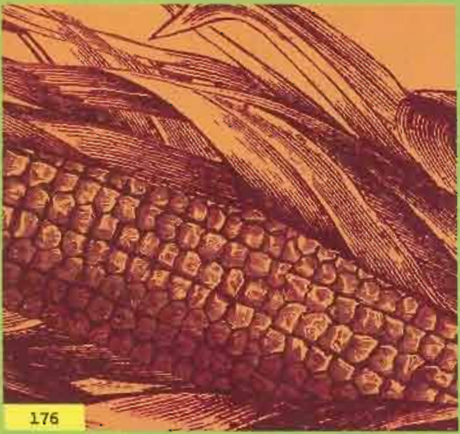
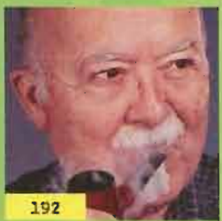

WIRED
MAY 2004
EAT HERE NOW
SUPER ORGANICS
Inside the new science of smart breeding
INFINITE SUSHI!
How robot fish farms will roam the oceans and feed the world
THE FUTURE OF FOOD
NEXTFEST
THE CARS, GADGETS, DRUGS & TV OF TOMORROW
PLUS:
The Cool World of Low-Temperature Surgery
Inside Frank Gehry's Geek Palace at MIT
Walt Mossberg, Kingmaker

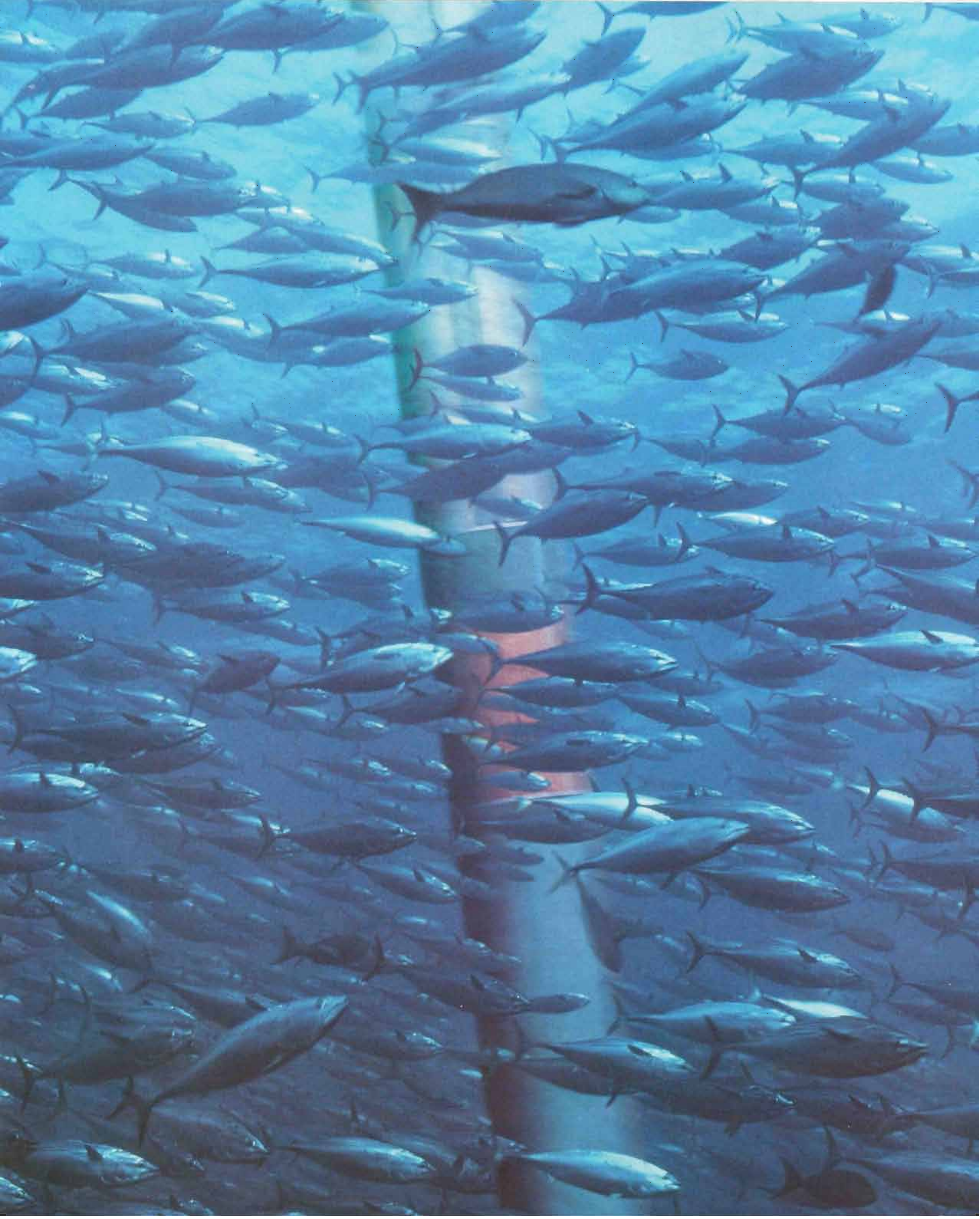
WIRED MAY 2004
www.wired.com/wired

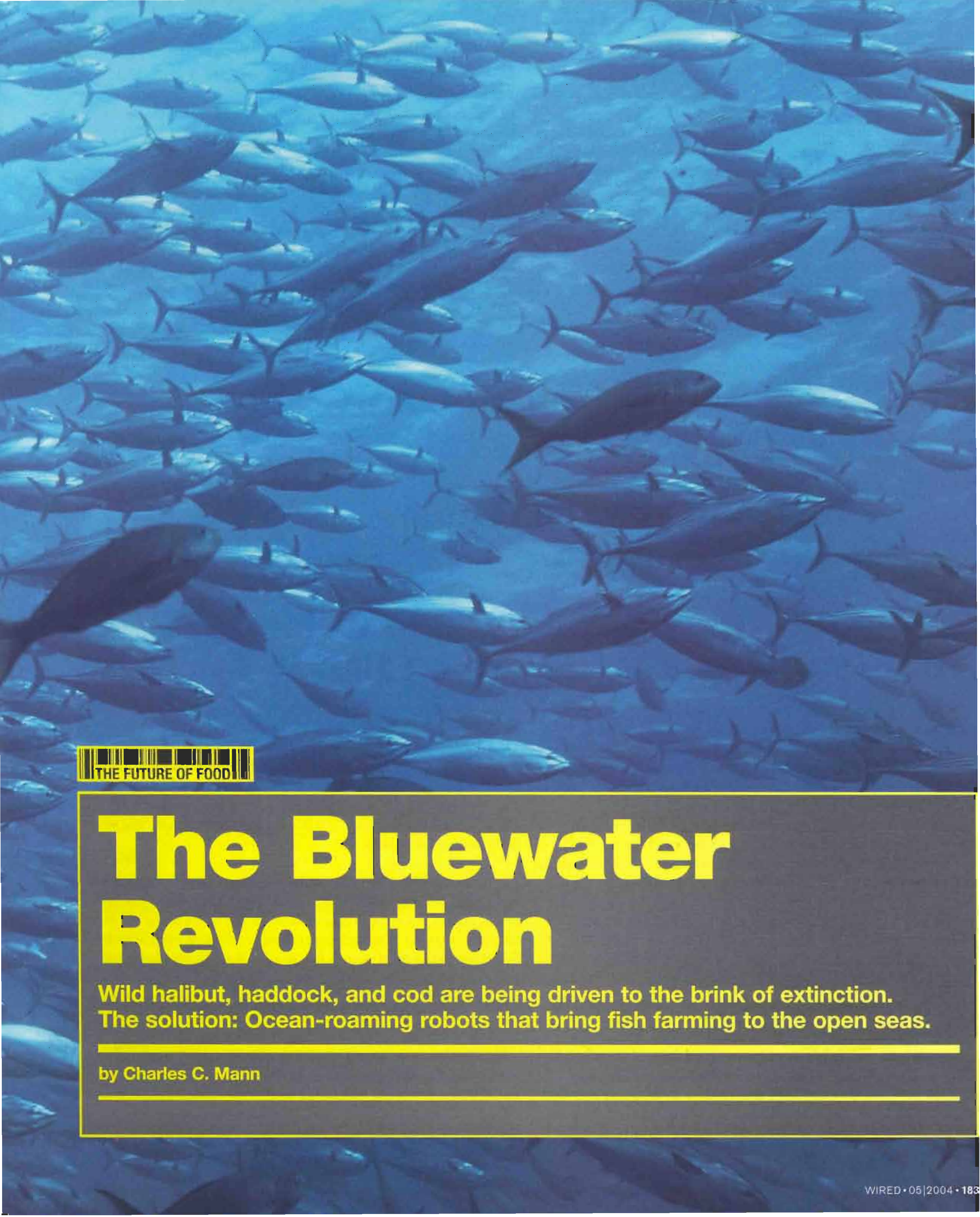
CONTENTS





FEATURES





THE FUTURE OF FOOD

The Bluewater Revolution

Wild halibut, haddock, and cod are being driven to the brink of extinction. The solution: Ocean-roaming robots that bring fish farming to the open seas.

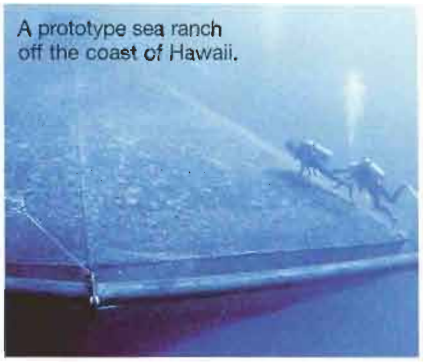
by Charles C. Mann

About 9 miles southeast of New Hampshire, near the Isles of Shoals, what seems to be an ordinary yellow navigation buoy sways in the Atlantic chop. Like a regular buoy, it's a metal cylinder that extends 10 feet above the surface and blinks its lights to warn away passing ships. Unlike a regular buoy, though, it has an access hatch that leads to an inner chamber crammed with enough electronics to merit its own IT staff. Indeed, this may be the first buoy in history that had its launch delayed by a software glitch.

The buoy is the antenna, eyes, and brain of a sprawling apparatus suspended beneath the surface like a huge aquatic insect, its legs of thick steel chain tethered to the ocean floor. The creature's body is a group of three cages, each resembling a gigantic toy top. Inside the cages are swirling, stupid mobs of fish.

The apparatus, an experiment operated by the University of New Hampshire, makes up the first fish farm ever on the open ocean. But this undertaking is more than the latest step in humankind's long effort to tame the seas. The university's Open Ocean Aquaculture Project may represent the best hope for *saving* those seas – or at least much of the life within them.

Inside the cages swim halibut, haddock, and cod, species fished in the Northeast for centuries. Of the three, the most important has always been cod, once so abundant that early European visitors reported catching them simply by lowering baskets into the water. "In relation to our present modes of fishing," the eminent biologist T. H. Huxley said in 1883, "a number of the most important sea fisheries, such as the cod fishery ... are inexhaustible."


A prototype sea ranch off the coast of Hawaii.

Fill it up with fingerlings in Florida – in nine months eat full-grown fish in Europe.

Today the abundance Huxley extolled is on the verge of disappearing. Unless something changes soon, biologist Daniel Pauly recently warned in *The New York Times*, there will be nothing left for the next generation but "plankton stew."

Twenty-eight percent of fish stocks worldwide are either overfished or nearing extinction, according to the United Nations Food and Agricultural Organization; another 47 percent are near the limits of sustainability. In waters off the US, roughly a third of stocks are in jeopardy, the US National Oceanic and Atmospheric Administration reports. The waters off New England and Newfoundland are by some measures the worst in the world; a University of British Columbia team led by Pauly predicted last year that many large species "will be all but gone from the North Atlantic region within a few decades." Humanity is setting off the aquatic equivalent of a neutron bomb, leaving the marine environment intact but killing off all its inhabitants.

Meanwhile, the demand for fish continues to rise. Driven by a growing human population as well as rising standards of living that leads more people to seek meat in their diets, fish consumption doubled between 1973 and 1997, according to a joint study by two leading think tanks, the International Food Policy Research Institute and the WorldFish Center. By 2020, the catch will have to increase again by nearly half just to keep up with demand. Fishing restrictions won't solve the problem: The seas are too big to police. Moreover, the greatest demand comes from developing nations in Asia, whose citizens can hardly be told to eat less protein than their counterparts in the West.

The answer lies in aquaculture: increasing the supply of fish by farming them as though they were livestock. "Without aquaculture, you'd be talking about a tripling or quadrupling of fish prices by 2020 or 2030, which would have very negative impacts on nutrition in developing countries," says IFPRI's Mark Rosegrant, one of the study's authors. Already, a third of the annual global fish harvest comes from farms, both on land and in shallow water just offshore. But today's methods won't be able to produce the volume of fish needed for tomorrow – they're too dirty, costly, and politically unpopular. Preventing catastrophic overfishing will require aquaculture on an unprecedented scale, and that means forging out into the open ocean. It will demand a shift as dramatic as that of the agricultural Green Revolution in the 1960s and 1970s – a Blue Revolution that is already under way.

The University of New Hampshire experiment, along with similar installations in countries from Portugal to China, is just the beginning. In the future, ocean ranches will be everywhere, except they'll be vastly bigger and fully automated – and mobile. Launched with lab-bred baby fish, these enormous motorized pens will hitch months-long rides on ocean currents and arrive at their destinations filled with mature animals, fattened and ready for market.

"It took thousands of years to make the Neolithic transformation from hunting and gathering to modern agriculture," notes Cliff Goudey, director of MIT's Center for Fisheries Engineering Research. The transition to open-ocean aquaculture, though, will have to take place within a few decades. "If it doesn't happen," he says, "I'm afraid we'll destroy the seas."

For thousands of years, Chinese farmers have raised carp in artificial pools shared by ducks and pigs. George Nardi was aware of that history, but it didn't prepare him for the scope of aquaculture in China today. As chief technical officer for GreatBay Aquaculture, a commercial seafood farm in Portsmouth, New Hampshire, Nardi had been asked to produce 200,000 baby flounder – enough for more than a thousand tons of meat when full-grown – for farms in the seaside city of Qingdao. In October, after he sent off the 1½-inch fingerlings via airfreight, he set out to meet them at their destination.

On his drive from Beijing to Qingdao, Nardi passed scores of land-based fish farms, each housing a dozen concrete tanks 20 feet per side and swarming with turbot or shrimp. When he arrived in

---

Contributing writer Charles C. Mann (www.charlesmann.org) *wrote about the promise and peril of genetic modification in* Wired *11.04.*

Qingdao, his hosts showed him still more, tank after tank filled with salt water from wells deep enough to catch seepage from the sea.

Between 1980 and 1997, the Chinese Bureau of Fisheries reports, aquaculture harvests grew at an annual rate of 16.7 percent, jumping from 1.9 million to nearly 23 million tons – two-thirds of the world's total production, according to the United Nations. By 2020, bureau deputy director-general Wang Yianliang has predicted, fish will be the staple protein of the planet's most populous nation.

Pauly, the University of British Columbia biologist, argues that China's statistics are exaggerated. But no one disputes that China and other Asian countries have made extraordinary strides in aquaculture. According to UN statistics, the six nations that produce the most farmed fish are in Asia. Most intend to increase their annual harvests. And all expect to do it the traditional way, using pools, rivers, and rice paddies.

Just one problem, says IFPRI research director Rosegrant: Even that huge effort won't satisfy the region's appetite. Asia won't be able to meet the growing demand using traditional techniques, and neither will the rest of the world. The usual approaches – the land-based method practiced in China and near-shore farming employed elsewhere – are simply too limited.

The main problem with raising fish on land is that it doesn't – so to speak – scale well. Crowding animals into confined spaces increases the potential for devastating epidemics. At the same time, it creates demands for electricity and water that Asian infrastructures can't fulfill – a serious problem, given that an aeration or filter failure can kill an entire harvest in minutes. "Ultimately," Rosegrant says, "there's only so many fish you can grow on land."

Near-shore operations don't require electricity or well water, but they face a different set of problems. In British Columbia, Newfoundland, and Norway, salmon farmers set baglike nylon pens in bays and inlets, where they're protected from extreme weather. The very calmness of the water, however, means that currents don't disperse the inevitable plume of waste. A farm of 200,000 salmon flushes nitrogen and phosphorus into the water at levels equivalent to the sewage from 20,000 people. Near-shore salmon farms "are a recipe for ecological disaster," says Don Staniford, managing director of the Salmon Farm Protest Group, in Scotland.

But the impact of environmentalist complaints pales next to that of the most powerful force pushing aquaculture into deeper water: the limited supply of waterfront real estate. "People in summer homes don't want a bunch of fish cages cluttering up their million-dollar views," says Richard Langan, director of the University of New Hampshire experiment. With zoning in riverways and along shorelines tightening in every part of the world, "there's no room left for farming. The industry is being pushed into the sea."

A peek inside Chris Duffy's office serves to illustrate this point. Duffy is operations manager of GreatBay Aquaculture, and his walls are covered with maps showing every fish farm in northern New England and eastern Canada. "Up here the water is too cold for salmon," he says, pointing to the north. "South of this line" – his finger moves to the tip of Maine – "the state says no aquaculture, because developers don't like it. That leaves only this zone in the middle. There's practically nowhere else to go. That's why everyone is looking in places like" – the finger moves east, into the Atlantic, and taps the map at a location many miles offshore – "like *this*."

L-DOPA

Hungry Planet

The global appetite for animal protein is soaring. So is consumption. The problem is how to keep putting meat on your plate.

World population is expected to grow 10 percent by the end of the decade, but demand for fish and other meat — beef, pork, and chicken — will rise 25 percent. What gives? Call it the curse of the emerging middle class. As consumers become wealthier, the first thing they may want is a TV — but the next is animal protein. "When disposable income increases, people tend to improve their diet," says Steve Blank, an agricultural economist at UC Davis. "They don't necessarily change volume, but meat is one thing they add."

The average American eats 56 pounds of meat annually. But US consumption is relatively flat; it's expected to grow just 5 percent by 2010. Less-developed countries will see bigger increases. In China, for example, consumption will rise 43 percent by 2010: The average citizen will consume 15 percent more fish, 36 percent more pork, 45 percent more beef, and 68 percent more poultry than in 1999. (Even then, per capita meat consumption in China will be half the US total.)

Open-ocean aquaculture may meet the growing demand for fish, but satisfying the desire for other animal products poses a bigger challenge. That's because fish rate especially high in what the industry calls feed conversion – the ratio of food an animal consumes to meat it produces. A pound of deep sea-raised salmon requires roughly 1 pound of fish and fish oil. Chickens take in 2 pounds of feed for 1 pound of flesh. Raising the beef for four Quarter Pounders requires at least 9 pounds of grain.

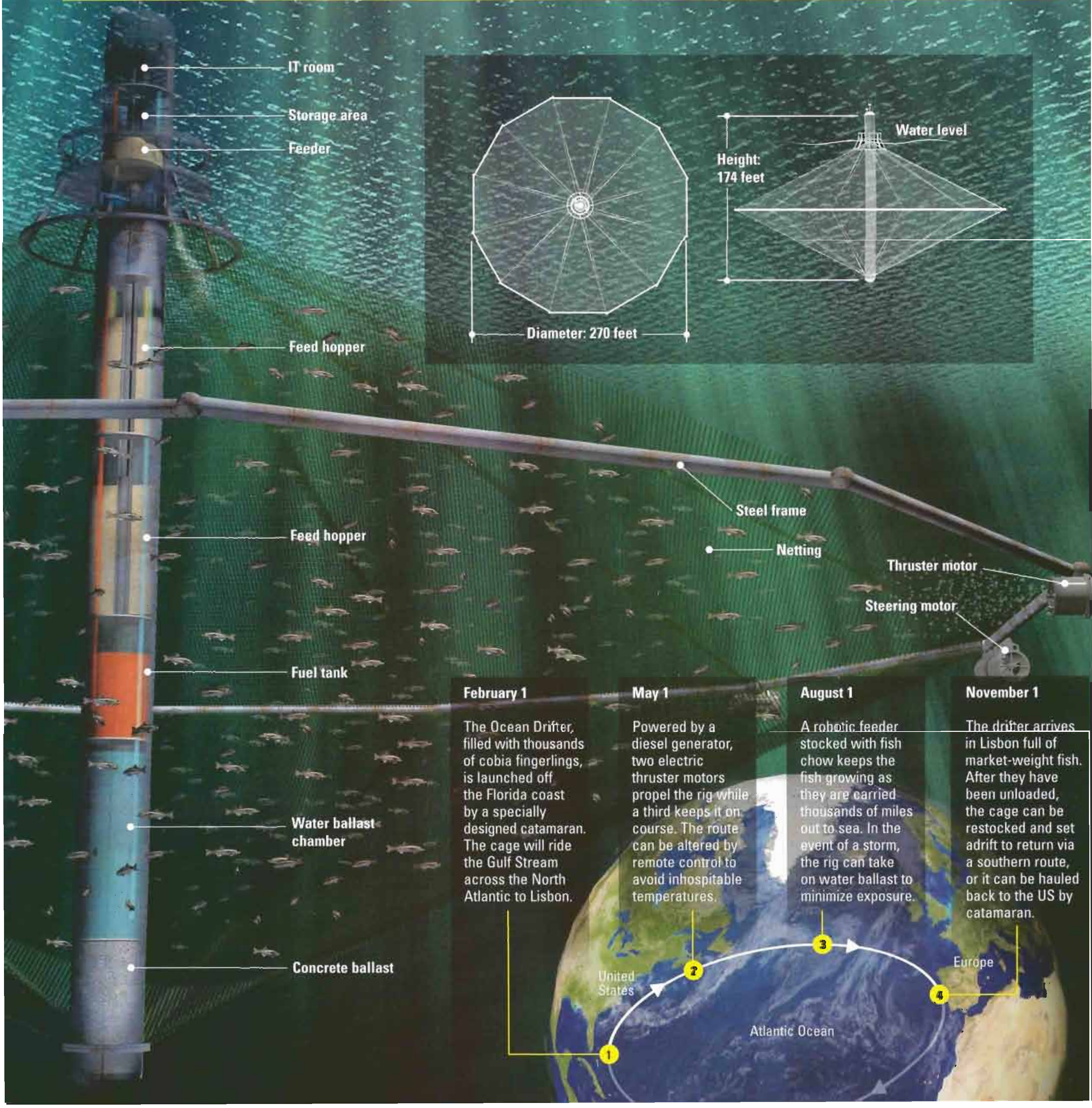
Unlike farming fish, the production of poultry, pork, and beef isn't likely to get much more efficient than it already is. But distribution is ripe for an overhaul: producers can make the most of their animals by selling various parts where they're more valued. On menus in China, for instance, cow stomach – not steak – is a delicacy. "Tenderloin stays in North America and Australia," says Dermot Hayes, professor of agribusiness at Iowa State University. "The tail, internal organs, and reproductive organs go over to China."

Chalk one up for global trade. – **Joanna Pearlstein**

High Seas Drifter

How fish ranches will ride the wide-open ocean currents.

The first wave of open-ocean aquaculture is taking place in cages tethered to the seafloor, but soon those enclosures will be free to roam. MIT engineer Cliff Goudey has designed the Ocean Drifter, a robotic seafood ranch designed to ride ocean currents. This next-gen farm will feed, protect, and ferry tens of thousands of fish as they journey from a hatchery on one continent to market on another. **– Erik Malinowski**



February 1

The Ocean Drifter, filled with thousands of cobia fingerlings, is launched off the Florida coast by a specially designed catamaran. The cage will ride the Gulf Stream across the North Atlantic to Lisbon.

May 1

Powered by a diesel generator, two electric thruster motors propel the rig while a third keeps it on course. The route can be altered by remote control to avoid inhospitable temperatures.

August 1

A robotic feeder stocked with fish chow keeps the fish growing as they are carried thousands of miles out to sea. In the event of a storm, the rig can take on water ballast to minimize exposure.

November 1

The drifter arrives in Lisbon full of market-weight fish. After they have been unloaded, the cage can be restocked and set adrift to return via a southern route, or it can be hauled back to the US by catamaran.

The sea is a "high-energy environment," says David Fredriksson, an engineer working on the University of New Hampshire project. High-energy environment is an engineer's way of saying prone to sudden hurricanes, monster waves, and abrupt currents that wreak havoc on human-made objects. The budget of *Waterworld*, Kevin Costner's notorious 1995 bomb, ballooned by millions of dollars after an unseasonable storm tore apart its elaborate floating set, constructed in a supposedly calm patch of the Pacific. *Waterworld* is why people don't set up farms in the middle of the ocean.

Only one year after the release of *Waterworld,* Net Systems, a trawling gear outfit in Bainbridge Island, Washington, became one of the first enterprises to sell equipment for open-ocean aquaculture. "We were way ahead, which was our big mistake," says senior engineer Langley Gace. "When we came out with our first product, nobody knew what it was."

Rather than a floppy nylon pen, Net Systems uses a rigid cage that resembles two huge cones glued end to end, joined by a steel ring around the middle. Fifty feet high and 80 feet at its widest point, the company's largest cage has an inner volume of more than 100,000 cubic feet, enough for tens of thousands of fish. The whole structure is covered tightly with netting and tethered to the buoy that contains the equipment room and feeding mechanism. A steel cylinder 3 feet in diameter runs from the bottom of the cage to the top in a fashion reminiscent of a child's gyroscope. The cylinder is capped by a pump that forces air into and out of its body. Depending on the mix of air and water, the cage floats on the surface or sinks to a desired depth.

The ability to float beneath the waves is the key to solving the *Waterworld* problem. However rough the surface, the sea 60 feet below is "a quiet, almost a gentle environment," says Jim McVey, aquaculture research coordinator for NOAA. "The fish like it. The equipment likes it. Heck, *I* like it."

In addition to the University of New Hampshire project, aquaculture firms are using Net Systems cages in waters near the Bahamas, China, the Philippines, Portugal, Puerto Rico, and Spain. And Net Systems, with help from the university, is already working on the next stage: a 20-ton buoy that will automatically feed and monitor fish for weeks at a time. "Ultimately, you should be able to run the farm from a desk onshore," says Michael Chambers, project manager of the UNH experiment.

Goudey, the MIT fisheries engineer, views these efforts as small prototypes. Backed by federal funds, he has begun work on an immense next-generation design, 174 feet tall and 270 feet in diameter, called the Ocean Drifter. Unlike its predecessors, which are fixed to the seafloor, this enormous cage will roam the seas, propelled by three electric thruster motors attached to the rig's steel equator. Powered by a diesel generator mounted atop the central spar and steered by software, it will venture hundreds of miles from shore. When the fish are big enough to sell, a specially designed ship will embrace the cage and hoist it aboard.

"The ocean is full of predictable currents, or gyres," Goudey says. "If you could get the cage into one of these gyres, it would essentially stay in the same place, or at least have a predictable trajectory. Even if you had just a slight ability to adjust its movement, you'd be able to control its path pretty exactly." In his view, "you could build a fleet of these things in the Straits of Florida, fill them with fingerlings of, say, cobia, and let them follow the Gulf Stream for nine months until they reached their intended 214➡

L. DOPA

The Salmon King

Sea ranching demands a fast-growing fish for all seasons. A company called Aqua Bounty has engineered the perfect catch.

The history of agriculture is the taming of wild plants – selecting the most desirable seeds year after year until grape-sized tomatoes become Jersey Girls and Big Boys. Today, ocean farmers are doing the same to fish. A Massachusetts firm called Aqua Bounty Technologies wants to move quicker. Much quicker.

This year, if all goes well, the FDA will approve the company's AquAdvantage salmon for human consumption – the first genetically engineered fish to get that stamp. (A half-dozen other agencies need to give a nod before the new salmon makes it into the kitchen.) Thanks to clever lab work, AquAdvantage fish reach market weight in 18 months, rather than three years.

Aqua Bounty's innovation builds on previous research into flounder. Unlike other fish, flounder thrive in frigid water because they have special "antifreeze" proteins in their blood. To control the production of the protein, the gene is accompanied by a promoter, a bit of DNA that turns it on and off. When days grow short, the promoter goes to work and the gene starts cranking out antifreeze. Aqua Bounty realized that the promoter could activate *any* gene, including the one that controls growth in salmon. (Actually, they ended up using the promoter from another antifreeze-making species, ocean pout.)

Thus, the DNA that turns on the pout's antifreeze spigot gives AquAdvantage a seasonal growth spurt. Salmon normally produce growth hormone only during summer. In winter, they stop secreting it to reduce the need for food. Scientists glued the promoter to a growth hormone gene, so it would be activated in winter, then introduced the resulting genetic construct into the fish. The resulting salmon have *two* active growth hormone genes: the original, which induces the fish to grow when days are long, and the new one, which does the same during the rest of the year.

A case can be made that AquAdvantage fish aren't transgenic; they simply make more of their own growth hormone. But that distinction hasn't assuaged critics. Greenpeace activists invaded the company's hatchery in 2001.

The opposition's vehemence baffles Aqua Bounty officials. "That's what happens in agriculture: People breed new species," says vice president Joe McGonigle. "We're just using modern tools. Our job is to use them wisely." – **C.C.M.**

← 187 market in Europe with a harvestable crop. Then you'd load them up again and send them back along the southern route with another crop."

Ping-ponging slowly between continents, these enormous, largely automated underwater ranches would drift into big-city harbors – fresh fish by the ton, delivered daily. No more giant factory ships with illegal 20-mile-long drift nets! No more airfreighting frozen slabs of tuna from the Atlantic for auction in Tokyo! Instead, hatcheries in Mexico would send baby tuna to Japan in million-cubic-foot cages. By the time the floating farms reached Tokyo, the fish, cosseted in their cages like Kobe cattle in their stalls, would be ready for sashimi.

Many obstacles stand in the way of this vision, among them a paltry federal ocean-aquaculture research budget ($780,000 this year) and no clear method for obtaining the necessary permits (NOAA recently persuaded Congress to introduce legislation to streamline licensing of commercial aquaculture operations).

Nonetheless, environmentalists still decry the aquaculture revolution. Their fears center less on ordinary waste than on a more insidious kind of pollution: genetic.

When fish farmers select breeding stock, they look for specially fast-growing, meaty creatures. Over generations, the difference between the choices made by humans and those made by nature lead the fish to evolve, in the same way human choices created European cattle breeds from ancestral populations in Asia and Africa. And just as today's huge, gentle milk producers are strikingly unlike their fierce, shaggy ancestors, farmed fish will become ever more distinct from those in the wild. Meanwhile, varieties specially adapted to open-ocean farming are bound to be created through genetic engineering (see "The Salmon King," page 189).

Preventing the farmed and the wild from interbreeding is surprisingly difficult. Fish leap from pools and tanks into nearby streams and wriggle through holes in near-shore pens gnawed by seals and sea lions.

To critics like Staniford, such escapes are potential genetic catastrophes. Farmed animals are selected to grow quickly but not to breed successfully – that's done in a lab. Wild fish breed exuberantly but have evolved to grow more slowly so they can ride out drops in the food supply. Laboratory studies suggest that ravenous farmed salmon could monopolize the food supply, then fail to spawn. "They displace the natural population and then neither survive," Staniford says.

Outside the lab, though, that displacement doesn't always occur. Since 1990, more than a million farmed salmon have jumped the fence in Puget Sound and its tributaries, according to NOAA's Northwest Fisheries Science Center. Almost none were seen again, apparently because their docility made them easy prey. Judging by autopsies of escapees, the pen-grown fish also had trouble finding food – they were too dumb to survive.

Moreover, Net Systems' seafaring cages are much harder to escape than traditional tanks and pens. Indeed, Gace knows of no instance in which it has happened. The outer netting is made of Spectra, a superstrong polyethylene fiber used by NASA to tether spacewalking astronauts to the mothership. Wrapped tautly around the frame, it leaves no slack for predators to grip, but the material is built to withstand the most ferocious attacks.

Nothing will ever reduce the chance of genetic pollution to zero – as they say in *Jurassic Park,* life finds a way. To some activists, this is sufficient reason to ban aquaculture altogether. To NOAA's McVey, though, the whole issue is overblown. Humans, inveterate tinkerers, have genetically altered every species grown on farm, garden, and lawn, and these varieties all hybridize with their wild relatives. On roadsides in southern Mexico, for example, crosses between corn and its nearest wild relative, teosinte, are common.

Most of the time, these hybrids are benign; often they can't reproduce. Sometimes, to be sure, they can cause problems. Sugar beet mixes with sea beet, a wild relative, to produce a weed that plagues European agriculture – the hybrid's buried, bulbous roots are woody and hard enough to make fields unplowable.

Farmers have had to be on the lookout for such hybrids for thousands of years. The Blue Revolution is simply moving this process into the sea. It's a momentous change, but one that humankind has seen before.

PING-PONGING BETWEEN CONTINENTS, THE RANCHES DELIVER FRESH FISH BY THE TON.

"The legal regime is a major issue," MIT's Goudey says. "Is this kind of thing a vessel? If not, what is it? How can you establish title to this kind of object in the open ocean?"

He sighs. "And then, of course, you're going to have to deal with Greenpeace."

Deep-sea farms will spew as much waste into the water as the near-shore facilities opposed by environmentalists, but they'll be operating in the open ocean – an area so devoid of life that it's routinely called a wasteland. In this vast, lightly inhabited ecosystem, sea-ranching advocates say, the stream of waste will serve as a nutrient base for plant and animal life. Much as docks and pilings become centers of aquatic communities, the giant cages will become ecosystems in themselves, with as many fish outside the cages as in them.

"They could – and some of the preliminary research suggests this – enrich the environment, rather than impoverish it," NOAA's McVey says.

To aquaculture enthusiasts, the advent of open-ocean farming – giant, autonomous farms ferrying genetically altered fish across the ocean – is both fascinatingly novel and mundanely obvious. On one hand, it's unlike anything that has been attempted before. On the other, it's merely a long-delayed extension of the Green Revolution into the 70 percent of the planet that's covered by water. Like the Green Revolution, it will probably have some negative environmental effects. But it will also feed countless millions – and possibly stop humankind from plundering the seas bare.

"There are risks, absolutely there are," says McVey. "But we have the chance to set in motion a second agricultural revolution in our lifetimes. Plus, as a bonus, we can help save the oceans. I honestly can't think of anything more exciting than that." ■ ■ ■