Eat,
Poop,
Die

Also by Joe Roman

Whale

Listed: Dispatches from America's Endangered Species Act

Eat, Poop, Die

HOW ANIMALS MAKE OUR WORLD

Joe Roman

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To my dad, José Roman; uncle Joe Sweeney; and friend and colleague Jim McCarthy—whose atoms are now part of new constellations

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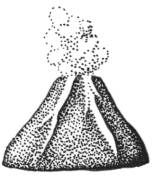

Just before dawn on November 14, 1963, the *Ísleifur 2* had set a bottom longline off the southeast coast of Iceland. Most of the crew were belowdecks—resting up before they retrieved the line and unhooked the cod—but the engineer noticed a strong smell of sulfur as he finished his morning coffee on deck. He checked the wake of the vessel. There was no sign of sewage—no cause for alarm—so he joined the other men below.

Half an hour later, the cook on watch noticed the ship starting to rock as if caught in a whirlpool. Dark smoke rose above the turquoise surface of the sea. He yelled down to the skipper. All hands now awake, they looked to see if there was a ship in distress nearby. But they saw only a plume.

Four hundred feet below, the seafloor trembled. Then the tephra—ash, cinders, and lapilli (rock fragments about the size of rabbit pellets)—spewed up from the ocean, dwarfing the fishing boat. Smoke from the explosion rose five hundred feet above the sea surface, once blue, now greenish brown. As the tephra column

reached a height of more than two miles, it became obvious: the crew had set their gear near a volcanic fissure.

There were no fish on the line when they finally pulled it in from the boiling sea.

By the next morning, a new island had risen thirty-three feet above the surface of the North Atlantic. The island continued to rise about two hundred feet per day in an uprush of magma, cinder, and ash, and within a week, the eruption column, white by day, pink at night, reached six miles into the air. Flashes of lightning creased the sky.

Inhabitants of Heimaey, the only town on the Vestmannaeyjar, Iceland's Westman Islands, reported seeing glowing embers on the horizon as seawater entered the new crater. Six large earthquakes rattled the town. On December 6, three French journalists took a speedboat from Heimaey to the new island and stayed for about fifteen minutes before an eruption chased them off.

The media attention in Iceland and abroad got people wondering what they should call this new landform. For a moment it seemed that the first person who had set eyes on the new island, the cook Ólafur Westmann, might be honored by having the island named after him: Olafsey (Olaf's Island). Others in Heimaey preferred Vesturey (West Island).

Icelanders take their names very seriously—the government still has final say over acceptable baby names in the country; there are no Lucifers, no Ariels—so the Icelandic government convened Örnefnanefnd, the place-name committee, to decide. The choice was announced on the radio, and soon after, one of Ólafur's shipmates found the cook cleaning up in the galley, dishrag in hand, on the verge of tears. "They gave it a terrible name," he muttered. "Surtsey."

The committee had turned to Norse mythology: During Ragnarök, the prophesied end of the world, the giant Surtur will bring fire to fight the god Freyr. The lava vent was a lethal red with water

boiling all around it, so the committee called the new landform Surtur's Island—Surtsey.

Westman Islanders, angry at not having been consulted, sailed to Surtsey's shore and erected a sign with the name VESTUREY. Surtur responded by pelting the islanders with pumice and mud. No lives were lost. Surtsey stuck.

IN ITS FIRST year, Surtsey expanded at thirty cubic yards a second, adding an area almost as big as the Great Pyramid of Giza each day. The lava plain was a glistening black with ropes of hot lava unraveling toward the sea.

Sigurdur Thórarinsson, a professor at the University of Iceland, was the first volcanologist to land on Surtsey, about three months after the initial eruption. He and a few fellow scientists were collecting geological samples along the shore when they noticed waterspouts in the ocean. Lava bombs crashed into the water and started falling around them. Each one up to a yard in diameter, the bombs landed on the beach with resounding thuds as the wet volcanic sand boiled beneath the red-hot lava. "Under such circumstances there is really only one thing to do," Thórarinsson recalled. "Suppress the urge to take to your heels and endeavor to stand still and stare up in the air, trying not to dodge the bombs until the very moment they seem to be about to land on your head." Stop and look up—but not for too long, or the soles of your boots will start to smolder. Thórarinsson noticed that the research vessel was moving farther offshore, away from the danger.

The volcanologists were soon enveloped in "warm and cozy" clouds of pumice, grains of rock so light, they floated in the air. It was hard to breathe, and visibility was down to zero, but at least the larger bombs had stopped falling. As the wind carried the pumice cloud away, Thórarinsson and his colleagues waded back to their dinghies and rowed to the ship.

No one returned to Surtsey until the vent stopped exploding.

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When the lava bombs subsided, Surtsey gave biologists the rare opportunity to study life from the first days of an island's emergence. It was an "ecologist's dreamworld," according to Charlie Crisafulli, who has studied Mount Saint Helens in Washington since it erupted in 1980. Unlike that eruption—which covered forests and grasslands, so there was some residual life beneath the ash—Surtsey rose in the middle of the ocean. It was inaccessible, at first, with no animals or plants and a hostile environment. As soon as he stepped off the helicopter, he realized that Surtsey was a perfect place to study how ecological communities assembled.

"The materials coming out of volcanic events can be toxic with sulfur, chlorine, and fluoride compounds," Crisafulli told me over the phone a few years after he visited Surtsey. "This is a huge problem for animals and plants." There were too many bads (toxins) and not enough goods (nutrients) for anything to survive on Surtsey. The gases, lava, and tephra that volcanoes belch out lack many of the basic building blocks of ecosystems, such as carbon and nitrogen, but the rocks are phosphorus-rich. "What's happened in an old landscape like the one you're sitting in right now, the Green Mountains, the White Mountains, the Adirondacks"—I was talking to him from my home in Vermont—"is that phosphorus has long weathered out of those rocks," Crisafulli said. "But volcanic landscapes provide a new, fresh batch of phosphorus that can often be rendered quite readily." So there was plenty of phosphorus on Surtsey, but nitrogen, at least in the form that animals and plants could use, was quite rare. Both elements are essential to life, forming the basic building blocks of DNA and protein and helping to power mitochondria, the workhorses of the cell.

During Surtsey's first decade, there was little vegetation in the volcanic sand and lava. When it rained, the water leached through the porous lava and eventually reached the ocean; when it didn't, Surtsey was like a desert or the highlands of Iceland, which are so

barren NASA once used them to train astronauts for the lunar landing. Any plants that did show up on Surtsey were faced with a shortage of nitrogen in the soil.

Nobody knew it yet, but the answer to the nutrient problem could be seen even as the vent was still erupting. A couple of kittiwakes, yellow-beaked seabirds common on the mainland, alighted on the craggy, vinyl-black shores. These birds, and the gulls and fulmars that followed, would deliver the first concentrated nitrogen in the form of uric acid, one pasty poop at a time.

The first life on this new landscape arrived by sea or fell out of the sky. Tiny seeds of wind-dispersed plants—willows, orchids, and ferns—rained softly over the island. To stay airborne, these seeds travel light, carrying little in the way of food or nutrients with them. They showed up on Surtsey's inhospitable shores, but with limited resources, they either never sprouted or soon withered and disappeared.

Large, buoyant seeds were swept ashore on the ocean currents. "If you are traveling by sea," Borgthór Magnússon,* one of the island's longtime naturalists, told me, "then you can afford to pack nutrients for your establishment." The first documented species on the new island was the sea rocket, a succulent that washed up along Surtsey's sandy edge and took hold. Its seed has a cork-like covering that helps it float and keeps it safe from salt water. But lava was still flowing into the sea in a drama of magma, gray ocean, breakers, and steam. Tephra, ash, and cinders from a nearby vent buried the young plants.

In the beginning, pioneers like the sea rocket were no match for the active volcano, but they kept arriving, and the island slowly cooled. Soon, ocean-borne seeds of sea sandwort and oysterleaf washed up on the bleak edges of Surtsey's coast. The seeds of both

* Borgþór Magnússon is the Icelandic spelling of the name; the *þ* is pronounced like "th" in English, so *þor* is "thor." For ease of reading, I'll use the English spellings of Icelandic names.

species are built for oceanic travel, packing enough nutrients with them to take root when washed ashore. Suited to the wind and cold, the sandwort hugged the barren sands where few other species could survive. It formed a bell of bright succulent leaves aboveground; deep roots stretched out below, absorbing water and nutrients from the crevices and sand. In cross section, the sandwort resembles a Portuguese man-of-war: a green sail above the surface and long tentacles below. Decades later, sandwort still covers parts of Surtsey in striking herdlike patterns, the most fetching plants on the island.

Oysterleaf is as seaworthy as its species epithet, *maritima,* implies. You couldn't engineer a better pioneer for a new island in the North Atlantic. Oysterleaf seeds usually stay dormant until they are shocked by the cold sea—temperatures in the thirties enhance germination. By the time the seeds reached Surtsey, they were ready to grow. The oysterleaf seedlings stayed close to the boulders at the rocky edges of the island, keeping their heads out of the wind. During Surtsey's first decade or so, the plants' low-hanging flowers provided rare splashes of blue against a monochrome landscape.

Life remained sparse at first. Only the most hardy and well-provisioned plants could survive. There were no pedestrian invertebrates—no daddy longlegs, worker ants, or crickets, the usual suspects that show up on the pumice of volcanoes. A few insects blew in. The first one recorded was a migratory moth, then a couple of midges. Many of these bugs—called *fallout fauna*—probably died of fatigue, desiccation, or low temperatures. One zoologist described the first insects to arrive in a volcanic landscape as "derelicts of dispersal."

Nonetheless, slowly but surely, animals—insects, birds, then seals—made their way to the young island.

It wasn't that long ago that animals were dismissed by many scientists as bit players on the planet; plants and microbes took center stage. But in the past decade or so, there has been a radical shift in

our understanding of how the world is shaped by predators and herbivores. Landmark studies of seabirds, whales, sea otters, salmon, wildebeests, bison, spiders, grasshoppers, cicadas, and other animals have shown that they can alter the landscapes and seascapes where they live, with major impacts on ecological function and the services these animals provide. Much of this remains unseen; few people realize that when they recline on the white sands of Hawaii and other tropical beaches, they are lying in the waste of parrotfish, the poop from coral meals.

Animals matter. Creatures—sometimes with fur or scales, sometimes red in tooth and claw, perhaps with talons and wings, wild and free-roaming—are a fundamental mechanism of sustaining life and a source for the nutrients it requires. It's only after thousands of years of serial depletion by our species that scientists are beginning to understand the interconnectedness of these energy transfers.

Follow the nutrients. The essential elements of carbon, nitrogen, and phosphorus move in geologic time, carried by gravity, wind, and currents. Downhill. Downwind. Downstream.

If they reach the deep sea, phosphate and ammonia molecules—the common sources of phosphorus and nitrogen—can be locked away in the ocean depths for hundreds of years unless they hit an area of upwelling, where waters are drawn to the surface. Such areas are rare in the ocean. There is another way for these vital nutrients to move thousands of feet up the water column: they can catch a ride in the belly of a whale.

Foraging sperm whales feed on giant squid and other deep-sea creatures, but they must return to the surface at least once an hour for a postprandial breath of air; there, they rest, digest, and often release enormous fecal plumes rich in phosphates, nitrogen, and iron. The nutrients in the plumes can be picked up by phytoplankton (also known as microalgae) and consumed by zooplankton, such as krill or tiny copepods. The krill or their fish predators might then be consumed by seabirds—gulls, fulmars, terns, penguins, petrels, shearwaters, albatrosses, boobies, and magnificent frigate birds—and

airlifted to their breeding grounds. Back at their nests, the birds feed their young by vomiting up their sea meals and excrete nitrogen-rich uric acid—the striking white paste that is released along with the feces—onto the land.

We can follow these elements from the deep sea to the coasts, rivers, forests, savannas, and mountains of the world. A geological journey that would take thousands or millions of years—the tectonic plates beneath Iceland move at a rate of approximately an inch and a half per year, about the speed of growing fingernails—can be reversed in a single dive, a short flight back to a barren rock, and a Pollock-like spatter.

Animals are the beating heart of the planet. In the same way that trees work as the Earth's lungs—inhaling carbon dioxide and exhaling oxygen—animals pump nitrogen and phosphorus from deep-sea gorges up to mountain peaks and across hemispheres from the poles to the tropics. Trillions of animals live the traveling life—they fly, run, swim, walk, even dig. Large and medium-size animals—whales, elephants, bison, salmon, and seabirds—can move nutrients hundreds and sometimes thousands of miles, across oceans, streams, mountains, valleys, prairies, and remote volcanic islands. These long-distance travelers are the world's arteries. Cicadas, midges, krill, and other invertebrates, if we take this idea a step further, are the capillaries, delivering nutrients to Earth's tissues.

It's not just poop and carcasses. Animals change the world through their consumption too. They eat plants. They eat plant-eaters. They change the chemistry of the world just by instilling fear.

Ecosystems are living things, emerging, maturing, dying, and even in death, they add richness to the web of life. Animals have major influences on these systems and the geochemical cycles that humans and all life-forms count on for survival. I can think of no better place to start my exploration of these pathways than on the once-barren rock of Surtsey.

***

I REMOVED THE laces from my trail runners, scrubbed off the caked mud with an old toothbrush, and scraped away any seeds that might've hitched a ride from my home in Vermont or the Icelandic mainland. Only about a dozen people were allowed on the island each year, and in 2021, Borgthór Magnússon, the field leader at Surtsey, had invited me to join their expedition. He'd made it clear that I should remove any stowaways I might be harboring. If a plant or insect wanted a ride to the island, it would have to find a bird or a raft of seaweed.

The day before, I had hiked up the Eldfell volcano on Heimaey, the largest of the Westman Islands, to get a peek at Surtsey. A dark mound about ten miles to the southwest, the island looked like a Devonian tetrapod crawling out of the slate-gray sea.

Bjarni Sigurdsson, one of the lead ecologists at Surtsey, and his grad student Esther Kapinga picked me up at the hotel. We stopped at the local N1 petrol station for supplies. There was a colony of hundreds of kittiwakes on the cliff above the station, flying in to feed their chicks the small fish that they had gathered in the fog. Their poop streaked the rocks like crosswalk stripes.

At the airport, we dropped off our gear as well as the supply of petrol and drinking water for us and the team already on the island. Dressed in black raincoats, Bjarni and Esther identified the plants around an old stone farmhouse near the airport while we waited for the Icelandic coast guard helicopter that would fly us to Surtsey. (It is typical in Iceland to call people by their first names; even the phone book, back when people used such things, was ordered by first name, not last.)

When we returned to meet with the coast guard, the fog over the airport was so thick that the helicopter that was supposed to pick us up couldn't land. The pilot suggested via radio that we drive out to the island's only golf course, where the weather was clearer.

We parked on the edge of the course, which had a beautiful view of the Atlantic, the fog smothering the volcanic cliffs to the north.

"No message yet," said Bjarni as we watched the fog creep over the green.

We got a visual on the helicopter as it approached over two sea stacks known as Haena and Hani, the Hen and the Cock. It circled offshore above the low-lying clouds, then flew away.

As we waited for the pilot to circle back, Bjarni got on the phone. "They're gone."

"Andskotinn!" Esther swore in Icelandic.

It was starting to sink in that we might not get to Surtsey that day—or perhaps at all. We retrieved the water and petrol from the airport and stowed it in the SUV.

Bjarni considered alternatives. We discussed driving to Reykjavík, but the coast guard wouldn't be available. It was a small country, Bjarni explained, and being too pushy wouldn't do the project any favors. (The coast guard ran these trips for the research team as a courtesy.)

When we ate lunch at a harbor restaurant, Bjarni noticed a large rubber inflatable boat tied up below us, mostly used to take tourists out to see whales and puffins. Could that get us to Surtsey? He asked around in case the coast guard fell through entirely but couldn't find the owner.

The fog was beginning to lift by the time we finished lunch, and we could see several fishing boats in the harbor, similar to the ones Bjarni once worked on to pay his way through university. Brawny with blond hair, thick retro glasses, a boyish smile, and a big appetite, he lived up to his name, which meant "bear" in Icelandic. His father had been a fisherman too. "Back in those days, at least two to four of the seventy-five boats in town would capsize every year, with all the crew," he told us. "So you were playing the lottery every time you took a boat. You knew there was at least a five percent chance that you wouldn't make it. It was just part of life."

You were lucky or you were unlucky.

"My father used to always go with the same captain, and one time, for some reason or another, he was too late or something, and

he didn't get hired on that boat. So he took a place on another boat that winter. His usual boat went down with all the men. So he was just lucky."

We could see across the harbor to Heimaklettur, or Home Rock, covered in grass and streaked with white seabird dung, a welcome sight to boats returning from sea and those of us hoping to leave. Bjarni called up the coast guard: "If you can come back this afternoon, the ceiling has lifted."

They said they would give it another try. We drove to the airport and paced the empty terminal like expectant parents. The fog poured in like a bad dream, blanketing the wet gray tarmac. We heard the thudding of the helicopter blades, but by then we couldn't even make out the runway from the terminal window.

"They are going to try for the end of the runway," Bjarni reported, still on the phone.

We listened to the muffled blades above the fog. And then it got quiet. The airport attendant gave us the thumbs-down.

"They wished us good luck," Bjarni said. We were on our own.

My heart sank. There would be no second chance for me to visit Surtsey. Bjarni and Esther would lose a year of research, since the biologists on the island were leaving at the end of the week. And things would be tough on the island too. Most of the drinking water and petrol for the five researchers at the station was sitting on the tarmac here.

"I will get to Surtsey even if I have to swim," Esther later said from the back of the SUV.

If we couldn't be air-dispersed, perhaps we could make it by sea. A crew from the BBC was scheduled to film on the island; maybe we could tag along with them the next day on the inflatable boat they had chartered. Bjarni stopped by the tour company to inquire. The captain asked for a thousand dollars a person. Bjarni wasn't sure if it was in the research team's budget.

We ate a somber dinner and headed back to the hotel. From my window, I saw the sky brighten through the night as the fog lifted. The Eldfell volcano just east of town filled the frame with the black-and-tan abstract shapes of a Clyfford Still painting. On most days, a volcano out the window would be a welcome sight. That evening—which was just one long day—Eldfell taunted me.

The next morning, as Bjarni and Esther did some botanizing, he got a call from the coast guard: "We're out doing fisheries patrols. Can you guys be at the airport in an hour?"

I threw my meticulously cleaned clothes into my duffel bag. We packed up the SUV and drove out to the airport. We boarded the deep blue EC225 Super Puma, all of us wondering if, at last, it was real. Life and travel are a series of lucky breaks and missed opportunities. It seemed that we were finally getting a break.

The pilot tightened the caps on the gas containers and looked up as I brought a big Rollaboard on deck along with the rest of the bags.

"You going to London or something?"

When I stepped off the helicopter onto the tiny, cracked landing pad, it felt a bit like I was walking on the moon—if the moon had a few pioneer grasses, an occasional gull, and a couple of scientists who were older than the ground they were standing on.

Borgthór Magnússon, Surtsey's field leader, made his first trip to the island in 1975 when he was twenty-three years old. Now he had a white, well-trimmed sea captain's beard and wore a tidy zip-up cardigan beneath his Norrona raincoat. As we walked out to the nesting grounds, I asked Borgthór what it felt like the first time he visited. "It was just a heap of ash, gravel, and lava. There were a few plants, and we knew almost all of them as individuals."

Borgthór still knew many of these particular plants, and a tour of the island was a bit like crashing a botanists' cocktail hour. There were a few newcomers, like the coltsfoot and black sedge, and lots of regulars. "I would say the *Honckenya* and *Leymus*"—the sandwort

and sea lyme grass, the latter a genus common along the coasts of the North Atlantic—"were the most successful colonizers." These keystone plants spread out over the barren tephra and volcanic sands. Sand dunes formed around the lyme grass. "The largest plant on the island," Borgthór said. "It makes good shelter for the great black-backed gull nests and for their chicks to hide in."

A few of these gulls eyed us from the basalt balconies along the meadow's edge.

There were surprises too. Borgthór pointed out a lone, thick-stemmed plant with long leaves on the edge of the breeding area: the northern green orchid, *Platanthera hyperborea*. "It's quite remarkable for an orchid to grow on Surtsey," Borgthór said, because it needs mycorrhizae, the symbiotic fungi that are essential to providing nutrients to the plant's roots.

Later, as I walked from the intertidal zone to the cabin, I noticed dozens of thin stakes, whittled by the wind, in the lava sand. Many of the island's first plants grew on the eastern edge of Surtsey, where sea and air currents had brought them from the nearby islands. In the first few summers, Borgthór and other researchers recorded every plant on the island. A few of these stakes must have marked the plants Borgthór and his colleagues came to know almost by name. The first were planted in 1968 and used until the 1980s, when they were replaced by GPS. Decades later, the plot looked like a graveyard memorializing the island's first settlers.

One morning in the fall of 1963, when Erling Ólafsson was fourteen, he noticed a gray plume rising high above the mountains to the east. As the magma hit the ocean, enormous cauliflower-shaped vapor clouds filled the sky. A dark curtain of ash poured back into the sea.

"I saw the smoke from my bathroom window in Hafnarfjordur," Erling told me. "I stayed for a long time, watching this smoke. Doing nothing, not even moving, just like a mushroom."

Erling never forgot the sensation of watching Surtsey erupt, but he soon turned his attention to something even closer: entomology. When he was young, Erling got a gift from his grandmother—a series called Averdens Dyr (roughly "Animals of the World"), books available only in Danish. Glued to the pictures, he taught himself the language to understand the text. He was drawn to the small invertebrates. By the time he reached university, Erling knew more about Iceland's insects than just about anyone. He caught the eye of a famous Swedish entomologist who was starting a research project on Surtsey.

Erling arrived on the island for the first time in 1970 in a small rubber boat. He set some of those early stakes marking the plant pioneers in the gray lava sands. There was an upper valley, with brown tephra, a flat open plain, a small estuary, and steep cliffs. Surtsey soon came to feel like a younger sibling to him. Earth's newest landmass was still in its geological infancy. "This is the first time that we scientists had land that was quite sterile," he said.

Erling's first trip to Surtsey coincided with the greatest ornithological event in the island's history. A pair of guillemots, small black auks with bright red feet, nested on the island—Surtsey's first breeding seabirds. For these denizens of the Arctic, the newly formed island had a lot to offer: easy access to small fish and krill in the ocean and virgin land free of predators. No arctic foxes. No rats. No people . . . at least, not until Erling and his colleagues arrived, though they were careful not to disturb the birds of the island's budding ecosystem.

After the guillemots, other marine birds started showing up. Fulmars are classic seabirds, procuring almost all their food from the ocean in the form of small fish, squid, and crustaceans. We could see their eggs, which looked like large golf balls in a lava sand trap, above the cliffs. "The only place in all of Iceland where fulmars actually nest on the ground is Surtsey," Bjarni told me, presumably because predators—and humans—left them alone. Great black-backed gulls feed on fish, birds, and marine invertebrates or scavenge along

the coast; lesser black-backed gulls are generalists, usually happy with the insect larvae turned up by a farmer's till or with vegetation, and they and herring gulls are relatively common in Reykjavík.

After the first fulmars and gulls arrived on Surtsey, the great black-backed gulls muscled their way into the prime real estate. The lesser black-backed gulls concealed their nests along the edge of the lava fields. As the colony expanded, so did the green grasses, a ripple effect of feathers, poop, and brawn.

What these birds have in common is that they all bring nutrients to the island. The white streaks of guano around their nests are rich in carbon, phosphorus, and the much-needed nitrogen. In addition to poop, there are carcasses and eggs. During his first visits, Erling recorded each bird he found, creating a timeline of new arrivals. By the mid-1980s, enough gulls and fulmars had arrived to change Surtsey; each of the hundreds of nesting birds released up to three ounces of poop a day—a double shot of nutrient-rich guano.

Near the research cabin, the sharp-edged lava shredded the leather of my pristine boots. When we reached the vast grasses of the seabird colony, it was like entering a different world. Here, the ground felt solid beneath my feet, comforting. There was a faint smell of ammonia and a burst of green so bright, you could see the colony from space, an oasis in the lava sand.

At the edge of the knee-deep meadow grasses, I noticed an increase of *Rumex,* broadleaved sheep sorrels so tall and full-bodied that they almost looked like trees. It was hard to believe there was almost no grass here until twenty or thirty years ago. And there wouldn't be any today if it weren't for the bird shit.

How can you tell that the nitrogen came from the birds and not the atmosphere? The isotopes, or chemical signatures, of the nitrogen in the soil and plants indicated that 90 percent came from seabirds, the rest from the atmosphere. At the center of the breeding grounds, birds deposited up to sixty pounds of nitrogen per acre per year. Outside the seabird area, it was only about a pound per acre per year. (For a rough comparison, farmers typically apply about a

hundred pounds of nitrogen per acre of active cropland. Many permanent grasslands, for grazing and hay, receive less than that, maybe twenty-five to fifty pounds per acre.)

Juiced with nitrogen-rich guano, scurvy grass, once a source of vitamin C for sailors, and meadow grass, a native of Europe and Iceland (known in North America as Kentucky bluegrass), began to thrive. Seabird colonies on Surtsey, green with annual meadow grasses, now have thirty times more nutrients and about fifty times more biomass than the black lava fields that surround them because of the guano, eggs, and carcasses from the birds.

These nesting areas are now so lush, the soils so rich, that "we could have cows out there," Erling quipped. "We could have fresh milk every day."

Surtsey sands without seabirds (top) and grasslands in the gull colony (bottom). (Borgthór Magnússon)

As the birds arrived, the plants, and the stakes commemorating them, spread out across the vast lava sands to the southwest. Plants have devised several strategies to spread their seeds. They can fly. They can float. They can stick to the feathers and legs of a bird or pass through its belly and land in its nutrient-rich poop.

As Borgthór and I walked along the edges of the breeding grounds, we were surrounded by lesser black-backed gulls, regarding us through red-ringed eyes, their smooth white heads standing out against the cragged dark lava. It was like being adrift among whitecaps. These seabirds were almost entirely constructed of ocean.

A gull called *Tut-tu-gu* overhead, the Icelandic word for "twenty," or at least that's how I heard it. If I couldn't learn Icelandic on this trip, at least I could learn, or approximate, the language of the plants and birds and come to admire the black-backed and herring gulls, often maligned in the city and elsewhere.

Before leaving for Surtsey, I had walked along the Reykjavík waterfront in search of a meal. A herring gull alighted on a café table and grabbed a leftover slice of pizza. Several gulls swooped in. A lesser black-back grabbed the prize. A couple of tourists walked by, and the man stamped his foot at the birds; he and his companion laughed. The gulls flew away. But not without the pizza.

I SAT AT the edge of the seabird meadow watching the fulmars fly in. This was well after dinner, but it wouldn't get dark tonight—or anytime during our stay. I had been lost in the abstract expressionism of the bird-dropping paintings, but here was a Surtsey still life: a gull wing, green sandwort, a white fulmar egg against the dark lava sand. It seemed that the beige palagonite ridge, part volcano, part ocean, had been brooding over the North Atlantic forever, even though it was younger than many of us on the island. Someone walked across the lava field. I could hear it crumble.

A muffled cackle rose from beneath my feet as I walked the grasslands: a fulmar warning me away from its nest. There are about two or

three hundred breeding pairs on Surtsey. On the mainland, there are up to two million in summer—more than half the world's fulmars nest in Iceland—but they are restricted to ledges and crevices, hiding away from predators like foxes. *Fulmar* in Old Norse means "foul gull." They feast on the smelly livers of fish and have done well in modern times, enjoying the processed waste and trash from fishing boats.

Young fulmars, once valued for oil and down, protect themselves by stress-vomiting a bright orange streak of grease. Don't get too close. "The spit smells like rotten fish-liver oil, and it's similar in texture," Borgthór said. The distance isn't great, but they can project a few feet. Erling warned me that if I got the vomit on me in Surtsey, I wouldn't be able to rid myself of the smell for the duration of the expedition or even longer. Birds that make the mistake of attacking a fulmar get covered in the foul-smelling goo, rendering them incapable of flight and putting them at risk of drowning.

An adult returned to its nest from the open sea and vomited up a fresh fish meal. Try as it might, the chick didn't get everything. Sloppy eating must bring some nutrients to the burgeoning meadow too. I gave them a wide berth.

Here in the center of the breeding colony, where nutrients are abundant, the number of plant species has declined since Borgthór and colleagues started measuring diversity and productivity in 1990. Outcompeted by the four dominant knee-deep grasses, many of the pioneer plants have disappeared. There is now a dense grassland where ten different species once grew.

Things get interesting along the edges. The ecological processes are at their most dynamic at the border between the chaos of lava and the spongy wealth of grass—at the boundary of the ripple, where the new birds, mostly lesser black-backed and herring gulls, are moving in, helping to gentrify Surtsey, transforming it from a pioneer community to a grassland. Seventy-eight species of plants have been identified on the island. The lowest diversity was on the lava field, no surprise, but the number of species—if not their abundance—is also relatively low within the bird colony, where the nutrients are high.

Only a few grasses dominate. The lushest parts of the grassland are practically monocultures compared with the fringes, where grasses give way to barren lava.

This borderland reminded me of what ecologists call "the intermediate disturbance hypothesis," developed to describe trees in rainforests and animals that live in intertidal zones. Stable areas—like the meadows of Surtsey, where a few dominant grasses with plenty of nutrients outcompete other plants—allow a few species to thrive. In contrast, ecosystems under constant change are tough places for animals and plants. The rocky shoreline at Surtsey, where new lava boulders tumble down continuously, is too dynamic for many species to take hold. Moss doesn't grow on a rolling boulder. The sweet spot for biodiversity, where new plant species can find a niche, is often the intermediate zone: not so many nutrients or so much stability that a few species take over but still stable enough that an emerging community won't be wiped out entirely by a sudden change in the landscape, and even newcomers can survive.

It brought to mind the Icelandic Viking origin story: In the beginning was chaos—in the north, snow and ice; in the south, heat and fire. Life emerged on the land between the two.

A few years ago, several scientists on a research cruise in Baffin Bay, a pristine part of the Canadian Arctic, were surprised to come across an area with high concentrations of ammonia, something you might expect to find along an industrialized, polluted coastline. The models that atmospheric scientists like Jeff Pierce of Colorado State University had put together suggested that there shouldn't be any ammonia in that remote part of the Arctic.

And then the scientists looked out the window, or perhaps just at a chart. "The ammonia concentrations were highest when the ship was near places known to have seabird colonies in the summertime," Pierce told me. That made sense; seabird poop in big colonies often emits gases that are rich in nitrogen. He and his colleagues added

an inventory of migratory seabirds to the model. "We realized that seabirds were almost certainly the missing source of ammonia in the Arctic."

This pungent gas can hook up with sulfuric acid, abundant in the region, to form particles. The particles form droplets. Clouds with more droplets are denser, and they appear whiter and brighter. Pierce likened it to looking down on a glass of water on a black table. "If you put three ice cubes in, there's going to be some light reflected by those ice cubes, but for the most part, you'll see the black surface. Now, if you took those ice cubes and crushed them into tiny ice fragments, they would be really good at reflecting the light from above." So if you looked down at the glass with the crushed ice, it would appear white, even though it had the same amount of ice. The ammonia from the seabird colonies formed lots of small droplets. The clouds still held the same amount of water, but like the crushed ice, they now had a lot more surface area and reflected more sunlight back into space.

"So you have this effect on climate," Pierce said. The clouds over seabird colonies keep the Earth cooler because they're brighter, with the biggest effect in areas with the most birds. Large colonies are found from the Arctic Archipelago, north of Canada's mainland, to Iceland; the diffusion of ammonia can extend hundreds of miles from the seabird colonies. Birds help keep the Arctic a little colder, perhaps in their own small way dampening the effects of climate change one splat at a time.

One or two new plant species have been recorded on Surtsey in each year of its existence. The first ones came by sea, some others by air, taking root as the nitrogen built up on the island. But the vast majority, about three-quarters of the seventy or so established plants, came on the wings, guts, feathers, and legs of birds, mostly gulls.

Insects, some arriving on the winds, others on the wings of birds, started settling in. More than three hundred species of beetles and other terrestrial invertebrates have been found on the island,

including a weevil so rare that it was thought to be new to the planet until others were found off the coast of Scotland. The insects are painstakingly collected with tweezers, paintbrushes, or straws or by dragging white sheets over the grasses. At least 143 species are considered permanent settlers. Regardless of their status, each new species is a cause for a celebration.

Over time, the insects attracted insect-eating birds: snow buntings, meadow pipits, and wagtails. A few graylag geese flew in from the Icelandic interior. The gulls were not impressed. They screamed and honked at each other. "It is definitely not a happy marriage between gulls and geese," one ornithologist told me.

Every year, the fabric of the island has gotten thicker, more lustrous, and more diverse. Gray seals showed up in the 1980s. They hauled themselves out along the northern spit of the island, gave birth, and nursed their white-haired pups. The pups pooped. The adults pooped. Add to that the placentas and the occasional carcass, and you've got a marine subsidy, a nutrient supply moving from the ocean to the land. It is smaller than the seabirds'—about twelve pounds of nitrogen per acre—but in a new area with greater access to the sea. For the island's avian scavengers and plants, these nutrients have been a reliable and substantial yearly bonus. Seals like coastal flats, not cliffs, so their breeding opened the lower shores to oysterleaf, sea rocket, and saltbush. They created a seal oasis among the dark gray sands and lava boulders of the north.

Surtsey's seals, like its seabirds, demonstrate how animals can move nutrients onto barren land and, in so doing, create full-fledged ecosystems from scratch. Sable Island, a strip of sand more than a hundred miles off the coast of Nova Scotia, provides another example among many. In the past fifty years, the number of gray seals that pup on the island has grown from a few thousand to more than ninety thousand, making it the largest gray seal breeding colony in the world. The nitrogen the seals bring fertilizes the dune grasses of the island, now home to a population of feral horses—living proof that Erling's herd of dream cows on Surtsey's seabird meadow is possible.

The plume of nitrogen from the seal poop stretches out into the waters beyond Sable Island, increasing the phytoplankton on its leeward side by 20 percent. Though the algae are microscopic, you can see the seals' signature—a bright green splash of chlorophyll—from space, like that of the seabirds on Surtsey.

"Whenever people of my generation have a nightmare, we're dreaming of running away from a volcano, right?" said Freydís Vigfúsdóttir, a seabird biologist who was born on the Westman Islands in the 1980s, well after Surtsey cooled. "I've walked on many lava fields before, but the one on Surtsey is different. I could hear rocks falling underneath me. The sound of waves. Obviously, there were caves beneath us, and I remember thinking, *If I fall, no one's ever going to find me*."

On Surtsey and on other, more accessible parts of Iceland, such as the Snæfellsnes Peninsula, I've occasionally been touched by a sense of awe. The barren landscape—carbon-black and brick-red mountains cloaked in gale-force winds beneath a rising moon—brought to mind the Romantic sense of the sublime. There was beauty in it. But there was terror too.

"If nature decides this is the time," Freydís said when we chatted a few months before I traveled to Surtsey, "then you're toast." She shrugged.

Most Icelanders had no interest in letting nature take its course. "Lava was seen as something very, very ugly," Bjarni told me in Heimaey. "It's really psychological. If the locals could control the lava fields, they would flatten them and put in a lawn." Or at least put in some lupine, a purple flowering plant introduced from Alaska that can supply its own nitrogen via symbionts in its roots.

During their stay on Surtsey, Bjarni and Esther focused on the microscopic and microbial differences in the soil across Surtsey, ranging from the vegetated bird-breeding areas to pure pumice. I followed them to one of their sampling sites. Bjarni unearthed

two-year-old tea bags from the ground. "I ask the microbes, 'Do you want red or green tea?'" The TBI—tea bag index—is used around the world. To keep things consistent, they use only Lipton. "We're all nervous," he told me, "that Lipton will stop making red tea."

Esther took a core sample through a dead bird.

While they were running transects earlier that day, Bjarni had noticed a ringed plover giving him and Esther the eye. When he looked straight at it, the bird flitted away, part running, part flying, staying low to the ground but clearly visible. Plovers had been seen on the island before, but no one had ever found a nest.

"When you see a plover running or flying low to the ground, always go the opposite way to find its nest," Bjarni said. The ringed plover is a humble bird, its nest little more than a scrape in the volcanic sand. Bjarni ignored the bird's attempt to lure him away and found three speckled eggs on top of the lava. A first for the island, and the seventeenth species of breeding bird.

The absence of humans, it turns out, requires careful curation. In 1969, one of Surtsey's researchers found a leggy plant with sawlike leaves that stood out among the sea rockets and grasses. It looked like a new species to the island, so he called in an expert, who turned over the rocks and found some unusually rich soil amid the lava. It was *Solanum lycopersicum*. A tomato plant had rooted in a visitor's night soil. The plant and the poop were bagged up and carted away.

To avoid the same mistake, we drop our drawers at the edge of the waves. With high ceilings—after the fog lifted—a long distance between the walls, and a view of the Westman Islands, chalk white with gannet poop, it's the most magnificent bathroom in all of Iceland. You can even get a flush, but there's a catch. You have to perch on the round lava boulders and time it right, preferably when the tide is low, so all of your poop will be washed out to sea. The ocean can make a ferocious noise, tumbling the boulders before tossing them ashore.

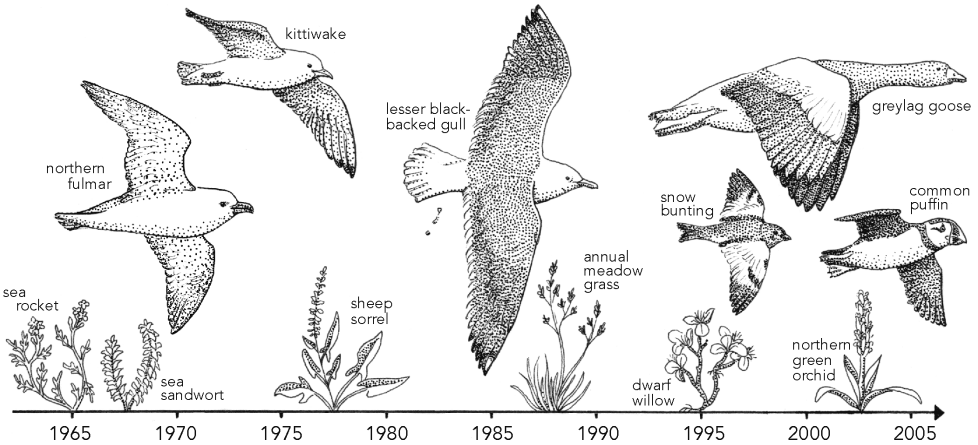
Volcano ecologist Charlie Crisafulli thinks of colonization after eruptions as musical chairs. Luck and timing play a big role in what persists in the volcanoscape on the mainland. If a stand of trees or group of animals escapes the lava, they can disperse their seeds or move out from their refuge when the eruption ends. A grasshopper or beetle on the edge of the eruption can hop, fly, or crawl in.

Surtsey, though, is more like ocean roulette. "It's a very small target in a big frigid sea, and most of the adjacent land is already depauperate," Crisafulli noted. The Icelandic mainland is isolated along the Mid-Atlantic Ridge, with only a few animals and plants. It has no native terrestrial mammals except for the arctic fox (which crossed the sea ice in the Little Ice Age); it has no amphibians, no reptiles, and no mosquitoes. There are only a few animals anywhere near Surtsey, and those that make it to the island find it a hard place to survive. There's no standing fresh water, so for ducks and waders, it is an inhospitable place to breed. Plus, it's cold, windy, and foggy.

We had learned this the hard way on the tarmac in Heimaey. We arrived here in part because of Bjarni's determination and the generosity of Iceland's coast guard. But mostly, it was luck—a small weather window when the helicopter happened to be in the area. The BBC filmmakers tried just as hard to reach the island, but when they showed up in their boat off the northern spit, the wind, waves, and boulders made landing too treacherous. Years earlier, Bjarni noted, a photo from Surtsey had been chosen as one of Iceland's photos of the year: "It was a picture of my PhD student falling out of the boat when we were landing."

The BBC film crew had to turn back, and that could just as easily have been our fate. For all the birds, plants, and insects that reached Surtsey, many others did not; they died, took another turn, or never left the comforts of home. For all of us, it could have gone either way.

Not long after Surtsey emerged, Iceland's botanists, geologists, and ornithologists banded together to keep it pristine, limiting



A Surtsey timeline. The earliest plants to establish themselves on the island were sea-borne species; they packed their nutrients for the journey. After the arrival of the lesser black-backed gull and other seabirds, nitrogen from guano helped catalyze the establishment of meadow grasses. The future might belong to the puffin as the island erodes away. (Based on Magnússon et al., 2009)

annual visitors to a few researchers. Even at full occupancy during the expedition, the island was home to only a handful of scientists. But for more than three hundred and fifty days a year, Surtsey is completely free of humans. The birds, insects, and plants are the true owners of this island. And even the birds abandon the island in the winter. With fewer than six hours of sunlight between November and January, darkness consumes Surtsey. The plants hold down the island in the gloom with no visitors other than the occasional marine mammal swimming by.

There are plenty of rocks in the ocean, but Surtsey is one of the youngest, with the lightest of human footprints. "Surtsey is the only volcanic island that has been studied closely from the very first day," Erling said. In 2008, it was added to the UNESCO World Heritage List because of this protection and the biological studies conducted there.

There have been plenty of eruptions on the mainland, but there are animals and plants around those lava fields or relict communities that survive the blasts to help seed recolonization. "Surtsey taught

us that seabirds could bring nutrients, seeds, and insects in nesting material," Erling said. There are so many invertebrate species on the island that the source can only be nesting birds.

As I sat on the edge of the meadow, I thought of another volcanic island half a world away, described by a different scientist who had first landed there when he was a young man in his twenties. The Galápagos, "a broken field of black basaltic lava, thrown into the most rugged waves," brought Darwin close to "that mystery of mysteries—the first appearance of new beings on this earth." At least a few of the beings he observed probably got their start on islands enriched by seabird dung.

"I'll never forget the feeling when I left Surtsey after the first summer," Erling told me later. He'd returned to Heimaey, with its own history of eruptions and colonization. The grassy hills were unsettling. "I had not seen a green color for three months," he said. Even after Erling returned to Reykjavík, Surtsey was never far away. The brown hills and gray sands became the palette of his life. "It is the home of my heart. As simple as that."

Pálsbær, the research cabin named for Paul Bauer, an American philanthropist, rides the edge of the lava field like a fishing boat on the dark winter sea of the North Atlantic. The researchers gathered around the wooden table at the heart of the cabin in the long dusk that passed for evening on Surtsey in July, bathed in light from two candles. The Westman Islands could be seen out the window. One chalky block, flecked with gannets and covered in guano, was as bright as a lighthouse beacon.

There was a celebratory air. Earlier, Borgthór had been walking along the edge of the breeding colony, and when he came back to Pálsbær, he casually mentioned, "One hour ago, I found a new species on the island." It was a blue sedge growing between the grassland and lava field. *Carex flacca* is common in Iceland, but here it was a big discovery. Likely bird-dispersed, perhaps by geese, it had

probably been on Surtsey for a few years. It was the seventy-ninth plant species found on the island, evidence that its diversity was still growing, thanks to the birds.

Borgthór poured some wine into a brown mug—the honorary Sturla cup—and handed it to me. (Sturla Fridriksson wrote several books about Surtsey, including the one I had used for reference before arriving.) Icelandic lamb was served. The researchers had spent the day counting—plants, birds, a few thin strips of seaweed—and the talk inevitably came around to the culinary properties of seabirds.

Although the population of Iceland is smaller than 400,000, culinary traditions vary across the island. Fulmar chicks are favored by some; young black-backed gulls by others. Gannet chicks are collected on the steep white cliffs we could see out the window. Soup made of puffins, with their heads left on, was a favorite in Heimaey, where locals capture the birds in nets around the nesting areas. In the fjords of the east, shags, also known as cormorants, are roasted, salted, or smoked. "They have delicious brown meat," noted one of the researchers. Perhaps it wasn't the late-night one-upmanship of marine biologist versus fisherman on the *Orca* (Quint's boat in *Jaws*), but there was an air of camaraderie and competition in the unyielding twilight.

The birds could fight back. A great skua, a fine pirate of a bird, once attacked Bjarni's uncle. "He was a big man but nothing against this Messerschmitt. The skua knocked him cold."

Borgthór admired fulmars not for their culinary properties but as survivors. To my untrained eye, they looked like gulls, but they are closely related to giant albatrosses. And they have good genes. "There's a picture of my mentor, George Dunnet," said Borgthór, "tagging a fulmar when he was a young man. Fulmars don't breed until they are ten years old, and then they have one chick per year." He showed me two black-and-white photos. The one on the left, a fulmar and a man with dark hair and smooth skin, was taken in 1951; the one on the right, a fulmar and an older man with a receding hairline and facial grooves, was from 1986.

"It's the same person and the same bird," Borgthór said. The fulmar hadn't aged a day.

On the last day of the expedition, everyone was up by six checking insect traps, finishing soil samples, flying a drone over the northern spit. We all mustered at eight to survey bird nests. Borgthór used a sixty-foot rope to define a thousand-square-meter circle. Holding the rope tight, we walked in a circle around Borgthór, starting at the center of the breeding colony.

"Hreidur!" someone called out, the Icelandic word for "nest." In the first circle, there was only one gull's nest, a ring of dead grass among the densest lyme grass and chickweed. After twenty years of hosting seabirds, the ground was soft and spongy, disguising the gaps in the lava below. It was a bit like walking on a trampoline, with the occasional white feather drifting through the waist-high grass.

We did our best to count the birds and minimize disturbance. I heard a croak beneath my feet—a fulmar ready to projectile-barf a stinking gob of fish guts. I gave it a wide berth. The gulls had retreated, their nests little more than a cowlick: a small bed of straw, a few feathers, perhaps the remnants of an egg. An embedded naturalist, I did my best to hold on to the rope through the meadow. The crooked lava hidden beneath the grass felt like a sea frozen in mid-gale.

"Hreidur!"

We recorded thirty-four nests that day, many of them on the edge of the grassland, helping the habitat expand over time.

The researchers, too, were dispersed by wings, or in this case rotor blades. As we waited for the helicopter, I mentioned I was thinking about booking a hotel room. The photographer leaned in. "I would wait." This was Iceland, and it was too soon to plan. The helicopter was still about twenty minutes away.

We watched it approach over the horizon, touch down on the tiny landing pad, and unload the geologists who would take our place at the hut. We put on our headphones, loaded up our gear, and were off. I had no idea where we were going. Back to Heimaey? To Reykjavík? Iceland's unofficial motto is *Thetta reddast,* pronounced "*Thay*-ta *ray*-dast" and roughly translating to "It'll all work out." As we lifted up over the North Atlantic, I felt like a hitchhiker, little more than a burr in the belly of the whirlybird.

I was on the island for maybe seventy-two hours all told, though it felt sort of endless and unpunctuated, since it never got dark. Surtsey disappeared. One of the coasties passed back a note: *Reykjavík at 18:15*.

When I first spoke to Erling in 2019, he had just celebrated his seventieth birthday; he was a man shaped by the seabirds and seals of the North Atlantic just like Surtsey itself. Seventy is the hard stop between work and retirement in Iceland. But even on his last trip, Erling told me, his sparse gray hair emerging as if from fumaroles in the breeze, "there is always the same excitement. Every time. I just leave the boat or helicopter and the first thing I do is grab a handful of sand and kiss it."

At the end of Erling's last trip, in 2020, Surtsey wasn't ready to let him go. The departure of the research crew was delayed for one day, then several more, because of bad weather. The coast guard helicopter couldn't land on the tiny landing pad, and a boat was out of the question. Supplies were running low, and the next team was overdue. In the end, the coasties dropped down a rope, and Erling and crew were plucked off the island like wildflowers.

When I visited him in his office, in a building on the edge of a parking lot and a lava field, Erling was surrounded by the thousands of beetles, flies, and spiders, pinned and mounted in boxes, that he had collected in Iceland over the decades. He was organizing his

life's work for the next generation of entomologists, and he looked a bit like a man in exile.

He still seemed heavyhearted about leaving Surtsey. "It was like being torn up by my throat," Erling said with tears in his eyes. "Erling was almost born on this island," Borgthór said. "Or at least, he grew up here." Erling told me wistfully that he had considered joining the Surtsey expedition this year but couldn't get through the pain of saying goodbye yet again.

I stopped in the bathroom on the way out. Above the toilet, there was a picture of a cormorant defecating on the shore. It was one of Erling's most prized photos.

Eat, poop, repeat. The guano effect ripples far beyond Surtsey. Seabirds breed in the Arctic, in the Antarctic, and on islands throughout the world. The Southern Ocean is home to the greatest number of seabirds—think penguins, petrels, and albatrosses—and about four-fifths of all the world's seabird poop and the nitrogen and phosphorus it contains. Surtsey's story has played out on islands around the world, in some cases for centuries, even millennia. Guano is a precious natural resource, and its high concentrations in the Southern Hemisphere once prompted a global chase, from Peru to the guano islands of the South Pacific.

In the nineteenth century, sailing vessels from Europe and North America stopped at remote islands around the world. It was a boom time for whale oil and bird poop. The oil was used for light and lubrication in the big cities of the north. The guano supplied nutrient-depleted fields and croplands with nitrogen and phosphorus—it was considered the best fertilizer in the world, as we'll discuss later. Guano extraction imperiled many seabirds by destroying their island burrows and nesting habitats. The harvesters often persecuted native seabird predators, such as Andean condors and peregrine falcons, and their commutes between harbors and

breeding islands also shuttled in invasive predators. Perhaps none has been more damaging than *Rattus rattus,* the ship rat.

"It's chalk and cheese," Nick Graham of Lancaster University said of the difference between a rat island and a rat-free one. He was waiting out the coronavirus pandemic with his three offspring in the United Kingdom when we spoke. Graham has worked on the Chagos Archipelago in the Indian Ocean for more than a decade. The islands he studies are more or less identical except that some have a history of shipwrecks and fleeing rats. For the native wildlife, it was yet another game of ocean roulette, and the arrival of a new predator was like a bullet to the head. On the rat islands, the rodents ate seabird eggs, chicks, and even adult birds on occasion. This had ripple effects throughout the ecosystem.

"When you set foot on an island without rats, the skies are full of seabirds. It's noisy because of the cacophony that those birds are making. And it smells of guano and ammonia, particularly if it has recently rained. It's a really rich, pungent, loud environment.

"But when you set foot on an island with rats present," Graham said, "there's next to no seabirds. The skies are empty." There is no smell, and the only sound comes from the small waves lapping on the beach.

Graham wondered how these differences might affect the islands' reefs and vegetation, so he took a risk and spent the last of the grant money he had from the Australian Research Council. On six islands with rats and six without, he and his colleagues collected soil samples and new leaf growth from a coastal shrub, then they snorkeled out to the reef flats and gathered macroalgae and solitary sponges. From the start, the difference in the number of seabirds was obvious: there were seven hundred fifty times more seabirds on islands without rats than on those with them. More birds meant more poop. The deposition of nitrogen was two hundred fifty times higher on the islands with birds, an enormous resource for the native plants and animals.

They dived off the reef crest, where the corals drop down to deeper water, and counted fish and collected turf algae and jewel damselfish, which feed on seaweed. Damselfish grow at a faster rate on the reefs of islands without rats. Known as the gardeners of the reef, they defend their algal farms, protecting the small shrimp and the nutrients that their poops provide for the algae. Fish biomass is 50 percent higher on the reefs with seabirds than on those without, which was surprising, considering the reefs were unfished and already in good shape. Graham and his colleagues are now interested in the impact of seabirds on fish fecundity. With more nutrients, the fish could have more offspring dispersing out to nearby islands, expanding the footprint, the poop-print, of the birds.

But can't too many nutrients be bad for corals? We've seen declines around cities without good sewage treatment. "People often think of nutrients as being bad news for coral reefs," Graham noted. That's because a lot of human inputs are from fertilizers and sewage, which are phosphorus-limited and have lots of nitrogen. If the corals are impaired by this excess nitrogen, they will bleach at a lower temperature, kicking out their essential symbionts. "But if you increase nutrients with a balanced input of nitrogen and phosphorus, which is what the seabird guano provides, corals grow faster," he said. Corals will stay healthy at higher temperatures, retaining their symbionts, and be more thermally resilient in the face of climate change.

It's no surprise that the birds and their poop, eggs, and carcasses enhance the growth of plants—Surtsey and other studies showed that years ago—but marine fishes respond to this subsidy too.

After the bird survey, Borgthór and I sat on the edge of Surtsey's vertiginous southern cliff. We could hear the island falling apart below. I had assumed that the round lava boulders I stumbled over while walking along the shore were a couple of decades old, but Borgthór said that many had likely fallen into the water mere months ago and were tumbled and rounded by the surf.

I spent a long time staring into the white splats on the dark lava during that endless summer afternoon. When I looked up, the seabirds returning to the cliffs stitched the sky like a dark seam on a baseball. After feeding offshore on capelin, sand lance, and krill, they carried some back in their bills or gullets for their chicks. A fulmar, likely with a taste for fishing-boat discards, breezed by overhead. A puffin circled the cliff edge. Black guillemots returned from the sea, wings flapping quickly before they swooped into their nests, the white stripes of feces their landing strips. Calling overhead, the black-backed gulls made their way to the meadow they had formed. Though they're just gulls elsewhere, perhaps fighting over a piece of pizza, they will always be glorious birds on Surtsey.

There was a tug-of-war between the physical forces that had built this island, and were now inexorably eroding it away, and the biological ones, the nutrients and the accreting biomass in the foothills of the barren palagonite. Many of Surtsey's seabirds are older than the boulders, and some of the fulmars might even be older than the island itself. Here was a rare opportunity to observe how animals could build an ecosystem almost from scratch. You could see the process unfolding during a short afternoon hike, or, if you were a biologist, you could follow it over the course of a career. Any scientist will tell you that research projects often have high turnover, with young people coming and going as they move into academic, government, and nonprofit careers, but the team studying Surtsey has had excellent retention. Many scientists, like Borgthór and Erling, have made annual visits over the course of their careers. This would be Borgthór's last expedition. He was retiring later that year.

Nothing lasts forever. Several of the smaller islands to the east emerged about five thousand years ago. They've been reduced by erosion to basaltic shards, steep cliffs with gannet nests and species-poor grasslands. They portend Surtsey's future. And Surtsey shows us what the old seabird outcrops looked like in their youth: supple, constantly changing.

At about three hundred acres, Surtsey has already shrunk by about half in the five decades since it was formed. Its profile is a little more chiseled, with steeper cliffs and the northern spit now sticking out like an elf's hat.

"In the future," Borgthór told me, "this will be the land of the puffin." The adorable bright-beaked seabirds will burrow beneath the thick grasses, as they do on neighboring, steep-cliffed islands. (More than half the world's Atlantic puffins live in Iceland.) The fragile lava will slough into the sea, leaving behind a hard inner core of palagonite, the basaltic glass that formed when the lava, still hot, flowed into seawater. "Eventually, maybe in ten or fifteen thousand years," he said, "Surtsey will probably be gone."

He let that sink in.

"But then we will have another eruption and a new Surtsey."