Lucky star. This leather star has escaped a deadly wasting syndrome—so far.

CREDIT: JAN KOCIAN

Death of the Stars

The biggest known die-off of sea stars is sweeping North America's coastal waters. Researchers are hurrying to identify the culprit and understand the impacts

THE SEATTLE AQUARIUM SITS ON PIER 59, ABOVE THE COLD, DARK waters of Puget Sound. As children run inside its wood-beamed atrium, Lesanna Lahner peers into the largest display tank. A few salmon swim idly past barren rocks. "This used to be full of sea stars," says Lahner, the aquarium's veterinarian. No more. The five-armed echinoderms, sometimes known as starfish, are victims of a mysterious wasting syndrome that has ravaged the east and west coasts of North America.

Lahner first heard the apocalyptic reports from recreational divers this past October. Sea stars were dying in droves in nearby coastal waters. The deaths were grisly. White lesions appeared, then the bodies sagged, ruptured, and spilled organs. Alarmed, Lahner sent divers to investigate what was happening under the aquarium's pier. About 40% of the sea stars appeared sick, some barely clinging to pilings with drooping arms. By November, all three species that typically live under the aquarium had vanished. "We've seen sea star deaths wax and wane, but never on this scale," Lahner says.

Sea stars in the display tanks, which draw water from the sound, also became ill. Lahner isolated the sick, moving them to quarantine tanks. She monitored their slackening heartbeats with an ultrasonic device. She called the author of the textbook *Invertebrate Medicine*, which has just one paragraph on treating sea stars and other echinoderms, for help. "Sorry," was all he could say. Lahner tried antibiotics, but they were useless. Sea stars collapsed and liquefied in the blue plastic tubs. Others flailed, pulling off their own arms, which eerily crawled around. With growing horror, Lahner began euthanizing any sea stars that showed severe lesions.

Some of those dead stars now rest in Lahner's office, their remains preserved in carefully labeled jars. She has mailed samples to pathologists and geneticists, who are rushing to understand the most widespread disease outbreak ever documented in any echinoderm. There is little time to waste, as the epidemic could burn out—making it harder to identify the pathogen. "A lot of people are scrambling," says ecologist Benjamin Miner of Western Washington University (WWU) in Bellingham, who is surveying the coast and conducting experiments in his lab.

Meanwhile, concern grows. The plague is ravaging perhaps 20 kinds of sea stars along thousands of kilometers of coastline. Some west coast species could even go extinct, biologists fear. "The magnitude of the potential loss to invertebrate biodiversity is so overwhelming," says ecologist Drew Harvell of Cornell University. The loss of sea stars, a top predator in much of the coastal ocean, may also shuffle food webs, testing a classic ecological theory in a long-term, real-world experiment. It could be decades before populations recover, Harvell notes, and sea stars again become the iconic species of the intertidal.

Disaster foretold

When novelist John Steinbeck and biologist Edward Ricketts took a now-famous expedition into the Gulf of California in 1940, the gulf sun star (*Heliaster kubiniji*) was everywhere. Pounded by waves, the black-and-green mottled echinoderms "simply increase their tough-

ness and fight back at the sea with a kind of joyful survival," Steinbeck marveled in *Sea of Cortez: A Leisurely Journal of Travel and Research*.

But the gulf sea star was no match for an enigmatic disease that arrived in the summer of 1978. White lesions spread and populations crashed. The sick and dead animals were coated with bacteria, but researchers weren't sure if they were the culprit or just a secondary infection. The outbreak, researchers suggested, was likely related to strong winds that brought warm water into the gulf (*Science*, 28 May 1982, p. 989). "The thought in the 1980s was that this was a one-time thing," recalls Peter Raimondi, a marine ecologist at the University of California (UC), Santa Cruz.

They were wrong. In 1997, disease struck again. This time, the damage was concentrated off southern California, where an El Niño climate pattern had brought exceptionally warm Pacific waters. At the time, ecologist John Engle of UC Santa Barbara was studying intertidal communities in the Channel Islands, off Santa Barbara. As the stars died, he got a powerful lesson in how their loss can remake marine ecosystems.

Despite their torpid appearance and benign reputation, sea stars are fearsome predators—"the lion of the intertidal," says Bruce Menge of Oregon State University, Corvallis. Even a small star can rip barnacles or limpets from rocks using the hydraulic system that powers its many tube feet. When prying apart mussel shells, some stars evert their stomach, sliding it inside the shell to digest their prey. Unlike other kinds of animals, echinoderms can stiffen their connective tissue for extra power, some in less than a second. And although sea stars aren't known for speed, the sunflower sea star (*Pycnopodia helianthoides*) can hustle along at more than a meter per minute, thanks to the thousands of tube feet beneath its 16 or more arms, and even catch fish. If food is scarce, sea stars easily resist starvation. They just shrink.

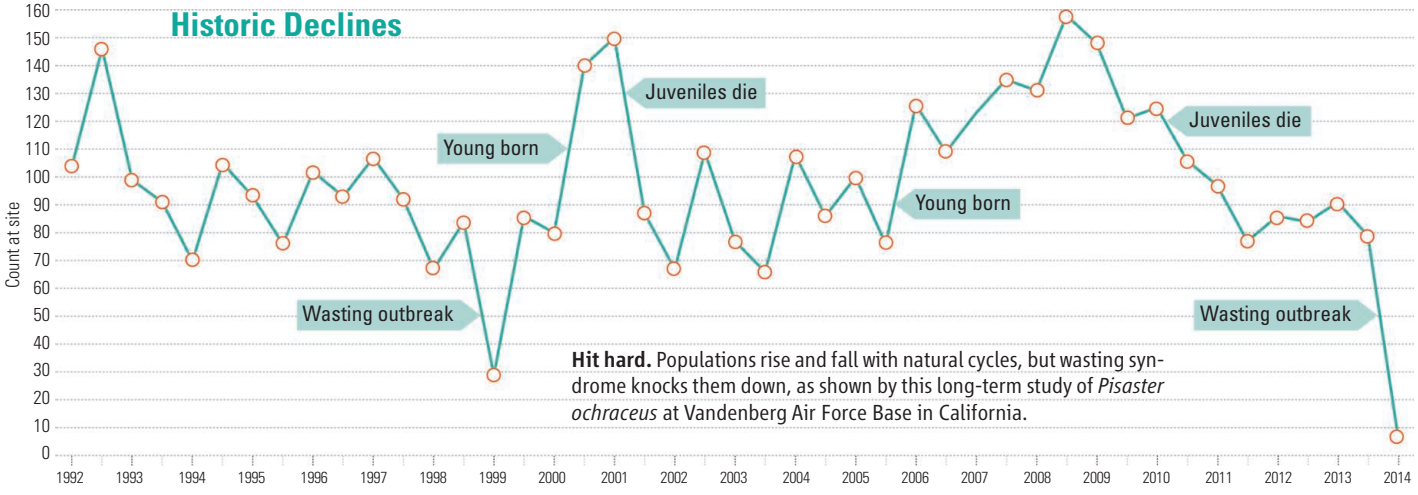
When these predators vanish entirely, however, life turns upside down. During the starfish plague of the late 1990s, Engle recalls watching some of *Pycnopodia*'s former prey, sea urchins, run wild around the Channel Islands. The urchins overgrazed the giant kelp forests, in turn distressing fish that liked to settle into the kelp canopy to find food and refuge. For the most part, sea star populations in southern California never rebounded, Engle says. "The whole system really changed."

Losing grip. Deeper water species, like this Stimpson's sun star in Washington state, were among the first to succumb, with arms drooping and detaching.

Falling stars

In June 2013, biologists at Olympic National Park in Washington state noticed something odd in the waters off a scenic landmark called Starfish Point. More than a quarter of the point's namesakes were dotted with lesions or other signs of illness. The report might have gone unnoticed except for a scientific consortium—called the Multi-Agency Rocky Intertidal Network (MARINe)—that Engle and other researchers helped cobble together in 1997. With a shoestring budget for database operations, MARINe's mission is to keep tabs on the health of near-shore ecosystems, using standardized methods. After the report from Olympic National Park, MARINe collaborators agreed to quickly check on their roughly 200 sites along the west coast.

By August, the white lesions had been spotted on starfish as far north as Alaska. In British Columbia, divers reported that abundant populations of sea stars had been reduced to ghostly piles of bony white ossicles. "It was hideous," says Jeffrey Marliave, vice president of marine science at the Vancouver Aquarium in Canada. By November, the syndrome was present at more than half of



Hit hard. Populations rise and fall with natural cycles, but wasting syndrome knocks them down, as shown by this long-term study of *Pisaster ochraceus* at Vandenberg Air Force Base in California.

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Patchy. Wasting syndrome appears concentrated in the north and south, but has started to appear in Oregon as well. Map does not show outbreaks in Alaska or along the east coast.

84 surveyed sites, as far south as San Diego. Citizen scientists checked out more than 300 other locations, with similar results. Mortality ranged up to 100%. Thanks to MARINe, the west coast outbreak has become "the best tracked marine event we've ever had," Raimondi says.

There are many strange things about the outbreak. Past episodes in the west have been associated with warmer coastal waters, but recently those waters have been relatively cool. And this time, a similar sea star disease appears to be spreading along North America's eastern coast as well. Because there is no equivalent monitoring network in the east, the reports have been largely anecdotal. So far, observers have described severe and rapid die-offs in Maine, Connecticut, Massachusetts, and Rhode Island.

Researchers are wondering how the disease has managed to infect so many species, and why they succumb in a particular order—first the sunflower sea stars and giant pink sea stars, then bat stars. Nor do they understand why the western outbreak started in the north and moved south, the opposite of past events. And why have populations in Washington and California suffered intensely, while those in Oregon seem unscathed? "It just pops up willy-nilly," Raimondi says.

Perhaps seabirds, which like to prey on sea stars, are moving it by air. Maybe local currents cause a waterborne pathogen to build up in some areas but not others. Infected prey might explain why even stars in aquaria not directly connected to coastal waters have died; the pathogen may come in with mussels and clams collected to feed the captive animals. Solving the central mystery—the identity of any pathogens—has become a far-flung affair, with labs across the nation joining the hunt.

Contagion

At the University of Rhode Island (URI), Kingston, marine pathologist Marta Gomez-Chiarri and her graduate student Caitlin DelSesto have kept sea stars at a marine lab on Narragansett Bay. They first noticed something disconcerting in 2011: The stars in tanks fed with fresh seawater were wasting away, but those in recirculating tanks with filtered water remained healthy. This past October, the researchers discovered they could kill a seemingly healthy star simply by putting it in a tank that had held sick sea stars. "It was something in the water," Gomez-Chiarri says. Something infectious.

In the following weeks, as snow pelted the Cornell University campus, shipments containing dead sea stars packed in dry ice began arriving at the small laboratory run by microbial oceanographer Ian Hewson. He has studied potential pathogens in a range of invertebrates (water fleas, gorgonian sea fans), and he had recently begun to examine viruses in sea urchins. Not long before the outbreak in sea stars began, "I remarked that I wished there was another mass mortality of echinoderms," he recalls. Unfortunately, he got his wish.

As the volume of sea stars increased last winter to 10 deliveries a week, processing became routine. Opening each cold, clammy plastic bag, Hewson or a student would pull out an arm and slice off a centimeter's worth. It goes into a blender with purified water, and then the researchers amplify the DNA to look for bacteria, which can be identified by their 16S ribosomal genes. The genetic sleuthing, along with other tests, has already ruled out a number of potential killers: fungi, protozoans, larger parasites, and some kinds of bacteria.

Viruses, however, remain a big unknown. Researchers had never described a virus in echinoderms until this past December, when Hewson and a trio of undergraduates identified parvoviruses in three species of sea urchins. Viruses don't have ribosomal markers, however, so Hewson has to identify them using other time-consuming and expensive methods. "This is the biggest study I've done by an order of magnitude," says Hewson, who received a rapid grant from the National Science Foundation in November with Miner of WWU.

Narrowing the list of suspects isn't easy. Hewson has been finding 1200 to 2000 species of bacteria on both healthy and diseased sea stars, in addition to viruses. That's not surprising, because seawater naturally contains a multitude of microbes. And the puzzle is complicated by the rapid death of sea stars, which leaves little time to spot the initial pathogen before secondary infections erupt. Nevertheless, Hewson has tentatively identified about a dozen viral and bacterial candidates, by comparing samples from healthy and diseased animals and looking for microbes that had been replicating.

Eventually, Hewson plans to hunt for pathogens in water and sediment samples that have been collected from aquariums and field sites. "Hopefully they will be useful down the line," says virologist Mya Breitbart of the University of South Florida, St. Petersburg, whose lab is hunting for viral pathogens, primarily in east coast sea stars with the wasting disease. In addition, Hewson is eyeing museum specimens to figure out if the outbreak is being caused by a long-standing or

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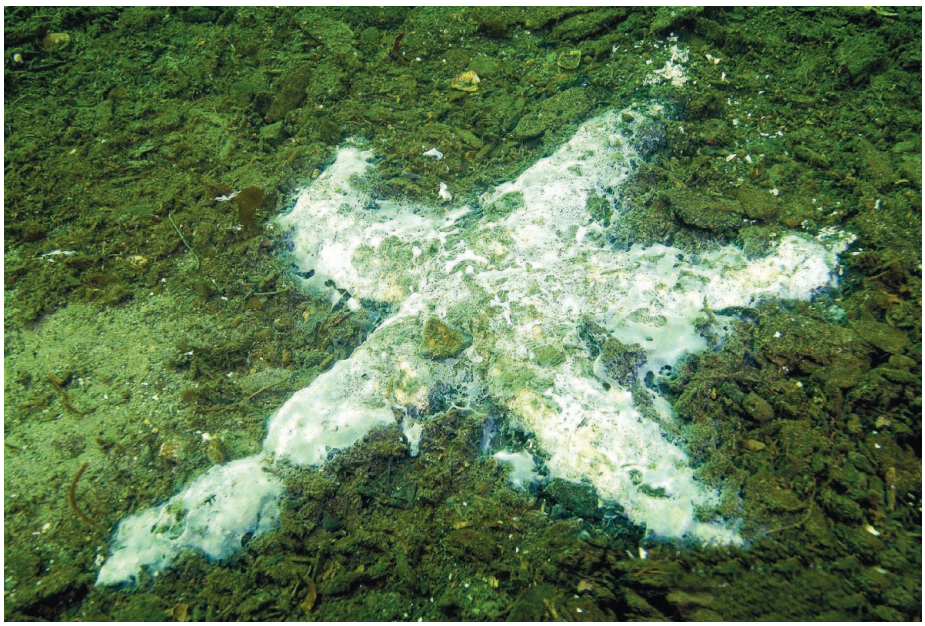
newly introduced microbe; he will soon visit the Natural History Museum of Los Angeles County in California to slice samples from stars collected over the past 70 years.

Other detective work is under way in Washington state. At a fish laboratory run by the U.S. Geological Survey (USGS) in Nordland, rows of large plastic tubs contain about 50 sea stars in quarantine. Overhead, a network of gray pipes delivers water that has been double-filtered with sand and purified with ultraviolet light. The tanks are kept at 8°C, a comfortable temperature for echinoderms. Pumps whir, pipes gurgle.

Colleen Burge, a former student of Harvell's and now a postdoc at the University of Washington (UW), Seattle, has looked at the possibility of infected prey. She fed healthy stars with mussels collected from stricken tide pools, for example. In other tanks, Burge added diseased arms. After 3 months, only one star had died. "Obviously, we've had a lot of success keeping them healthy," she said with frustration in late March. Since then, they have infected more sea stars by heating the tanks. Even though the outbreak seems not to have been influenced by warming waters so far, heat makes individual animals more susceptible.



Ghost. Some sea stars leave only ossicles and bacteria behind (*top*), while researchers find others while they are still sick, such as this sunflower star (*bottom*) collected in Washington state.

Dismal experiment

Outside the labs, researchers continue to survey tide pools and near shore waters. At the Port Hadlock Marina in Washington state, about 14 kilometers from the USGS lab, Harvell, Burge, and Cornell graduate student Morgan Eisenlord recently examined a dock at low tide. They were concerned that the shift to daytime low tides would expose sea stars to more heat. The pylons were covered with delicate, white sea anemones, tentacles floating gently. Burge spotted a large red *Pycnopodia* clasped to one of the wooden posts with its 18 arms. Harvell walked over. "I wouldn't mind taking a look at him," she said. "His arms look a little weird."

One arm bore a white lesion. Another had apparently pulled itself off. The crippled starfish had crawled a little distance away, beige gonads hanging out (see photo, right). Eisenlord dropped the arm into a plastic bag to take back to the lab. As the rigging of sailboats clinked in the wind, Harvell's yellow Labrador retriever trotted along the sun-warmed dock. But Harvell was gloomy. The Pacific Northwest is a hot spot of sea star diversity, she says, and it's become imperiled.

On a grand scale, the epidemic is replicating a classic experiment performed a half-century ago. Robert Paine, then a young ecologist at UW, wondered about the role of sea stars in the intertidal zone. On a rocky coast not far from Port Hadlock, he systematically plucked the common sea star *Pisaster ochraceus* from certain tide pools and watched what happened. One species of mussel, no longer eaten by sea stars, outcompeted all the others. Diversity plummeted. In a now-classic 1966 paper in *The American Naturalist*, Paine coined the term "keystone predator" to describe the apex influence of sea stars.

Now, human hands aren't needed to repeat Paine's experiment all along the coast. What's more, baseline data on intertidal populations extends back 2 decades or more in many places, making it possible to draw statistically meaningful insights into how communities change as a result of the die-off.

For better or worse, the natural experiment continues to expand. There's an early report that previously untouched sea stars in Oregon might be afflicted. And a worrisome development from New England: URI's Gomez-Chiarri has found that sick sea stars can infect not only their own kind, but sea urchins and sea cucumbers, too.

Watching nervously from San Juan Island off the coast of Washington, Harvell fears the kills could worsen as water continues to warm. And there's a good chance that an intense El Niño will reach the west coast in August, Raimondi says. "We could be at the beginning, middle, or end of the outbreak," he says. "We don't know. And that's very disconcerting."

–ERIK STOKSTAD

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