CHAPTER ONE

What Rises with the Tide?

It is the microbes that will have the last word.
Louis Pasteur

You always remember the moment something bad turns big. For me, a bad situation assumed epic proportions in December 2013 when I was at the Nature Conservancy's All Science Meeting in California. I received an email from my colleague Pete Raimondi saying that thousands of starfish from at least ten species were dying fast in the waters around Monterey, California. I already knew that a species of giant sunflower starfish (*Pycnopodia helianthoides*) was dying catastrophically hundreds of miles to the north, not far from my home on San Juan Island in northwest Washington State. I had seen underwater photographs taken by Neil McDaniel near Vancouver, Canada, showing a disaster unfolding in the deep canyons there. In photos taken on October 19, the rock cliffs were covered with healthy-looking stars. In photos taken only ten days later, all that was left were hundreds of dead bodies piled on the sea floor beneath the cliffs (see figure 1). We had assumed this was a localized event affecting a single species, like others we had seen. Doubts about the geographic restriction of the starfish die-off had surfaced,

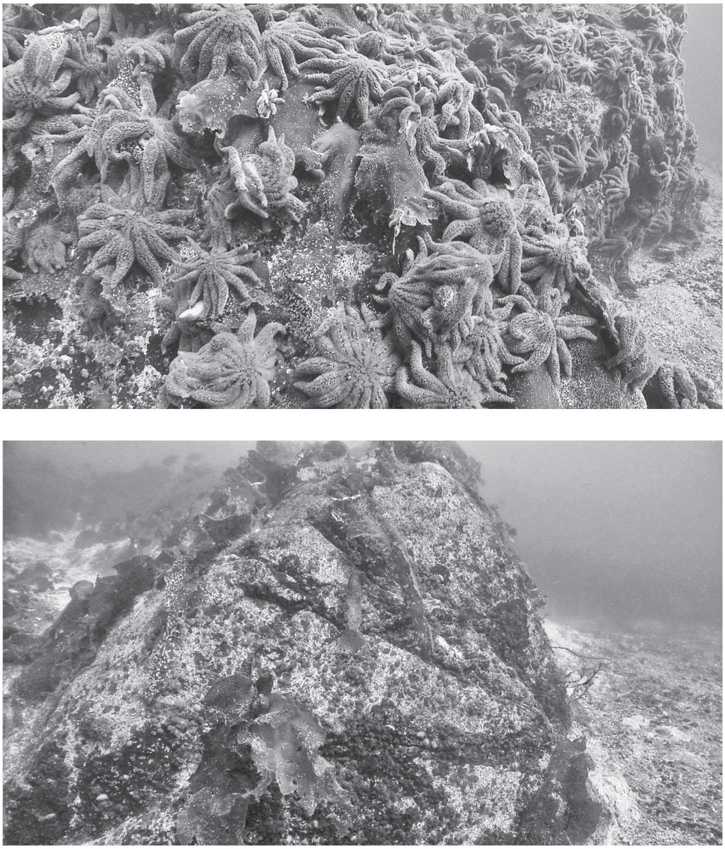

Figure 1. Mass mortality of the sunflower star over two weeks in British Columbia, 2013. Photos by Neil McDaniel.

however, when we learned in November, only a few weeks before the Nature Conservancy's meeting, that the Vancouver, Seattle, and Monterey aquariums had each lost hundreds of stars in their tanks. Against this background, Pete's email signaled something much more worrisome than a local die-off of one kind of starfish. It seemed we were seeing the beginnings of a disease outbreak that could end up affecting starfish along the entire Pacific coast.

In addition to being concerned about the broad geographic extent of the outbreak, I was worried that it involved starfish, and not just one species but many. Starfish may seem innocuous and almost inanimate given the glacial pace at which most species move, but they are the lions of our seascape. Even a few starfish can control the structure and composition of the surrounding ecosystem by eating huge numbers of the mussels and oysters that would otherwise dominate. Observing ochre stars preying on mussels and the changes that occurred when he removed them, experimentally, from his study areas on Tatoosh Island caused Bob Paine, one of my mentors, to invent the term *keystone species*. Added to that, the West Coast of the United States has a bright medley of different starfish species, second only to Australia for temperate waters. There are approximately eighty species described in the eminent marine biologist Eugene Kozloff's key for Puget Sound and the San Juan Islands in Washington. The catastrophic loss of not only ochre stars but other species as well over a broad swath of ocean could have a domino effect on ocean ecology, causing a cascade of changes that might ultimately impact animals—such as abalone and salmon—that humans depend on for food.

I left my session early and called Pete to hear firsthand what he and his fellow divers had seen in Monterey. He told me that they had watched the giant sunflower stars die first: they lost strength in their tube feet, their arms tore off and crawled away from their bodies, and their organs spilled out, leaving the stars to fall off the rock walls and docks. A week later, they had watched the same thing happen to other species. Sun stars (*Solas-*

ter sp.), rainbow stars (*Orthasterias koehleri*), giant pink stars (*Pisaster brevispinus*), giant stars (*Pisaster giganteus*), mottled stars (*Evasterias troschelii*), vermillion stars (*Mediaster aequalis*), and bat stars (*Patiria miniata*) all began to die rapidly in high numbers. One of the last to go was the ochre star (*Pisaster ochraceus*). The sea bottom, Pete told me, was littered with dead, decaying starfish arms and bodies, with crabs picking at them. The only species left gripping the rocks were the leather star (*Dermasterias imbricata*) and the blood star (*Henricia* spp).

It took me a moment to get past the gruesomeness of Pete's descriptions and assess their import. Many different species were dying over a very wide geographic range, from Vancouver all the way to Monterey on California's central coast. Almost all the most common starfish species were affected. Captive aquarium populations were being hit as badly as wild ones. They were dying rapidly, and few if any were surviving. It seemed unlikely that the culprit was some kind of horrific new coast-wide pollution problem—the die-off was too widespread. I had to conclude that we were facing a new marine epidemic, a disease that was killing an astonishing number of different species at a blistering pace and with a vast geographical reach.

The Nature Conservancy meeting turned hectic for me after I talked with Pete. I tried to attend sessions but my phone was ringing almost non-stop. One call was from Katie Campbell, a broadcast reporter with KCTV in Seattle. She wanted help with a television news story about all the dead starfish washing up on the beaches around the city. She had been told to call me because I lead a government-funded research network that specializes in ocean disease outbreaks and I teach an ecology of infectious disease course at the University of Washington marine lab near

Seattle. I filled her in on what I knew about the event. When we finished our conversation, I thought, "What am I doing at this meeting in California when stars are dying in large numbers in my home waters?" The die-off was unfolding in full public view all over our beaches and people were upset and concerned. I checked my tide table and saw that if I made it to Seattle the next day I could catch a low tide at around 8:00 pm. If I went to the right place, I could immediately see how the outbreak looked and begin collecting data.

Soon I was back on the phone, talking with Laura James, who called to tell me stars were dying at her favorite dive site, Cove 1 at Alki Beach, right near downtown Seattle. Cove 1 is surprisingly diverse, housing giant pacific octopus and their babies, five species of sea star, urchins, crabs, sea slugs, and anemones. Laura, an obsessive and brilliant underwater videographer, told me that she first noticed stars falling off the pilings in late October. She had been worried and went back repeatedly to film the underwater horror that was unfolding.

Laura does a lot of diving in the dark at night. A few weeks earlier she had recorded nighttime video footage that she directed me to watch on my laptop. I stared at the screen as hundreds of ochre, mottled, and sunflower stars peeled off the pilings, arm by arm as tube feet lost their grip, the scene ghoulishly lit by Laura's video lights. Some stars were so far gone that their bodies ripped away, leaving only an arm or two hanging, organs spilling out. Underneath, the pilings were surrounded by hundreds of decomposing stars slowly turning into a white bacterial mat. I told Laura I would come help and headed for the airport. It wasn't the first time that I had dropped everything to jump on a plane to document a disease emergency. The scale and pace of starfish mortality seemed ominous and important to see firsthand. Like a crime scene, the site of a massive wildlife die-off contains hundreds of critical details to notice and record. To begin the process of understanding this event, to fit together the puzzle pieces, I needed to see the scene for myself. How many stars were on a beach? How many stars were dead? What sizes were they? How many were dying? Were the sick ones grouped together? Were the sick stars grouped on a warm area of the beach or near pollution or freshwater stresses? Was the beach a rocky ledge? Was it composed of rocky cobble, gravel, or sand? Indeed, it would soon be apparent that we were experiencing the largest epidemic in marine wildlife history, one that demonstrated how frighteningly fast an outbreak can spread and virtually eliminate an entire chunk of ocean biodiversity.

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Our oceans and the life forms they support are under siege, threatened by a formidable collection of forces that cause both sudden mass mortalities and a slow degradation of biodiversity. The top threats are the warming and acidification that accompany climate change, over-fishing, pollution from human activities on land, nearshore dredging, and oil extraction. Faced with such a ponderous list, it is hard to prioritize. As a marine ecologist specializing in disease, I worry most about the threat posed by microbes, because in oceans beset by all these stresses, microscopic disease-causing organisms can gain the upper hand, cause death on a massive scale, and thereby bring about rapid, wide-scale ecological change.

Microbes are scary in part because they are changeable and not under our control. Pathogenic organisms in the microbe category—viruses, bacteria, fungi, protozoans, and other disease-causing agents that don't fit neatly into these groups—are constantly evolving, their genetic codes often changing rapidly and staying one step ahead of their hosts' defenses. Think about one of the deadliest of human diseases, the Ebola virus, which causes fever, severe headache, vomiting, diarrhea, and hemorrhagic bleeding in its victims. Available evidence indicates that the virus has existed in bats in Africa for a long time, occasionally jumping to human beings but never breaking out beyond Africa. Then in 2013 a horrific epidemic of Ebola virus started in Guinea, Liberia, and Sierra Leone, spreading faster and further in Africa than previous outbreaks. Declared a Health Emergency of Special Concern in August 2014, it ultimately killed over 11,000 people and reached Europe and North America. Why was this outbreak so much bigger than earlier ones? Scientists aren't sure, but one hypothesis, backed up by intensive study of the changing viral genome during the epidemic done by a team led by Daniel Park of Harvard's Broad Institute, is that a key mutation allowed it to become more transmissible among humans. Because viruses have a very short life span and so many new virus particles are produced in the body of a single host, there is ample opportunity for such mutations to occur.

Microbes are dangerous too, because many can attack and infect more than one species or spontaneously develop that ability through a favorable genetic mutation. Pathogens that have a wide host range, called multi-host pathogens, tend to be deadly for at least some of the species they can infect. By deadly I mean they can kill every individual within a susceptible species, even driving them to extinction, while persisting in a more resistant host species. Contagious individuals in a resistant species can keep exposing healthy individuals in a susceptible species until the susceptible species is wiped out. In these situations, we say that the pathogen has a reservoir in the resistant hosts—a nice comfortable hideout from which to spread. The starfish epidemic of 2013–14 was caused by a multi-host pathogen. It affected almost all the major species of the entire group we call starfish.

Those of us who study non-human diseases are very concerned that mass mortality caused by multi-host pathogens is becoming a common and recurrent event, threatening biodiversity in both terrestrial and marine environments. The frogs of the world's rainforests are a high-profile example. Many rainforest frog species have been not just devastated but eradicated, at locations around the planet, by a skin-attacking fungus, *Batrachochytrium dendrobatidis,* called chytrid for short. This lethal fungus grows in the skin of the frogs, spreading its killing tendrils and exploding cells from the point of entry throughout the frog's skin. It can kill some species within days and is wildly contagious. In others, it lingers longer, so the infected frog continues to shed infectious spores from its skin into nearby streams. In 2015, using data from museum databases and field counts, John Alroy estimated the epidemic has caused the extinction of more than two hundred species of frogs. The chytrid epidemic has happened so quickly and in such remote tropical locations that the exact number of extinctions is still unknown, but we do know that many species are forever gone from our planet.

Lyme disease, carried by white-tailed deer, is also caused by a multi-host pathogen. As reservoir hosts, white-tailed deer can carry the Lyme disease bacterium (*Borrelia burgdorferi*) for many years before transmitting it back to ticks, which in turn pass it on to other species like humans. Rabies and Ebola are other examples of pathogens that have wildlife reservoirs and can infect humans.

Pathogenic agents with the potential to infect a suite of related species are bad enough in terrestrial environments. Put them in the ocean and you've got big trouble, since there is no way to get them out. Outbreaks in our oceans are different than the epidemics we face on land, in part because the oceans are a microbial frontier. Oceans harbor a far more complex mix of bacteria and viruses than exist on land, and our knowledge gaps about the biology of these diverse ocean microorganisms are much larger. In addition, to many of us, the oceans are out of sight and out of mind—we can't see a new outbreak beginning and act in time to collect the needed data or change the outcome.

To make matters worse, we have created a perfect storm of outbreak conditions in the oceans. Aquaculture and human sewage introduce new pathogens and fertilize existing ones—and it turns out that salt water is a hospitable environment for many pathogens that typically infect animals on land but can't live in air. Shipping spreads pathogens around the globe. Pollution and climate change weaken organisms' immune systems and thus their ability to fight new threats. The warming of surface waters from climate change makes conditions more conducive to pathogen survival over a wider area. Given the many ways we have mistreated our oceans and made conditions friendlier to microbes, it is no wonder that we are beginning to see more outbreaks of marine diseases.

The great starfish epidemic that opened this chapter—sea star wasting disease—is only the most recent of the ocean plagues. In the mid-1980s, the world saw its first case of a disease threatening an entire ecosystem when an infection decimated the two main reef-forming corals in the Caribbean. Near the end of that decade, several species of abalone along the Pacific coast of the United States began to sicken and die, victims of a slow-rolling outbreak caused by what turned out to be an unusual kind of bacterium. In 1984, a disease struck farmed Atlantic salmon in Norway, and subsequent outbreaks, caused by the same virus, have occurred sporadically in farmed salmon all over the world. In the 1990s, a disease caused by a fungus began killing coral species that hadn't been affected in the earlier bacterial plague.

Scientists have tracked and investigated these outbreaks, learning a great deal about their causes, courses, and consequences. I have been fortunate enough to be among them, and have led several teams of scientists to track outbreaks and consider solutions. It started with an international team that originated when the World Bank granted us funding to study the destabilizing ecological effect of coral disease outbreaks and to provide training in tropical areas such as Mexico, West Africa, and Indonesia. More recently, our team has expanded to include a focus on the health of temperate waters and to number more than forty scientists. With funding from the National Science Foundation, our Research Coordination Network for Ocean Health focuses on training the next generation of scientific leaders and developing surveillance of new infectious disease outbreaks to detect how climate change fuels these outbreaks in the ocean. There is still a great deal we don't know, but we have learned enough to be fearful about what could happen and hopeful that together, we can find ways to keep our oceans healthy.

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When I'm at home on San Juan Island, enchanted by the natural beauty surrounding me, it's difficult for me to keep in mind the many threats facing the oceans and their bountiful life. The island, where I live part of the year, is one of several in a group in the Salish Sea, north of Puget Sound and Seattle. By all appearances, it's a marine paradise where people coexist harmoniously with ocean life. On land, the hills are clothed with forests of towering cedar and Douglas-fir trees mixed with red-barked madrona, and rolling farmlands fill in the spaces between the patches of pristine wilderness. The waters around the islands are clean, deep, and cold, part of a vast network of coastal waterways that stretch from Puget Sound far up the Strait of Georgia to Desolation Sound on northern Vancouver Island, and they encompass the richest coastal sea in the United States and Canada.

Our waters have, for some groups of marine organisms, the highest biodiversity in the world. The Salish Sea is packed with five species of salmon, jumping so thick some days during the summer run that it feels like they could leap into your boat. It's a good thing there are lots of them, because they have supported an impressive pod of southern resident killer whales, or orcas, each of which might eat three hundred pounds of salmon per day. From the deck of my house, I can look across our forest-ringed bay to the crossing of two waterways, Haro Strait and the Strait of Juan de Fuca, and past that to the shores of both Canada and the Olympic Peninsula. Best of all, our shore is on the daily run of that pod of southern resident killer whales. Many days in the summer, we see water spouts and the tall black fins of breaching whales as they pass by. I usually hear them first, the great exhalation that echoes for miles across still water. I am so well-tuned to that combination of sound and vibration that I stop whatever I am doing when the faintest orca echo reaches me, much like a dog would. Sometimes they wake me in the early mornings with their breathing and the breaching that ends in a thunder-clap of a splash.

The environment seems healthy and pristine. Most of the creatures in the long food chains from eelgrass to whales are thriving compared to those in more impacted waters. But under the surface, all is not well—not even here. In the aftermath of the starfish epidemic, sunflower stars are virtually absent, and other stars are much less abundant than they once were. The disappearance of the stars has had major ecological consequences. And the salmon—food for the orcas and humans—are in decline, with pathogenic microbes playing a role. The southern resident orcas are classified as endangered, with the declining salmon population a principal cause.

The mismatch between the outwardly healthy appearance of my home waters and what I know to be the underlying threats to their health helps me understand why it is that many people I talk to don't readily appreciate the seriousness of the situation. As long as seascapes remain scenic and we can still buy salmon at the grocery store, there seems to be no cause for alarm about the condition of the ocean. Why should we be concerned about disease outbreaks when each affects only a tiny proportion of ocean life? The answer lies, of course, in the words of the ecologists: everything in the ocean is connected. Since humans depend on the oceans for much of our food—worldwide, humans derive about 15% of their animal protein from the ocean—the interdependence of marine species matters. Disease outbreaks in non-food species can affect species we harvest in ways that we may not be able to predict and in ways that are painfully obvious. Corals are a case in point: we can't eat coral polyps, but the destruction of coral reefs in the tropics, due to a multitude of factors that prominently include disease, is having serious impacts on the many fish species that use reefs as nurseries and habitats and on which millions of humans depend for much of their food. Further, the species we do harvest for food are particularly vulnerable themselves, often precisely *because* we eat them and are thus likely to raise them in aquaculture, where pathogenic microbes can thrive.

Looking beyond our own self-interest as consumers of food from the ocean, there are other reasons to worry about the spread and multiplication of marine diseases. The oceans support much of the planet's biodiversity. Of the seventy phyla into which E. O. Wilson categorizes all life, from bacteria to vertebrates, twenty are exclusively marine; they occur in the ocean and nowhere else. While there are more total species on land, due to the huge number of terrestrial insect species, the oceans house the greatest diversity of life forms, including unique types of body plans, like the radial, tube-feet-equipped design of the starfish phylum, the echinoderms. The incredible diversity of underwater life, a product of billions of years of evolution, is a treasure endangered by the injuries we inflict on our oceans.

Because of the interconnectedness of life forms, biodiversity loss in the oceans is not just a matter of individual species being picked off by diseases or other killers. The loss of just a couple of reef-building corals in one locality, for example, can have effects that reverberate through the entire reef ecosystem, causing the loss of hundreds if not thousands of species dependent on the special environment of the reef. I learned this lesson early in my career when I watched disease turn coral reefs into rubble. With the decay of the physical habitat, the ecosystem lost its internal regulation and many species declined or disappeared. As coral reefs around the globe—sites of the highest marine biodiversity on our planet—continue to be imperiled by the deadly combination of ocean warming, sea-level rise, pollution, and opportunistic infection, so too are their rich assemblages of species. Kent Carpenter, with the International Union for Conservation of Nature, led a team of scientists from around the world who estimated in 2008 that fully one-third of coral species are now considered in danger of extinction and entire reef systems are at risk. The numbers have become even more dire following the extreme heat waves of 2015 and 2016, which decimated coral reefs around the world.

As the example of coral makes clear, marine disease is not the sole cause (or even, for many taxonomic groups, the major cause) of the loss of biodiversity in the ocean, but it is emerging as a causal factor that works in concert with the others. Many scientists have tended to view disease as a "canary in the coal mine," a sentinel of change in oceans suffering from the cumulative impacts of human activity. As an ecologist, I think now that infectious disease is more than just an indicator; it is itself the new major change agent in the ocean. A warmer, more polluted ocean is turning out to be a sicker ocean, and infectious disease is often what's felling the species that call the ocean home.

There is no reason to believe that the outbreaks I describe in this book are the end of the story. The microbes, ever ready to exploit the vulnerabilities we create for them, will spring on us new surprises. But science is not without its weapons. By studying the pathogen-host interactions at the root of disease outbreaks, we are learning how we might gain the advantage in controlling some diseases and devise policies that can prevent and limit the spread of future outbreaks.