient aquaculture feeds that control the amount of waste. Enzymes that help animals absorb more nutrients from feed can make a big difference. They include phytases for releasing phosphate from plant material, proteases for breaking down protein, and enzymes that make carbohydrates easier to turn into energy.

“There is a great interest in enzyme technology, which is ubiquitous in pig and poultry industry and increasingly in warm water aquaculture,” says David Nickell, head of marketing for DSM Nutritional Products. “You end up growing more fish with the same amount of feed or the same fish with less feed.”

To keep fish from getting sick, feed makers also add vitamins, minerals, organic acids, and amino acids.

Fish have different immune systems than mammals, Nickell explains. The mucus that coats the skin of finfish contains compounds that kill bacteria and fungi. But pathogens can get into fish via injuries or the digestive tract. That’s when an army of white blood cells—phagocytes—springs into action. At times, though, the response can lead to inflammation and openings in the skin and gut that disease organisms can exploit.

The antioxidant and anti-inflammatory vitamins C, D, and E can help, Nickell says. DSM’s aquaculture ingredient blends also contain prebiotics, probiotics, and nucleotides. The nucleotides, for example, provide raw materials for fish to quickly manufacture more white blood cells.

More is known about the immune systems of salmonids—salmon and trout—than about other farmed fish species’. When the industry began scaling up in the 1980s and early 1990s, bacterial and viral disease outbreaks caused huge fish die-offs. But scientists learned that salmon have a rudimentary antibody-based immune system. That enabled Merck Animal Health and other companies to develop vaccines that are now in wide use.

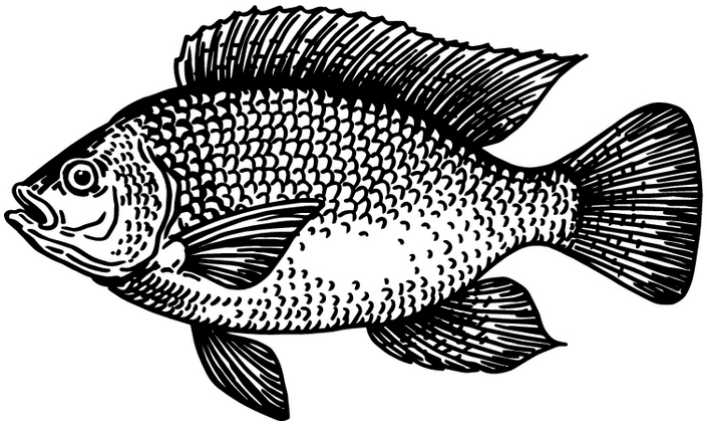
“With vaccines we see massive decline in antibiotic use,” says Chris Beattie, head of Merck’s aquaculture business. But fish disease outbreaks come in waves. “You tend to solve one challenge, and another crops up three or four years later,” he observes.

Ulvetanna's newest salmon vaccine, introduced in Norway, contains seven antigens that protect against five major bacterial and viral diseases. The vaccines are mainly delivered by injection when the fish are young. Although that sounds like a hassle, machines can automatically sort and inject the fish, which are normally sedated for the procedure. Beattie says tilapia farmers are now starting to use vaccines as well.

But there are no vaccines for shrimp diseases yet. In fact, not much is known about the shrimp immune system. What's more, it's difficult to monitor shrimp feeding rates and health because they are raised in low-visibility ponds containing phytoplankton and algae that produce oxygen and food.

That's why the shrimp experts at Novozymes and Bayer Animal Health are working with farmers in Thailand and other countries on good farming practices. Kevin Mann, business development manager at Novozymes, says his team stresses a holistic approach to maintaining healthy ponds. That includes not overfeeding, selecting disease-resistant shrimp stock, and keeping away disease-carrying birds and other animals.

Novozymes produces naturally occurring microbes that help maintain pond water quality so that shrimp don't live in stressful conditions and pathogens can't thrive. "They are designed to be used as preventative strategies—like a probiotic for the environment," Mann explains. One community of microbes prevents the buildup of hydrogen sulfide by metabolizing it. Another helps moderate the growth of algae to avoid algal population booms and crashes.



The goal is to reduce the shrimps' susceptibility to disease without the need for antibiotics. Overuse of antibiotics can encourage disease-resistant organisms to emerge that could impact farmed—as well as wild—populations.

A different sort of resistant organism is causing headaches at salmon farms in Norway and Scotland. Farmers there add chemicals including emamectin benzoate to feed to control

parasitic sea lice, which attach to the outside of salmon and eat their mucus and skin. **Thanks to the spread of resistant lice <http://dx.doi.org/10.1016/j.pt.2014.12.006>** , infestations, which can severely reduce output from salmon farms, have been on the upswing.

A sea lice problem in Western Canada inspired Stephanie J. Peacock, now a postdoctoral fellow in biological sciences at the University of Calgary, to look for answers. She was able to rule out chemical resistance as a cause for the outbreak in British Columbia. There, plentiful wild salmon, which are not treated with emamectin, prevent resistance to the chemical by serving as hosts for nonresistant lice, she explains.

Peacock's research suggests that the lice population exploded mainly because treatment timing didn't account for warmer water temperatures. "In a warm year like 2015, not only are lice growing faster and need to be controlled earlier, but the wild salmon may also be coming by sooner than you thought," Peacock says. The lice spread between wild and farmed populations, and the abundance of farms means lice no longer die out in the winter.

Raising fish sustainably

In many ways, farmed seafood rates high for sustainability compared with other animal protein. Much less feed is required to produce a kilogram of seafood than the same amount of beef or pork, for example. Fish farms also don't use hormones or antibiotics for the purpose of making fish grow faster.

Yet for some consumers, aquaculture has a rather fishy reputation. Fish farms have been accused of destroying sensitive mangrove and coastal habitats, corrupting wild populations, and dumping chemicals and antibiotics into waterways.

The **Seafood Watch <http://www.seafoodwatch.org>** program of the Monterey Bay Aquarium publishes guides to help consumers choose farmed fish that do not negatively impact surrounding ecosystems. Taylor Vorees, a senior aquaculture scientist at Seafood Watch, says fish farmers in both the West and Asia are well aware of consumers' desire for more sustainably raised seafood. "We're being asked 'You rated us red; can you help us improve?' "

Vorees stresses that Seafood Watch's focus is on the systems used to raise fish—where they are sited and to what degree they allow nutrients, chemicals, or animals to escape into the environment. He says most fish farms have improved those variables.

"A lot of consumers might think about salmon farming the way it was in 1992, when it had serious issues," Vorees says. Most categories of farm-raised salmon still get a red rating, he acknowledges. "But the industry has come a very long way."

One ongoing concern is the use of antibiotics for diseases that can't yet be controlled by vaccines. The problem is compounded in Asia because assessments are hampered by a lack of data. Seafood Watch is part of an international collaboration to improve tracking and environmental practices at Asian shrimp farms.

Thanks to pressure from consumers, more retailers and restaurants are relying on third-party certification schemes that audit the practices of specific fish farms. Producers that meet stringent criteria for ecosystem impacts, feed traceability, disease management, and social responsibility can use the logo of the Aquaculture Stewardship Council. Other auditing and label programs include Friend of the Sea and GlobalGAP

Whole Foods, a major buyer of trout from Fish Breeders of Idaho, enforces its own standard. "Nobody is pickier about what they get than Whole Foods," Fish Breeders' Ray says. "The inspection takes about four solid days. They go through all of our records. We can't use any chemicals or antibiotics."

Some companies see sustainability concerns as a business opportunity. One way farms can avoid impacting the environment is to move indoors. In the Pearl River Delta region of Southeast China, Sino Agro Food is building what will be dozens of 8,000-m^2 facilities to grow freshwater giant prawns.

Constructing the buildings and equipping them with recirculating water filtration systems requires a lot of up-front capital, says Anthony C. Ostrowski, chief scientific officer of Sino Agro. But the company benefits from higher-density, **year-round prawn production <http://sinoagrofood.com/?q=content/Zhongshan_project_FAQ>** .

Local consumers pay more for Sino Agro's live prawns than for chilled or frozen ones, Ostrowski says. "And there is high demand for product that is certified sustainable, raised in a good environment, with no chemicals or antibiotics." Over the next 20 years, he predicts, indoor farms will grow in importance. They require less land than ponds, and the fish don't escape into the wild.

The amount of land devoted to raising soybeans and other crops to feed fish is significant as well. **A recent study <http://www.sciencedirect.com/science/article/pii/S0160412016300587>** by researchers at Johns Hopkins University and elsewhere estimates that in 2008, 100,000 km^2—about the area of Iceland—was used to grow feed for aquaculture. Jillian P. Fry, aquaculture project director for the Johns Hopkins Center for a **Livable Future <http://www.jhsph.edu/research/centers-and-institutes/johns-hopkins-center-for-a-livable-future/projects/aquaculture>** , says aquaculture's growing impacts on crop land and water use are not well represented in measures of sustainability.

Companies like Calysta that use industrial fermentation to produce protein and omega-3 feed ingredients counter that their methods will help relieve pressure on land-based agriculture that is used for feed crops.

The venture capital firm Aqua-Spark, one of the backers of Calysta, is seeking yet more sustainable methods. It has invested in start-ups pursuing land-based production of fish such as Arctic char and halibut in facilities that minimize contact with the environment.

"We had learned that there was very little investment activity in a sector that is expected to double at least—or ideally triple—by end of the century," says Aqua-Spark founder Mike Velings. "Our idea is to add technology to the farm and help with market access and distribution."

Velings says he'd like to make as many as 60 investments all along the aquaculture supply chain. "Our goal is to show you can have a healthy, affordable, sustainable fish farm with good financial returns and at scale—so that no one has an excuse not to do the right thing."

Aquaculture comes in many flavors

Farmers around the world raise around 500 species of fish and shellfish using practices that vary widely. Atlantic salmon are raised in Norway, Chile, Canada, Scotland, and Maine in sea net cages that are generally located in protected ocean zones such as coastal bays (1). But a high density of salmon in one area can put too many nutrients in the water and attract pathogens and parasites. In the future, cages will likely move farther out to sea to take advantage of strong ocean currents.