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Seaweed farmers in Tanzania tend to their crops. Not only is seaweed a nutritious food, but cultivating it can help to ease ocean acidification.

Cultivating a sea change

Can aquaculture overcome its sustainability challenges to feed a growing global population? **By Sarah DeWeerdt**

On a summer morning in 2019, Andy Suhrbier pilots a small aluminium boat out to a mussel raft in a quiet cove on the eastern shore of Puget Sound in Washington State. As the boat approaches, a mother seal and her pup resting on the raft slip into the water. Suhrbier climbs from his boat onto the raft; the only sign of life is a vague smell.

Suhrbier tugs on a couple of ropes attached to one of the raft's beams. Soon, a mesh-lined plastic cage emerges with water and silt pouring out of it. He picks off several sea stars and tosses them back into the water, then flips open the lid like a pirate opening a treasure chest.

Inside is more dark sediment – mostly waste from the mussels, the source of the smell. Suhrbier sifts through it. He is looking for something.

"Look at this monster!" he says, holding up a sea cucumber nearly a foot long. Its deep red body covered in orange bumps stands out from the muck like a gold doubloon. "That's definitely market size."

Suhrbier is a biologist with the Pacific Shellfish Institute in Olympia, Washington, a non-profit research organization that works to promote healthy wild shellfish populations and sustainable shellfish aquaculture along the US west coast. Two years earlier, he had put sea cucumbers in cages and suspended them beneath the mussel raft, as part of an effort to develop aquaculture in Puget Sound. The hefty size of the cucumbers is a promising sign.

Suhrbier and his colleagues think that sea-cucumber farming could have two benefits. First, the animals could help to prevent excess waste from building up underneath aquaculture installations, such as mussel rafts or net pens used to hold bony fish such as salmon. (Sea cucumbers, soft-bodied animals related to sea urchins, move slowly over the sea floor eating detritus – the vacuum cleaners of the ocean.) Second, a ready source of farmed sea cucumbers could reduce the poaching of wild stocks to feed the growing market in east and southeast Asia.

Globally, aquaculture produced 82.1 million tonnes of aquatic animals in 2018, and wild fisheries produced 97 million tonnes, according to the United Nations' Food and Agriculture Organization (FAO). But the value of farmed fish was higher, around US$250 billion compared with $151 billion for wild-caught fish. Aquaculture production of animals is projected to increase by one-third by 2030, reaching 109 million tonnes, and will supply the majority of aquatic protein in people's diets by 2050.

"We need to grow the amount of seafood available, as world populations grow, to provide enough protein for everybody," says Monica Jain, founder of Fish2.0 in Carmel, California, an organization that promotes investment in sustainable seafood businesses. With the catches from wild fisheries remaining largely flat and some stocks already overexploited, "aquaculture is really the only way to do that". But as the industry grows, Jain and other aquaculture advocates want to make sure that it does so sustainably.

Double alchemy

Aquaculture is a relatively small proportion of the global food system – terrestrial meat production (both livestock and wild game) totalled around 342 million tonnes in 2018, and production of grains and cereals was 2.7 billion tonnes. However, aquaculture is more diverse, particularly in terms of the animals farmed. These range widely across taxonomic groups, including bony fish (carp, tilapia and salmon, for example), crustaceans (shrimp, prawns and crayfish), molluscs (clams, oysters and mussels) and echinoderms (sea cucumbers). Various species of seaweed are also gathered. There are freshwater, saltwater, brackish water and self-contained terrestrial aquaculture systems. And each has its own sustainability benefits and challenges.

One subsector that offers huge environmental advantages and has no equivalent in terrestrial agriculture is non-fed aquaculture. Marine bivalves, such as clams, mussels and oysters, get their nourishment by filtering microscopic plants, detritus and nutrients from the water that surrounds them. They require minimal inputs and can even improve the water quality. In this sense, Suhrbier's sea cucumbers represent a kind of double alchemy: non-fed aquaculture species grown on the wastes of other non-fed aquaculture species.

Similarly, cultivated seaweeds can remove excess nutrients, such as nitrogen, that contribute to the formation of areas of oxygen-poor water where marine life has difficulty surviving, known as dead zones. By taking up carbon they can also help to alleviate ocean acidification at a local scale. Moreover, "seaweeds are incredibly nutritious," says Alecia Bellgrove, head of the DeakinSeaweed Research Group at Deakin University in Warrnambool, Australia. "They are, for example, fantastic sources of trace minerals, which are often lacking in our diets based on terrestrial foods."

Aquatic animals that require feed – mainly prawns and bony fish – also have an environmental advantage over animals raised in terrestrial agriculture. Because most are cold-blooded, they convert food into body mass more efficiently than birds and mammals, which need energy to help regulate their body temperature. So it takes less feed to produce a kilogram of salmon, for example, than it does to produce a kilogram of, say, beef or pork.

However, some of the most lucrative aquaculture species are carnivorous, and therefore sit higher in the food chain than any terrestrial species raised in agriculture. Take the Atlantic salmon (*Salmo salar*), for example. In the mid-2000s, salmon aquaculture, now a $15.4-billion industry, was growing rapidly. Feeding the salmon demanded an increasing share of the world's fish meal and fish oil, which was sourced from small forage fish, such as anchovies, sardines and capelin. But while demand from the salmon farms grew, fishing yield for the forage species remained relatively flat. It took at least 4 kilograms of wild-caught forage fish to produce just 1 kilogram of salmon.

"Our farming practices resulted in the net production of fish on the planet."

From an environmental point of view, "It made no sense," says Scott Nichols, founder of Food's Future, a consultancy in West Chester, Pennsylvannia, which promotes the development of sustainable aquaculture businesses. As a biochemist working at US chemical company DuPont in the mid 2000s, Nichols helped to develop a way to produce omega-3 fatty acids from yeast. The fatty acids were then incorporated into salmon feed to replace some of the wild-fish component. The new feed was tested through a partnership between DuPont and the aquaculture firm AquaChile based in Puerto Montt, Chile, in the form of the salmon producer Verlasso in Miami, Florida.

"We were able, after a couple of years of production, to get to the point where for every kilo of salmon that was produced, we were using less than a kilo of wild-caught fish," Nichols says. "So our farming practices resulted in the net production of fish on the planet."

Other companies soon joined in, producing omega-3s in genetically engineered canola oil or single-celled algae. Meanwhile, fish-oil and fish-meal producers are increasingly making use of fish trimmings and other by-products that previously went to waste. Fish meal and fish oil, which are still used in a variety of aquaculture feeds, as well as in products such as food supplements, accounted for around 10% of the world's total fish production in 2018, according to the FAO. But nonetheless, Nichols takes heart from developments. "What looked on the face of it to be dismal in 2006 now looks to be very promising," he says.

Disease detectives

An increasingly important threat to aquaculture sustainability is disease, which affects all subsectors of aquaculture and causes an estimated $6 billion worth of aquatic animal losses every year. Diseases include parasites called sea lice in salmon; white spot syndrome virus in prawns, which emerged in the early 1990s and devastated prawn farming throughout Asia before spreading to the Americas; and tilapia lake virus, which threatens the economic and nutritional gains that freshwater aquaculture has made possible in many low- and middle-income countries.

As aquaculture is scaled up, the problem of disease will also become greater. "As you expand the volume of production, you are going to get significant losses," says Grant Stentiford, a pathologist and head of aquatic animal health at the Centre for Environment Fisheries and Aquaculture Science, Weymouth, UK. "You've used up potentially large amounts of resource to get absolutely nowhere."

To deal with such threats, some large producers who supply the export market are moving to self-contained, land-based systems. Others are moving away from the coast into deeper waters that might dilute the threat of disease. Vaccines have also made a difference, reducing not only the threat of many fish diseases, but also antibiotic use – another major environmental concern about the industry. And high-throughput sequencing of the microbial DNA in aquaculture systems could provide early warning of disease outbreaks.

But many of these solutions are expensive and, therefore, out of reach for the small and medium-sized producers who make up the majority of the global aquaculture industry, producing food for subsistence or local markets in low- and middle-income countries. Moreover, diseases that threaten aquaculture are emerging every three to five years on average. The dearth of knowledge about aquatic

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Sea cucumbers are retrieved from the mesh-lined cages at Puget Sound in Washington state.

pathogens makes diseases hard to predict and spot.

It can also be a challenge to deduce their cause. For example, ice-ice disease results in bleaching of *Kappaphycus* seaweed, which is grown in large amounts in southeast Asia and Tanzania for the production of food additives, such as the thickening agent carrageenan. The disease has caused yields to plummet over the past decade, but "the causative agent is still not known", says Valéria Montalescot, senior project manager for GlobalSeaweed-STAR, a four-year research project based at the Scottish Association for Marine Science in Oban, UK, which aims to boost knowledge about seaweed cultivation in low- and middle-income countries. *Kappaphycus* is usually grown from cuttings, so the whole crop across multiple countries might be the result of just a few clones, possibly making it more vulnerable to disease, Montalescot adds.

Diverse yields

Climate change is complicating efforts to fight disease. Higher water temperatures can alter the microbial community of a body of water, encouraging the growth of pathogens, as well as stressing organisms and making them more vulnerable to disease. One suggested cause of ice-ice disease is that temperature-stressed seaweeds release compounds that attract bacteria, for example.

And temperature is not the only issue. Both increased rainfall and salinity intrusion from sea-level rise can alter water chemistry in ways that are detrimental to aquaculture organisms. Storms can destroy aquaculture crops or infrastructure in the water and on land. "From an environmental point of view I think climate change is the greatest challenge" for the sustainability of aquaculture systems, says Nesar Ahmed, who studies global seafood sustainability at Deakin University's Melbourne campus.

Climate change also intersects with aquaculture's pressure on water and land resources. Inland aquaculture demands 429 cubic kilometres of fresh water each year — much less than the demand from terrestrial agriculture, but still enough to pose a strain on increasingly drought-prone areas.

In south and southeast Asia, prawn cultivation has contributed to the destruction of 38% of the world's mangrove habitats, which have a variety of important ecological functions, including sequestering carbon and buffering coastlines from storms and sea-level rise. The loss of mangroves has also resulted in saltwater intrusion rendering inland areas unsuitable for terrestrial agriculture.

Some farmers are now producing prawns among intact mangrove stands. Although there are concerns that this practice might also damage the health of the mangroves, it is part of a larger trend to create aquaculture systems that include multiple species and involve interrelationships more like the ones that keep natural ecosystems in balance.

Some examples of this integrated aquaculture are long-established, such as stocking rice paddy fields with fish or prawns. The animals eat pests and fertilize the rice crop, increasing rice yields and providing an extra source of protein or income for small-scale farmers, Ahmed says. Growing two species in a single body of water also reduces overall water use.

This type of rice–fish system has been practised for hundreds of years in China and has been designated a Globally Important Agricultural Heritage System by the FAO — a designation that aims to preserve agricultural knowledge that can contribute to a more sustainable and resilient food system. Large-scale aquaculture operations, such as Cooke Aquaculture based in Blacks Harbour, Canada, have also been experimenting with multi-species systems. The company keeps salmon in net pens near both mussel and kelp rafts in the Bay of Fundy, Canada.

In theory, integrated aquaculture can help to increase yields, decrease risk by diversifying operations, and is generally a more environmentally sound form of aquaculture. But in practice, it can be difficult to quantify these benefits. For example, because nitrogen moves freely through water, it is difficult to track uptake of excess nitrogen produced by bony fish by seaweed growing nearby. And then there are the complexities of managing an operation with multiple species — not just producing them but also harvesting, processing and marketing them.

Suhrbier knows such difficulties well. The sea cucumbers he and his team harvested from under the mussel raft were the right size, weight and colour for the export market, but the mussel producer he was working with was unable to renew its permit at that location. The raft was lost, and with it Suhrbier's chance of follow-up experiments to develop sea-cucumber aquaculture techniques. "I was really shocked and saddened to see that go because it was one of those places where it just makes a lot of sense for sea cucumbers to be," Suhrbier says. The new location of the producer's rafts isn't a good habitat for sea cucumbers.

Suhrbier is still experimenting growing sea cucumbers alongside other types of aquaculture operation around the Puget Sound area. But, like an increasing number of aquaculture researchers, he is beginning to think that producing the animals needs to move in a simpler and more radical direction. Growing sea cucumbers in cages is labour intensive. What if the animals are placed in the vicinity of aquaculture operations and left to roam freely — like a marine equivalent of a ranch or even a permaculture system?

"If we could mainly enhance the wild population around these areas, I think that would be a great benefit for everybody," Suhrbier says. "I'm trying to have something that fits in: easy, cost effective and as passive as it can be."

Sarah DeWeerdt is a freelance writer in Seattle covering biology, medicine and the environment.

Correction
This article gave the wrong campus location for Alecia Bellgrove, who is at Deakin Univer-sity in Warrnambool. Nesar Ahmed is at the university's Melbourne campus.