Aquaculture's Turquoise Revolution

LESLEY EVANS OGDEN

Multitrophic methods bring recycling to the seas.

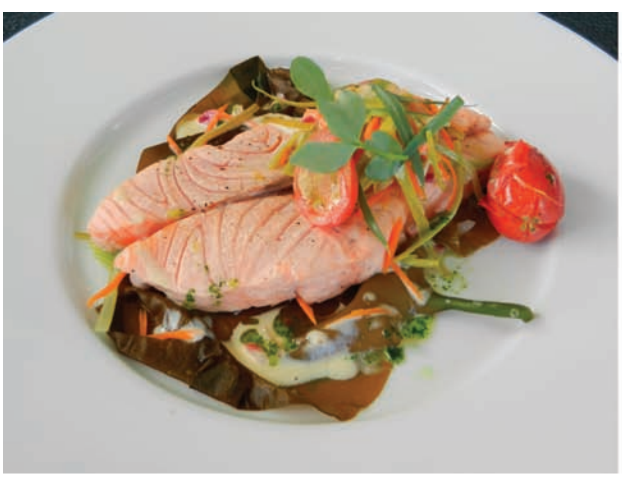
On the menu at the Rossmount Inn in Saint Andrews, New Brunswick, on the Atlantic coast of Canada, you may find kelp-wrapped salmon–avocado tartare with sesame cranberry–apple vinaigrette, citrus–soy glaze, cilantro, and chives. It sounds mouthwatering, but this is no ordinary seafood. The farmed seaweed (*Saccharina latissima*) and Atlantic salmon (*Salmo salar*) are not only side by side on the plate; they've been grown side by side, too. Like the old adage *one man's junk is another man's treasure*, at Cooke Aquaculture in New Brunswick, wastes from farmed salmon provide food for farmed seaweeds attached to ropes downstream, and rafts of blue mussels (*Mytilus edulis*) are also getting in on the nutrient bonanza. It's a culturing method known as *integrated multitrophic aquaculture* (IMTA), which follows from the idea that in natural ecological communities, nutrient waste from one organism is reused as food for the next. In nature, the efficiency of nutrient recycling is not 100 percent, but natural ecosystems are thrifty. Little is truly wasted.

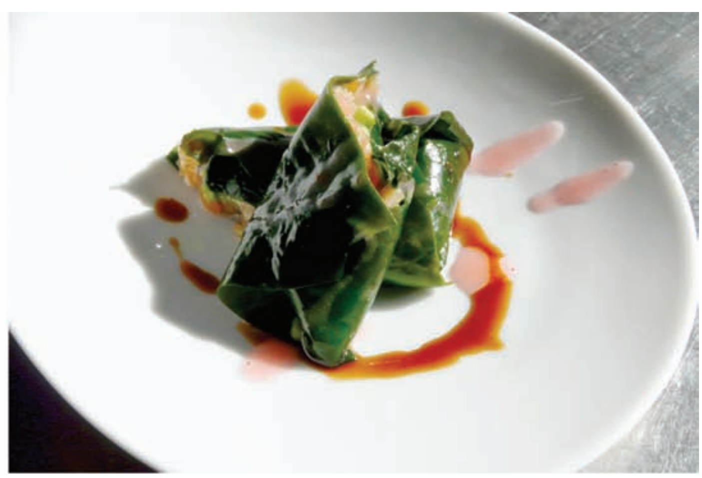
Nutrient recycling is at the heart of Thierry Chopin's dream of a "turquoise" revolution. IMTA, hopes Chopin, will help aquaculture move toward more sustainable systems. Chopin, a professor at the University of New Brunswick and scientific director of the Canadian Integrated Multi-Trophic Aquaculture Network, believes that by shifting from single-species intensive operations to multispecies systems that mimic the functioning of natural ecological communities, we may green aquaculture's blue revolution—to turquoise.

Blue revolution: Growing pains

With many wild fish populations declining, in large part because of overfishing and ineffective fisheries management, a classic tragedy of the global commons, there is both increased pressure and increased optimism that aquaculture will step into the breach. Globally, aquaculture is the most rapidly growing sector of food production and is now the source of nearly half the world's seafood supply (see "Suggested reading"), but the rapid expansion and intensification of aquaculture has seen a parallel growth of negative environmental impacts.

In open net-cage aquaculture, such as that of Atlantic salmon, water is





Chef Chris Aerni, of the Rossmount Inn, in Saint Andrews, New Brunswick, created these delicacies from salmon and kelp raised through integrated multitrophic aquaculture. Photograph: Thierry Chopin.

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continuously exchanged between caged fish and the surrounding ocean. Fish respiration, fecal material, and waste food release organic and inorganic nutrients, including carbon, nitrogen, and phosphorus, into the waters. Some nutrient waste (e.g., nitrogen and phosphorus) dissolves and is consumed by phytoplankton and macroalgae (seaweeds), but larger fecal particles and uneaten food quickly sink and can accumulate in seafloor sediments. There, they become available for bottom-feeding animals. In large quantities, however, this material produces a nutrient oversupply, sometimes resulting in oxygen-poor dead zones on the seafloor.

Therefore, even though nutrients are essential for marine biodiversity, when their concentration becomes too high, they become pollutants. "Like chocolate," says Chopin, nutrients are good only in moderation. Aquaculture's nutrient pollution problem has radically improved in recent decades as a result of changes in feed composition and digestibility. These changes have also boosted the conversion efficiency from fish food to fish flesh. Nevertheless, as long as fish are housed at high densities in confined areas, the negative environmental impacts of aquacultural nutrient waste remain a concern.

Alejandro Buschmann, a professor at Chile's University of Los Lagos and researcher at the Centro de

Suggested reading.

Chopin T, Cooper JA, Reid G, Cross S, Moore C. 2012. Open-water integrated multi-trophic aquaculture: Environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. Reviews in Aquaculture 4: 209–220.

Diana JS, Egna HS, Chopin T, Peterson MS, Cao L, Pomeroy R, Verdegem M, Slack WT, Bondad-Reantaso MG, Cabello F. 2013. Responsible aquaculture in 2050: Valuing local conditions and human innovations will be key to success. BioScience 63: 255–262.

Troella M, Joycea A, Chopin T, Neorif A, Buschmanng AH, Fangh J-G. 2009. Ecological engineering in aquaculture—Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. Aquaculture 297: 1–9.

Salmon cages at an integrated multitrophic aquaculture site of Cooke Aquaculture in the Bay of Fundy, with a seaweed raft in the background. Photograph: Thierry Chopin.

Investigación y Desarrollo de Recursos y Ambientes Costeros (Research and Development Centre for Coastal Resources and Environments), explains that nutrient pollution is enhanced more in marine than in terrestrial food production systems as a result of the more three-dimensional nature of the food lot. “In one [surface] hectare, you can have several thousand tons of fish, but you can have only a few cows,” he explains. With fish farming taking place over a relatively small surface area, there is a huge biomass in that small area, with the fish producing high nitrogen fluxes into the environment. In the coastal fjords of southern Chile, where large numbers of salmon farms are concentrated, there has been concern about nutrient pollution from fish excretion, which has spurred the enhanced growth of algae that produces coastal eutrophication, as well as a recognition that perhaps by adding appropriate nutrient-consuming species to the aquaculture system, nutrient wastes could be converted into an economically beneficial resource.

IMTA: (Re)pioneering science

Chopin, originally trained in the physiology and biochemistry of seaweeds, was keenly aware of nutrient impacts from his research on how phosphorus and nitrogen affect macroalgae’s production of natural sugars (carrageenans), which are used in products ranging from orange juice to toothpaste. Understanding that seaweeds need nutrients to grow and that finfish aquaculture releases lots of nutrients, Chopin began to wonder what would happen if the two were combined. His colleague Shawn Robinson, at the nearby St. Andrews Biological Station, run by Fisheries and Oceans Canada (DFO), was pondering the same idea for shellfish. The merging of Chopin’s and Robinson’s ideas marked IMTA’s shaky Canadian beginnings, a phase from about 1995 to 2000 that Chopin describes as “preaching in the desert.”

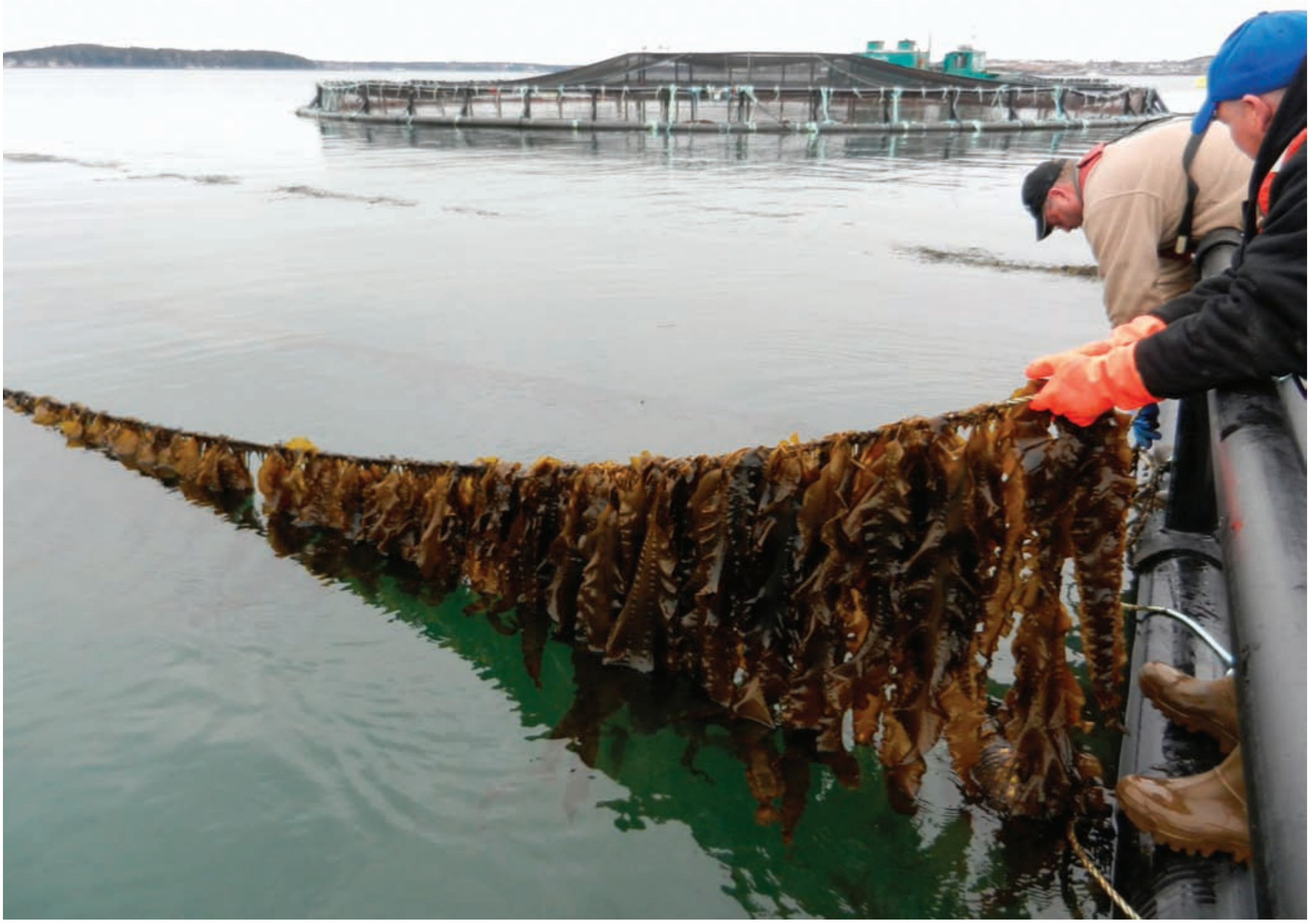
IMTA is, in fact, an ancient concept. Systems similar to IMTA date back thousands of years. Polyculture systems were used in ancient China (2200–2100 BC) and Egypt (1550–1070 BC), for example, in which fish were cultivated alongside aquatic plants and vegetables or in rice paddies. Shaojun Pang, a researcher at the Institute of Oceanology of the Chinese Academy of Sciences, in Qingdao, is investigating cultivated seaweed production techniques in China. The rice–fish system, Pang explains, has traditionally been used in many Chinese provinces, with multiple benefits. The farmers make use of limited land area to produce both crops and fish, and the fish transform nutrients into forms more readily absorbable by the rice, which increases its productivity. As consumers of invertebrates, fish also provide pest control, and in rice–fish systems, the outbreak of fungal infections appears to be reduced.

Examples of modern IMTA in China include farms in which kelp are grown alongside abalone. In Sanggou Bay, in Shandong Province, *Saccharina japonica* (a type of kelp) is attached on long lines in surface waters (1–5 meters), and abalone are grown in cages between the lines. Abalone feed on kelp. Abalone feces, in turn, provide the kelp with nutrients, so “the two components mutually compensate each other,” says Pang. In Fujian Province, several different fish species and abalones are grown in suspended cages in nearshore waters. The seaweeds *S. japonica* and those in the genus *Gracilaria* (used for abalone feed and for making agar, a gelatinous substance used in food and as a medium in microbiology labs) are grown alternatively in different seasons. This simple IMTA is widely adopted in Fujian and Guangdong Provinces, explains Pang, where large daily tidal currents aid with flushing the bays.

In the United States, the late John Ryther, of the Woods Hole Oceanographic Institution and later of the Harbor Branch Oceanographic Institute, in Florida, was a pioneer of IMTA in the 1970s. Ryther’s work on waste-recycling polycultural systems ignited interest long before the practice was termed IMTA. Also involved long before the term was coined was Jack Rensel, an independent aquaculture consultant at Rensel Associates Aquatic Sciences, in Arlington, Washington, who in the mid-1970s developed the polyculture of native spot prawns in and around Pacific salmon net pens.

Since 1999, with support from the National Oceanic and Atmospheric Administration, the US Department of Agriculture, academia, and industry, Rensel and his colleagues at the University of Southern California have been involved in developing geographic information system biophysical models (e.g., AquaModel, *www.aquamodel.org*) that use physical oceanographic inputs, including depth, current, salinity, dissolved oxygen, and flow velocity, to find the best possible sites for fish net pens. Rensel has recently examined the potential for growing Pacific oysters, Gallo (Mediterranean) mussels (*Mytilus galloprovincialis*), and seaweed alongside salmon in farms in Puget Sound. He used stable isotopes to trace nutrient uptake, and the resultant data suggest that salmon farm wastes contribute between 16 and 59 percent of oyster body tissue, varying with season and location. Gallo mussels, he found, were less effective for salmon waste nutrient removal, perhaps because they prefer warmer waters.

However, despite this global history, many recent aquaculture operations in North and South America; Europe; and, increasingly, even in parts of Asia, where polyculture has ancient roots, have been focused on culturing a single species. Chopin likens single-species systems in aquaculture to the dominance of monoculture systems on land. In agriculture, farmers typically specialize in only one species, such as wheat, cattle, or corn. Every single-species system generates environmental and economic issues that parallel intensification, explains Chopin. On land, “the green revolution has increased yields and increased productivity… but in the short term. Now soils are eroding and getting exhausted,” he explains. “On land, we’re rediscovering the value of crop rotation, fallowing, and multiculture.” The same



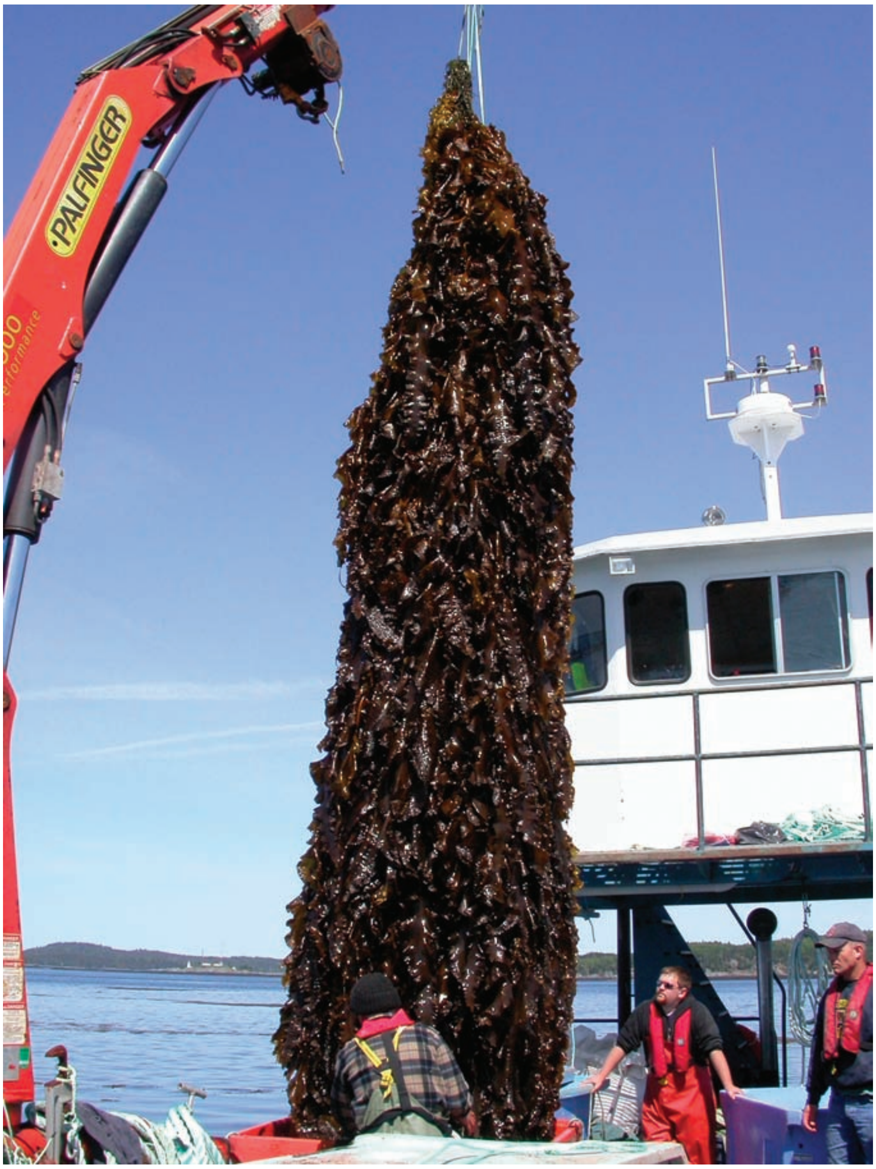
*A line of kelp (*Saccharina latissima*) is held above water near an Atlantic salmon (*Salmo salar*) cage at a Cooke Aquaculture facility. Photograph: Thierry Chopin.*

is occurring in aquaculture, so "there is value in diversification," argues Chopin. It took centuries on land to refine agronomy principles. Chopin thinks that it's now time to approach farming of the sea through the development of "aquanomy."

IMTA means more than just diversifying to a polyculture. *Diversification*, in this sense, means cultivating more than one trophic level such that the wastes from fed organisms such as fish are recaptured and converted to fertilizer, food, and a source of energy for other crops, which would mimic aspects of the more complex marine communities seen in nature.

In the Bay of Fundy, in coastal New Brunswick, Chopin and DFO's Shawn Robinson have championed a pilot IMTA venture through which Atlantic salmon housed in circular cages are flanked by rafts of mussels and rafts of seaweeds further downstream. Mussels can take advantage of small organic molecules, such as the fine-powder leftovers of fishmeal, fish excrement, and naturally occurring *seston* (the tiny living and nonliving particles swimming or floating in the water). Seaweeds make use of the inorganic molecules and "are nutrient sponges," explains Chopin. Direct markets for edible seaweeds are still small in North America, save the local maritime habit of chewing on crunchy dulse (a red alga) and its gourmet incorporation by adventurous local chefs near the IMTA pilot project in New Brunswick, but the market is growing in some unexpected places. Seaweeds are being used for pharmaceuticals and cosmetics and show up in ice cream, dental molds, microbiology labs (agar plates), and wound dressings.

Just as Chopin's IMTA system is, itself, an ecological partnership of several organisms, so, too, is the complex collaboration that has supported his project. The IMTA concept is slowly gaining traction in its transition from a research and development phase to what Chopin describes as "small-C commercialization." Its partners over the years have included natural and socioeconomic scientists from the University of New Brunswick and St. Andrews Biological Station, industrial partners, Canadian government agencies, and private foundations. In Canada, Loblaws supermarket now charges premium prices for what it calls "WiseSource" salmon, raised using



Cultivated kelp (*Saccharina latissima*) at a Cooke Aquaculture integrated multitrophic aquaculture site. A rope of hanging kelp has been folded and is transferred by crane to a container. Photograph: Thierry Chopin.

IMTA, and in Monaco, the manufacturer of cosmetic compounds Exsymol SAM has developed skin care products from IMTA kelp extracts.

Chopin is struck by the idea that, on land, waste recycling has grown in popularity, whereas in the sea, it has not yet been embraced. It's ironic, thinks Chopin, because one of the marine organisms most highly prized as food—the lobster—is in fact a bottom-feeding detritivore. This technical term, he says, disguises the fact that lobsters eat "the garbage of the sea… the excrement and dead bodies fallen on the bottom." When it comes to wild seafood, explains Chopin, "lots of what you eat is a product of recycling at sea." IMTA is an extension of this natural recycling idea, clustering fed (e.g., fish) and extractive (e.g., mussels, seaweeds) species together so that they can exchange nutrients. Like recent interest in the value of carbon credits, Chopin suggests that nutrient-trading credits could one day be established as a means to value nutrient load reduction and recovery—an important ecosystem service—through a credit system that could provide incentives for changes in aquaculture practices.

Expanding the net

Nutrient waste is not the only environmental issue surrounding modern aquaculture. Large fishmeal and fish oil requirements, escape of nonnative species, disease transmission, and the impacts of drug and antibiotic use are additional concerns. On North America's West Coast, another pioneer of IMTA is Stephen Cross, the founder and chief executive officer of Vancouver Island's SEA Vision Group. Cross spent his doctoral studies at the Institute of Aquaculture at Scotland's University of Stirling, investigating the biosafety of coculturing finfish and shellfish. Examining the downstream effects in the water column of salmon aquaculture, Cross found that shellfish and finfish could be cocultured, provided that harvest restrictions were in place for fish treated with antibiotics. His research spurred regulatory changes at DFO and the Canadian Food Inspection Agency to remove the 125-meter spatial restriction that previously prevented multispecies coculturing in close proximity. Cross is now licensed to coculture up to 11 species at his tenure in Kyuquot Sound, British Columbia, where he has been researching the transition to full commercialization of IMTA.

Cross calls his approach *sustainable ecological aquaculture*, because it addresses three pillars of sustainability: the environment, social equity, and the economy. Meeting Canadian organic standards, the system uses only native species, sequesters nutrients, avoids antibiotics, uses reduced stocking densities, and addresses First Nations (the aboriginal peoples of Canada) concerns about aquaculture in their traditional territory. The design uses alternative energy to minimize the system's carbon footprint, replacing typical engines with solar-powered hydraulic systems. Sablefish (*Anoplopoma fimbria*), native to the Pacific Northwest, are the only fed species, and the organic and inorganic extractive species include blue and green mussels, oysters, sea urchins, sea cucumber, sugar kelp, and nori kelp. In conjunction with graduate students at the University of Victoria, Cross's precommercial farm is investigating "some of the bigger-picture questions," he explains. His 18-cage operation is largely self-financed, but, he says, "I have yet to find anybody who doesn't think this is a good idea." He's hoping investors will soon make good on that confidence.

"Canada has a small population compared to [that of the United States]," remarks Rensel, "but they are doing much more IMTA development [than] other places." Still, "IMTA is not a silver bullet," he cautions, adding that, "it doesn't always work, and its success, at present, is very site specific." IMTA in New Brunswick has reached critical mass and is on the leading edge of this work, explains Rensel, but on North America's West Coast, he suggests, "IMTA should perhaps be targeted for less optimally located fish farms, where there is a buildup of sediments on the bottom," adding that it's likely to be more useful and more viable at those sites. Washington State fish farms have for decades been required to monitor sediments and to locate in non-nutrient-sensitive areas, but IMTA may be a useful addition to West Coast sites where benthic nutrient pollution remains a problem.

The future of IMTA

IMTA is an emerging science and practice and, as yet, it's not a sustainable aquaculture panacea. What Robinson, Chopin, and their colleagues have learned recently is that the amount of seaweeds required to soak up 100 percent of the inorganic nutrients being released by farmed fish probably exceeds the amount of seaweed that can be located at their IMTA site. Seaweeds, as photosynthetic organisms, need to be cultivated near the surface, where there is sufficient light, whereas salmon can exist in a greater depth range within the water column. "There's not going to be a one-species solution to the nutrient issue," says Robinson. Much of the organic waste is too big for filter feeders such as mussels to assimilate, although they do take up some of the fine particles and may play other roles at IMTA sites, such as helping control disease and parasites such as sea lice. Research in New Brunswick suggests that about 80 percent of the waste material that comes from the fish farms is settling

Stephen Cross holds up scallops and sugar kelp, two of the extractive species at his Pacific coast integrated multitrophic aquaculture facility. In the background is the shellfish system, a moving gantry that will be solar powered and will allow four workers to service the shellfish section of the sustainable ecological aquaculture system he calls the* SEAfood system. *Photograph: Stephen Cross.

Thierry Chopin's passion for a new paradigm in aquaculture inspired an integrated multitrophic aquaculture performance by Canada's Motus O Dance Theatre. Dancers swirl as kelps, blue mussels, and salmon, interpreting in movement the ecological premise of harmonious cocultivation. It's an art–science dimension that Chopin cunningly phrases as "putting the **culture** ***in*** **aquaculture.*" Photograph: Courtney Pyke.***

to the bottom, with only 20 percent remaining suspended in the water column. In China, however, studies suggest that IMTA seaweeds *are* effective at reducing nutrients, perhaps because of that country's magnitudes-larger and more developed scale of seaweed cultivation.

In the future, Robinson and his colleagues envision IMTA systems that include fish, seaweeds, sea scallops, sea cucumbers, sea urchins, sea worms, and even bacteria. Experimentation with these species has already begun, with mixed success. When the team attempted to put polychaete sea worms in a cage to eat the benthic nutrient fallout, the tiny Houdinis escaped, explains Robinson. "Obviously, there's a bit more to learn on that," he says with a laugh. "The ultimate objective is to create the most efficient engine we can for food production while minimizing the impacts to the environment." If we can increase the efficiency by 50 percent, that means we can grow twice as much food with the same environmental footprint, explains Robinson, adding that "we don't have to reduce its impact to zero for it to be valuable."

One of the greatest challenges that IMTA now faces is creating a workable, commercial, practical system. Using the early iPad and other tablet computers as an analogy for IMTA, Robinson suspects that lots of people are waiting to see who is going to emerge as a market leader. New Brunswick's Cooke Aquaculture has taken a leap of faith on IMTA, a move that Robinson thinks "deserves a pat on the back." Since becoming involved in the project in 2005, Cooke Aquaculture has invested nearly $2 million in IMTA research and development. Frank Powell, Cooke Aquaculture's alternative species manager, says, "It's early days for IMTA… so [it is] difficult to tell at this stage how large a scale it will be." Scaling up farming of new species within a system often depends on getting regulatory approval, explains Powell, but he says that his company will invest in IMTA for the foreseeable future. "As stewards of the marine environment, we strive to continually improve our methods," he adds.

As society begins to care more about food quality and sustainability, Robinson suspects that governments, which often lag behind technologies, will eventually need to introduce new food production systems that move away from managing on a species-by-species basis. We're now looking beyond "just the rabbits, just the deer, and just the wolves" and toward thinking more holistically, says Robinson, and some of our legislation and policies need to move along those lines, he argues. Buschmann agrees that governments have yet to recognize and promote the benefits of more sustainable aquaculture systems and approaches. "A lot of the economic models in the Western world focus on short-term gain; continuous growth; and money, money, money," says Chopin. "The challenge is that in the biological world, you cannot have exponential growth continuously." He cautions that sustained and responsible growth in the long-term should be the goal.

Whether they are dreamers or visionaries, for IMTA scientists and their intrepid commercial partners, the future looks turquoise. Applying truly blue-sky thinking, Robinson suggests there are other good reasons for figuring out how to work within Earth's ecosystems in terms of food production. "If we can't grow food sustainably on Earth, how are we going to do it on Mars?"

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