and when were these maps created? Most of the topo maps we use around here were published by the USGS in the early 1960s. How did they know where every hill, valley, creek, forest, and field was? Because people systematically walked the landscape, carrying surveyor rods, compasses, pen, and paper. An enormous undertaking. Wherever I go on the map, at least one person—a tired government employee carrying a tall pole with measuring marks atop it for his partner to read from a distant vantage point—has stood here before. Since 1884, the USGS has been sending dedicated crews out onto the landscape. Actually, back in 1777, before the United States was even formed, General George Washington appointed a geographer to the task of making maps. They now cover more than three million square miles. When I speak of topo maps, I'm smelling the dry, papery, slightly musty smell of the closet where my dad kept them rolled up in a poster tube when I was a kid. My eyes widen with thrill when he opens the closet, the light flicks on, and the brown tube adorned with funny old stamps descends from the top shelf. Out of the tube comes a long, slightly yellowed, cylinder of paper. Unrolling them on the floor, he traces his finger along the ups and downs of hills around our house. Although modern technology is rapidly replacing such paper copies, many GPS devices still rely on the 1960s topo maps, and these maps were created through a long and hard-fought field collection effort. On the flip side, those data are now over fifty years old, and things change—so you should always take every map you use with a grain of salt.

FOREST CONTRASTS

The central question at this site is: Why are the trees so different in the two places?

In a broad sense the trees aren't so different. The forests here, like at Bark Hollow and at Maggie's Forest (prior to cutting), feel generally like home to me. I'm a creature of the temperate deciduous forest biome, a creature that rests under the safe, dim blanket of maples, oaks, pines, and beeches—despite the mosquitos.

The uphill site could be almost anywhere within the eastern forest of the United States. Sugar maple and beech are two species typical of the northern hardwood forest type, which dominates New England landscapes a bit north of here before the transition to boreal forests of the far north. Northern red oak, on the other hand, is more typical of the oak-hickory forests to the south. At first I tell myself that the overlap of these three species here pinpoints our location to southern New England, in the transition zone between these forest types. But then again, in the hills behind my childhood house in Tennessee, there are places with those same three species that look almost identical. Except for the rocks, I suppose.

The downhill site, however, has more unique character. Swamp white oak, pin oak, black tupelo (aka black gum), royal fern. These species bring me to very precise locations: tupelos guarding a pond filled with Jefferson salamanders in the middle of a hemlock forest; pin oaks scattered in a dried-up vernal pool in a red maple forest on the edge of a cornfield; a grand swamp white oak in a muddy wetland surrounded by an upland of red oaks; royal fern gracing the edges of a stream cutting through a larger forested wetland, which in turn is encircled by a northern hardwood forest. In all the miles of forest I hiked through on my way to the hundreds of vernal pools in my surveys, I don't think I passed a single swamp white oak, pin oak, tupelo, or royal fern, except at intervening wetlands I accidentally encountered. All are wetland species. Because this wetland is dominated by woody plants—trees and shrubs—it's not a marsh. This is a swamp, with indicator species that relay a strongly coherent message. In fact, this place is called the "Great Swamp."

If you're from Pennsylvania, Tennessee, or anywhere in between, perhaps you'd complain about my list of wetland trees; you might think one of those trees doesn't belong. Black tupelo. Down south I find tupelo abundant on hilltop forests right next to chestnut oak, in dry, nutrient-poor soils. In New England I've never seen tupelo except in a wetland. Certainly not next to a chestnut oak. These seem like pretty opposite habitat types. What's going on? I honestly don't know.

It's useful to remember that species behave differently in different regions. Maybe in warmer climates black tupelos like dry sites, whereas in cooler climates, they like it wet. In Massachusetts I grow my beard out, in Tennessee I shave it off, in Arizona I sport a Fu Manchu. Although, I wouldn't be surprised if it turned out these upland and lowland black tupelos were secretly different species—for decades scientists have been debating how to lump or split the various tupelo species based on morphology, habitat, and genetics. All I can say is that here, this tupelo advertises a swamp.

You might also be familiar with pin oak as a planted tree on college campuses and other landscaped areas—areas that aren't wetlands. In some cases the land might have actually been a wetland before it was converted to a college, and the tree is just hanging on. But usually the pin oak was just planted there because people like them.

The hardest time for a tree is when it's very young. From the time the seed sprouts through its sapling years, a forest tree faces horrendous challenges—find water, find light, compete with neighbors, ward off herbivores—with almost no stored reserves to draw on. Adult oaks may be mighty, but even a dainty little fern on the forest floor can doom the helpless oak seedling growing beneath it. Often it's the species' unique strategies during that critical youthful stage that determine what habitats it will survive in.

Once it's high in the canopy, the tree has stores of energy in its trunk and roots, it has plenty of access to sunlight, is beyond the reach of many herbivores, and is now the one that casts shade on the struggling saplings below. When a gardener has tenderly nursed the tree through its sapling years, she can then plant it out in an open lawn and the old tree can be found thriving far from its natural habitat. But when found in a natural forest, the pin oak, like the tupelo and swamp white oak, tells us there's a swamp here.

But why is the Great Swamp here? The answer has already been—obliquely—laid out in the previous chapters. So while you ponder that, let's dwell on the question itself.

It's a question that doesn't get asked enough: Why is it here? People get hung up on the "what" and forget about the "where." In this modern world our spatial senses have atrophied. But context matters. Why is it *here*? As the animal tracker Sue Morse would say, "Half of tracking is knowing where to look; the other half is looking there." Knowing what something looks like doesn't figure into this maxim. Location is everything. Why is it *here*? "It" could be anything. A tree, a rock, a nest, a poop.

A POOP

Down in Tennessee for Thanksgiving, Sydne, Alder, Juno, and I met up with my friend John Norris to explore his land. Walking along a system of trails wide enough for his pickup truck, he guided us through a brushy field burned last spring to create bobwhite quail habitat. We turned left at a line of trees and descended through rows of overripe soybeans to the edge of a creek lined with raccoon tracks, then doubled back and made our way toward a forest above the burned field.

As we walked, John taught us about quail management, agriculture, and the local ecosystem. At several points along the walk, he ducked off the trail to check on his various wildlife cameras. Bobcats, deer, opossums, and squirrels flashed across the digital screens. John knows his land well; he knows his species well; he is a great naturalist. We approached an intersection where one trail led up into the forest, with John a few steps ahead. Before he turned to check on the last camera, John pointed down and, aware of my affinity for scats and eager to improve his own knowledge, turned to me and asked, “Raccoon?”

As I searched for the right words to respond, he told us he had seen the scat days before and looked it up. Sifting through Google images of poop with various tones, twists, and dimensions, he narrowed in on raccoon. The blunt ends, dark color, everything seemed to fit. But before I looked down, I knew it wasn’t a raccoon. Before I had even caught up to the place where John was standing, I had a species in mind.

John’s mistake was that he looked at the scat. If you want to identify a scat, don’t start by looking at it. The first question is not, “What does it look like?” Ask, “Why *here*?” Here we are, at a trail intersection with a field full of quail on one side and a forest on the other. Raccoon scat *here*? Impossible. To be sure, the raccoon who pressed her hands into the creekside mud has almost certainly been near this spot. And yes, she would have been physically capable of relieving herself here. But why would a raccoon poop here? This just isn’t the proper place for a dignified raccoon to poop. She would no sooner poop in this intersection than you or I would. No, that raccoon placed her scat in her usual latrine at the base of a tree, on the uphill side, near the creek.

Animals mark their territories in characteristic ways, with deliberate intention. Gray squirrels bite roughly furrowed bark of prominent trees on the downward-leaning side, creating a multishaded stripe that can stretch twenty feet or more up from the ground. Red squirrels, on the other hand, bite smaller round patches at the base of conifers and along branches higher in the tree. Groundhogs bite the base of woody plants near their den entrance. Deer thrash their antlers against small hemlock saplings, moose against larger saplings. Bobcats pee on the vertical surface of one-foot-high decaying stumps when available, or if a lone pine tree stands out in a thicket, the cat may be attracted to the soft needles under the pine, scrape up a pile, and scent the top of it. Otters choose the needles under a prominent pine on a jut of land sticking into a lake. Dominant predators generally like to poop in prominence, each species with its own specific tastes: on rocks or stumps, near important food sources, near someone else's mark, or in the center of trails—especially where two trails intersect. When each citizen places her note where it belongs, we all know where to look for which messages.

In our annual winter tracking course, Charley and I lead students crawling through a blueberry swamp full of snowshoe hares to our lunch spot: a corner of land that the swamp wraps around. On a map, it's a prominent location. We sit in a circle, one student leaned against a paper birch, one against an old, mangled hemlock sapling, one near the stump of a broken tree. The students don't know it, but Charley and I are playing a game. It's the game we've played for eleven winters now. Who will be the first student to notice the antler rub on the hemlock, the bobcat pee on the stump, or the bear claw marks on the birch?

As for the poop on John's land: the size of the trail, the intersection, the proximity to prey, the placement near the middle of the trail all screamed coyote. Just to be sure, John and I poked at the scat and found apple peels, still with a tinge of red. Definitely coyote.

BEARS

Up on the hill above the Great Swamp, the beech trees display prominent scratches from bear claws. Though less eye-catching, some of the tupelos down in the swamp also exhibit bear scratches. Why?

Claw marks of black bears come in two flavors. One flavor signifies intentional marking behavior. A big white birch on a travel route—a perfect place for reaching up and swiping to paint a sign that is both visually attractive and filled with the poignant fragrance of bear foot glands. Or perhaps a big oak—the biggest tree in the forest—a bulletin board with decades' worth of bear notes tacked to its face. Maybe a red pine along a road, dripping with sap. Or, equally good, a telephone pole dripping with creosote. Or maybe a tupelo on a hill in the middle of the bears' favorite dining swamp that she wants to claim for herself and her cubs. Next to such claw marks, the bark scowls with furrowed growth around bite marks. After she clawed and bit the tree, she turned and rubbed her back on the bark, imparting the fullest of her scent. A few wiry black hairs, pinched in the crevices, waver when you breathe on them. Spin around on your heels and look behind you to find small trees bitten and mangled. We can't decode it, but these marks are packed with information.

The second flavor of bear scratching is incidental: a mere by-product of climbing. Why climb? Various reasons. A bear climbs to escape from danger. A mama bear drops off her cubs in a big white pine, what Sue Morse calls a "babysitter tree," while she wanders into the adjacent wetland to eat emerging skunk cabbage leaves and other spring greens. In another treetop a lazy bear lounges in the crook of a branch. Although bears occasionally sleep in crude nests atop a tree, it's not typically rest but food that the bears are after. Usually, the bear biologists will say, "bear nests" that we see in trees are the unintentional remnants of feeding—branches snap as the bear bends them inward to reach the nuts at the tips, then the bear absentmindedly discards the branches in a pile. When trees hold aloft nutritious treats like tupelo fruits, cherries, apples, acorns, ash seeds, or beechnuts, bears climb to dine.

Here is a forest of beechnuts next to a forest of tupelo berries. Both fruits ripen in time for a bear to enjoy a satisfying supper in early autumn. Come spring, swamp margins fill with tender skunk cabbage leaves, quivering as the bear tears through the unfurling patches, devours this first post-hibernation salad feast and excretes cylinders made entirely of processed skunk cabbage. It's now clear why there are lots of bears here. In fact, it'd be a surprise if there weren't signs of bear here. Somewhere around there will certainly be intentionally marked trees, individual and prominent. But the claws climbing up to the top of every one of the beeches? Feeding sign.

The beech nuts are a special treat. Bears love 'em, along with turkeys, deer, blue jays, myself, and many other animals. But beech nuts are disappearing. Why? Just look at that beech tree standing in our chapter-opening image. The left side shows the classic smooth bark of beech. It's that slate-like surface into which vandal children scratch hearts around initials to memorialize relationships the trees will certainly outlive. Unless beech bark disease takes over. The right side of our beech is lumpy and mangled. Beech scale, a little insect native to the Black Sea, was accidentally brought to eastern Canada around 1890 and has since been spreading south and west across the United States. Lacking in wings and males, the female scales clone themselves and depend on the wind to randomly blow them to other beech trees to feed on. On a tree, a scale pierces the smooth beech bark and sucks out the juices below.

But it's not the scale that the tree is most worried about. It's the fungus that blows into the little holes left by the scale. Once under the bark, the fungus spreads. The bark bubbles and cracks. Nutrient flows are cut off. The wood weakens. Other insects, followed by woodpeckers and more fungi, invade. Soon the tree is so weak that, in a gust of wind a healthy beech wouldn't blink an eye at, the diseased beech snaps in half. Even if the beech doesn't die, it hasn't the strength to produce the volume of tasty beech nuts the animals once enjoyed.

HISTORY

Beyond just beech bark disease, this forest is far from pristine. The red oaks atop the hill stand above an understory in which red

Figure 4.3. Basal scars along old logging road at this chapter's uphill site.

oaks are absent. Soon the canopy will be beech, assuming they survive the bark disease. This is a forest in transition, still rebounding from past cutting. When I look north, each tree along a particular line of sight has a big scar near the base. Missing bark exposes inner wood like bones glaring through stripped skin. Each scar faces to the left. Where those scars are aimed, about eight feet out, there's another imaginary line along which all the trees have matching scars looking right back at the first set of scars. In between these two lines must have been an old logging road (fig. 4.3).

After being cut, felled trees were hauled along this road, perhaps first by horses and then later by a diesel skidder driven by someone like our eighty-year-old neighbor, who I still see wielding her chainsaw and driving heavy machinery through her woods. The logs were dragged down the road, bouncing and rolling left and right. The standing trees, watching from the side of the road, winced each time one of their fallen comrades banged into them, chipping another piece of bark off of the ever-widening scars. The logs, carrying tons of carbon in their wood, left the forest and passed into the adjacent field through the gate of the stone wall, bouncing one last time on the rocks of the threshold.

Those rocks. Not just in the wall but all over the uphill site. There's the big gray rock with the ants under it. The little round white rock. The dark rock that the oak leaf is on. The rock with chunks of bronze-colored minerals that the beech leaf is on. The lichen-splotched rock that the maple leaf is on. Put a shovel in the ground here, and you're bound to strike the rounded edge of a rock. As a settlement-era crop farmer, you'll need to haul these rocks off to the edge of your field, piling both big and small into a stone wall. As seasons pass and the ground goes through cycles of freezing and thawing, expanding ice below will drive new rocks up through the dirt onto the surface of your field. Removing the new frost-heaved rocks grown amid your crop will be an ongoing struggle. Maybe it's better just to graze cows and sheep here. You only need to use the choicest big rocks to build the wall that pens your animals, perhaps topped with chestnut posts supporting barbed wire.

Whether cropland or grazing pastures, historic farmland across the Northeast is delineated by stone walls (fig. 4.4). Every wall holds a mixture of types of rocks—combinations of schist, gneiss, granite, marble, conglomerate, and others. These aren't local rocks—they didn't come from the bedrock below. Instead, these stones are fragments of mountains and hills north of here. They were scooped up by the glaciers, carried along for centuries as the giant ice tumbler smoothed their sharp edges, and then abandoned when, in the warming climate, the ice turned to water and crept away. When the mile-thick sheet of ice let go of the rocks suspended in it, they fell to the ground. The rocks in these stone walls are from the layer of glacial till—the footprint of the glaciers—that now coats the whole glaciated landscape of the northern United States. In this area our till is typically about five feet thick, but it varies locally, with extremes of 200 feet thick.

Figure 4.4. A typical New England stone wall.

We expect to see glacial till everywhere in the Northeast, so exceptions are interesting. That's why Bark Hollow, with its bedrock peering through, was exciting. That's why the lake delta at Maggie's Forest, devoid of rocks, was exciting. And that's why this swamp is exciting. Nowhere do we see rocks. No stone walls, no stones on the ground, no stones below. Just clay, as deep as the students can dig. Why is there clay here? The same reason there's sand at Maggie's Forest—this is the other half of that story.

Where are we? The map puts the Great Swamp elevation at 200 feet above sea level—100 feet lower than Maggie's Forest. Our elevation is near the bottom of the rift valley—at the bottom of the glacial lake. The bowling balls fell out up in the delta, but the sheets of paper drifted on out to the middle of the lake. Here, they settled to the bottom, forming layer after layer of clay.

And the uphill site? I like to imagine it as a little island in the glacial lake, poking up above the waterline. Alas, the top of the hill is still below the top of the lake delta, and thus below the lake surface. It would have been more like an underwater hill onto which clay did not settle. At least my intuition says that clay wouldn't settle on such an underwater hill, and the geologists I spoke with this year all seemed to buy my theory for this site. But these were vague sentiments, not the sort of authoritative basis on which to found a chapter in my book. So it was time for an experiment.

Down in our basement this winter, the kids and I suspended clay in water. As we mixed, water particles interjected themselves in between the sheets of clay particles. The slurry grew thicker, and after about ten minutes dark slime oozed between our fingers as we closed our fists. Then, when the clay was fully suspended in water, we poured it into a large clear tub, half-full of water. In this large tub we had prepared a whole underwater landscape of various-shaped rocks, rock towers, and rock shelves. Nearby, a small fan simulated gentle winds on the surface of our miniature glacial lake.

As we poured in the clay mixture, our whole lake grew cloudy. But the cloudiness began to settle out as a dense layer of fog near the bottom. A heavy fog that sank down slopes, spilled over edges, and snuck around corners seeking out the lowest point. Before it settled out on the bottom, the bulk of the clay flowed downhill in this form.

After weeks in our basement, when the last of the clays had finally left the water column, the deposit of clay formed a horizontal surface at the bottom of our lake. Any underwater rock higher than this clay floor stood out as an island, with only a minimal dusting of clay on its surface. We experimented by alternating daily additions of red and gray ceramic clay to see layered deposits, and with clay formed from dry cat litter in another lake. When we finally drained the lakes, I left our basement convinced.

The hill in this chapter is the little underwater island I drew in the last chapter, figure 3.10a. Perhaps when the lake drained, for a short moment this hill lived as a true dry island. Today, with no clay mask, the hill retains the characteristic trait of almost everywhere else in the North: a surface covered with glacial till.

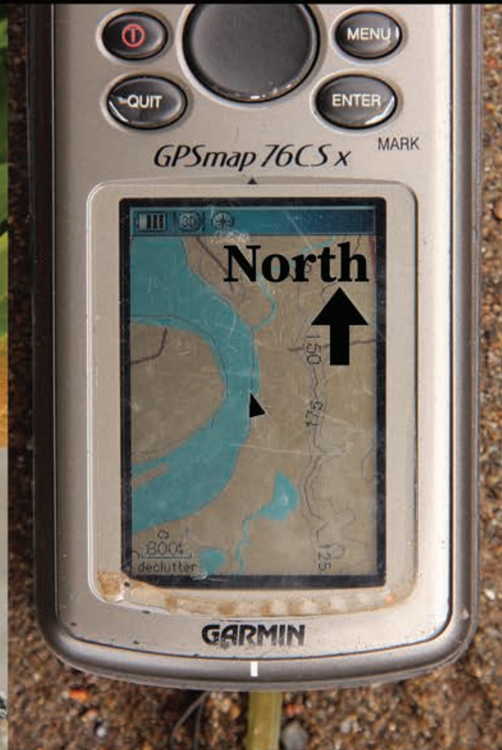
In the swamp below, clay hides the till. This is the clay that the *Field Naturalist* students were eagerly digging through. Under the pin oaks, swamp white oaks, and tupelos, a giant dish, crafted by a glacial potter, holds a swamp-sized serving of water. It is filled and refilled by rain above. The tightly packed particles in the dish's clay prevents the water from leaking out. Without the clays the water might just percolate down into the earth, leaving the surface dry like at Maggie's Forest. Wetlands form in different ways, often connected to the water table belowground. But this wetland is "perched" above the water table—it doesn't depend on flow from nearby groundwater, it just sits like a birdbath above the fray.

For 10,000 years this swamp held water. Then in the late 1700s people went to work trying to drain the swamp. Back before we knew that draining a swamp was a bad idea, they cut channels—like the straight-walled creek we crossed on our way in—to let the water flow out. Before the public understood that wetlands prevent flood damage and filter pollutants, the governor established a board of commissioners to construct a "great drain," levying taxes to support this work. Before our society valued the myriad species that specialize in wetland ecosystems, landowners went to work cutting down the trees, hoping to convert the swamp to viable farmland. In this way half of the world's wetlands have been lost. But here, this clay was too deep and the swamp too determined. Here, the swamp persisted.

MAJOR LESSONS FOR INTERPRETING A LANDSCAPE

- What is the spatial context of your site? Think both at a large scale (e.g., in relation to other sites) and at a smaller scale (e.g., from the perspective of a mammal looking to mark territory).
- Consider the origin of rocks and soils at the site.
- Consider subsurface hydrology.

West ← 460 ft 310 ft 280 ft



235 ft

0 ft → East

(overleaf)

Figure 5.1. If you're not confused, you haven't looked hard enough.

5. Change

We drop the canoe in the water. Juno steps in, followed by naturalist Julia Blyth, and then me. We float. Under the water, long arms of pondweed, waving in the current, brush the bottom of the boat as we drift downstream. A flotilla of ducks lean their heads forward as they strain to paddle away from us. A dead fish rocks belly-up. A great blue heron glides overhead and drops down toward the shore. The heron extends its legs to the ground and pulls its head up as its huge wings ease the landing with a few final flaps. As we go south, the sun is climbing on our left. In my head is a quote, of unknown origin, which my friend Megan always had pinned to her email signature: "If you want to ease your mind, take it down by the river."

Both Maggie's Forest and the Great Swamp were created by a glacial lake. We are now paddling on that lake—or what's left of it. When the dam burst, the lake shrank and shrank until it was just a sinuous line snaking down the old lake bottom. This river, the Connecticut River, is the remnant of the lake, and we can trace the thread of water, continuously flowing, all the way back 15,000 years (fig. 5.2).

On our right we pass a steep bank full of holes. The bigger holes, the size of softballs, must be the entrances to kingfisher nests. The smaller holes must be made by bank swallows. We hug

Figure 5.2. *Field Naturalist* students paddling on the river.

the shoreline as we drift downstream looking for animal tracks in the wet soil. At the base of the cliff, drag marks in the sand tell of beavers leaving the river, searching for food, and carrying it back into the water to eat. At the top of the cliff, the ends of corn rows peer over the edge, tempting hungry beavers (fig. 5.3). A few weeks ago I fought my way through that corn seeking today's destination, only to find myself lost in a huge, flat cornfield, exposed to a lightning storm, a half mile from the river, and a half mile from my car. I decided a canoe trip would be easier.

As we float downstream, the corn on top of the cliff gives way to big trees. Deadwood strewn about the base of the cliff forces us to steer the boat further from shore. Long, straight trunks as wide as our canoe angle gently down, their tops disappearing under the dark water. Sun-bleached limbs bigger than me pierce up through the surface. Some trunks bend out of the water only to reenter six feet on, like the body of a mythical sea serpent. The most recent victim—a great cottonwood lying by the shore with its head sub-

Figure 5.3. A view of the riverbank showing the cornfield, signs of beavers feeding, and bank nests of kingfishers.

merged—still clings to its furrowed bark. At its base, the trunk expands into an eight-foot-wide root ball, washed clean of dirt, like the frayed end of a giant rope.

Amid these fallen trees, a ten-foot-long mound of smaller sticks marks a beaver's home. A lodge. Beavers are famous for their dams, but on big rivers and lakes, there is no need to build a dam. Dams are for small streams where the water isn't deep enough. Here, the water is plenty deep. They need only build the lodge. In this case, it's a bank lodge—a hole dug into the dirt near the shore and covered with sticks. I can't look at a beaver lodge without seeing that one near the barfed-up voles.

A BEAVER LODGE

Fifteen years ago, in a winter animal tracking course, the instructor led Charley and me through oak forests down to an old beaver meadow. Once, the whole meadow was standing water, an area flooded when the beaver placed a dam across the stream below. But sometime in the year before we arrived, people took chainsaws to the dam and breached it, draining the pond. When we got there it was a big open field in which coyotes would hunt for small mammals. That day, the tracks in the snow showed that the coyotes were catching voles, much as I've seen coyotes doing on the grassy edges of roads and highways. We followed the coyotes to a major intersection marked with many variously aged scats. Assuming that the coyotes would mark the area appropriately, we looked for fresh scat. What we found were the barfed-up remains of many voles. The volume of voles spoke to how quickly the little rodents multiplied and took over the meadow that, not too many months prior, had been a pond. As to why they were barfed up, we still have no good explanation. Barfed-up shrews might make some sense. Shrews seem to taste horrible to mammals—perhaps it's the venom in their saliva, or just their stinky body odor—and so predators often grab them hoping for lunch but promptly spit them out before swallowing them.

Pondering the voles, we wandered into the center of the beaver meadow and found the beaver lodge. Unlike a bank lodge, beaver lodges that are constructed in the middle of a pond are a work of pure sticks—no shoreline is involved. But like a bank lodge, the entrance is underwater. That's why beavers like deep water—so that the door to their home is hidden from marauders. The lodge is tall enough so that, although the entrance is underwater, the rooms inside are high and dry. Now with that pond drained, the entire lodge was dry. The foot-high door stood out in the open, beckoning all to enter. Among the fifteen students and one teacher, only I was skinny enough and foolish enough to succumb. I dropped to my knees and cautiously poked my head in.

Built by first piling up a heap of sticks and then chewing a hole through it, the outside of a beaver lodge is a disorganized jumble of lines, like a two-year-old's scribbles on paper. The pointy sticks, many sharpened by the two-inch-long incisors of the giant aquatic rodent, angle menacingly outward in all directions. As I entered the lodge, I braced myself to be speared a thousand times over. I wormed my way up through the hallway, just big enough to squeeze through if I stretched my arms in front of me. In the darkness, my hands found an opening to the right near the end of the hall. I turned, following my hands further upward into a wider space. In the round room, I could now spin in tight circles, sit, and admire the walls.

Nothing poked me. Not a single stick protruded to snag my clothes. All the walls were perfectly smooth. Cooped up in that room for hours each day, the beaver family sat, discussing the thickening ice on the pond, news of the otter, whether their diminishing store of branches they planted in the muck at the bottom of the pond would last the winter, the ring of distasteful white pines that increasingly encircled their pond as they cut down the choicest hardwood trees, their hopes for expanding the system of terraced ponds further upstream with new dams next year, their dreams of the pond far downstream where the elder beavers had been born, and the legends of the Great River even farther downstream. All the while, the beavers idly chewed any errant bumps on the walls, wearing them meticulously smooth. I have toured great temples, churches, castles, caves, cliff dwellings, pioneer homesteads, and transcendentalist cabins. But none brought me the exhilaration of entering the house of a beaver.

THE BEACH

The steep cliff alongside the canoe fades, gently lowering and receding. The high vertical wall transitions to a low ramp, then into a long, flat expanse almost level with the water surface. The

Figure 5.4. A broad view of the river with the black triangle indicating the location of this chapter's site. (MassGIS, Sanborn LLC)

trees that once loomed over the water's edge are now 200 feet away, on the other side of an open sandy beach. We have arrived. This is Rainbow Beach (fig. 5.4).

We steer toward the beach, lurch to a stop, and step into the shallows to drag the canoe, sand grinding against hard plastic, clear of the water. Juno follows and we prepare to eat lunch and explore.

With the topographic map layer loaded into the GPS, I set it down in the sand by the water's edge and take a picture of the screen where a little black triangle shows our location (see fig. 5.1). Happy with our place on the map, I stand and look around. To the east, on the far side of the river, is a steep, muddy bank. To the west, on the far side of the beach, is the edge of the forest. I drop one end of a measuring tape and walk west. Doing my best to maintain a constant bearing, walking past a few scattered cottonwood saplings in the sand, I measure the distance from the water to the forest edge: 210 feet. At the edge, scattered sandbar willows transition into taller grasses and cocklebur and then into overhanging saplings of black willow and silver maple. Julia and Juno join me in the forest, and we decide that Juno will be a good scale bar for the pictures.

At 235 feet from the river, Juno stands in a dense thicket of short silver maple saplings, most no thicker than his wrist. At 280 feet, Juno stands between a young boxelder and a young silver maple, each about as wide as his two legs together. We walk past some small elms, and then, at 310 feet, Juno feels the furrowed bark of a respectable cottonwood, definitely wider than his body. To avoid stings, we have to carry Juno over the tall wood nettles to 460 feet, where, after I remind him of the protein-rich nettle tea we once made, Juno relaxes against a massive cottonwood, wider than the three of us combined. He looks out at some massive silver maples beyond while I crouch under a boxelder. Why do the trees get bigger the farther you go from the water?

While we are measuring, my batteries run low and I dash back toward the canoe for more. I reach the forest edge and begin racing across the sand. But then I stop. A little dark blur flits by and rests on the sand near me. My heart races. This is atop my list of species to photograph. I approach, and it flits away again to another spot. I fall to the ground and slowly creep up on it, trying to keep my shadow small and my camera out of the sand. Eventually, I get close enough to get a couple pictures. Grinning confidently, I stand up, the creature flees, and after grabbing fresh batteries, I hurry back into the woods.

HATCHERY

It isn't until a week later that, seeing little dark gaps in the meandering white paths along the edges of the tiger beetle's wing covers, I realize the creature I was chasing wasn't the right species. According to the field guides, in my picture sits a bronzed tiger beetle.

It isn't until mid-winter that I finally see the federally endangered species I'm after. But she's dead—she died one day ago, housed in a little plastic shoebox in a government facility. Yesterday, as Rodger Gwiazdowski put it, she was "the only adult Puritan tiger beetle on Earth." Now there are none—which is as it should be. Puritan tiger beetles don't overwinter as adults—only as larvae. As adults, the lucky ones only live two months. But in Rodger's cozy laboratory, adult beetles can hang on till the ripe old age of five months.

When Juno, Alder, Sydne, and I shuffle into Rodger's laboratory mid-morning on a Sunday, it's 18°F outside. We're across the street from a big quarry that digs sand from one of the deltas on the old glacial lake. Opening a metal door, we walk into a cavernous warehouse—warm, dingy, and mostly deserted. Around the room, gray waist-high concrete walls delineate large oval holding tanks for aquatic research. One of these tanks has been converted into a brightly lit laboratory, surrounded by white walls and big glass windows. Inside this shining bubble sits Rodger and his little beetles. As we arrive, I joke to Rodger that this building must be where they put the species they've given up on.

The last time I was in this building dozens of Atlantic salmon swam through these tanks. For forty-five years the US Fish and Wildlife Service poured millions of dollars into trying to restore the Connecticut River's salmon populations. Tens of thousands of salmon once journeyed the length of the Connecticut River every year—swimming from small headwater streams and beaver ponds where they grew up, down through the mouth of the river, out past

Long Island up into the Labrador Sea of the North Atlantic, down along the Newfoundland coast, and all the way back again to breed and die in the headwaters.

But then people dammed up the rivers, polluted the water, and started warming the climate. Salmon disappeared from the rivers, along with shad and many of our other fish. In the late twentieth century, we began cleaning things up. We stopped polluting the water. We built special devices—stairways and elevators—to help migratory fish get up over the dams. We started breeding salmon in laboratories and releasing hundreds of thousands of them each year, hoping to restore the populations.

Last year, I took Juno and Alder to visit the fish elevator on one of the major dams in the river. A dam past which the millions of salmon reared in the laboratory and released into the river would have swum on their way to the sea. A dam past which they would have to swim on their return. We entered the concrete-walled hydropower plant next to the towering dam and wound our way through giant gears and turbines up an open metal grate staircase. The space was filled with humming and roaring. Water rushing below the building spun the gears. At the top of the staircase, light poured in through open doors that led out to a viewing deck. The deck was wet from the constant spray of water spilling over the dam and crashing below. Looking down, we saw a few shad desperately trying to swim up the face of the dam and inevitably failing despite an impressive effort.

Suddenly, the enormous mechanical elevator began to move. Chains thicker than my arms hoisted thousands of gallons of water up to where we stood, thirty feet above the river. The giant cube of water was almost within reach when the back of it opened and dumped the payload, wriggling with fish, into a hidden chute in back. We hurried around to the other side to see the fish. In a dark hallway, big windows showed silvery shad and snakelike lampreys, longer than my children, swimming in murky water a few inches from our noses. The fish were soon shuttled through to another room where researchers sat in a private concrete tube, counting.

Later, I looked online for the total counts for the whole season. American shad: 385,930—not bad, considering the number was under 5,000 in 1955, but not the millions it once was. Sea lamprey: 35,249—definitely better than the two counted in 1957. Blueback herring: 137—a catastrophic decline from the 632,255 they counted in 1985. And the total number of salmon that swam up past the dam last year? Exactly three.

Despite nearly fifty years and over $25 million invested in the effort, the recovery of salmon in the Connecticut River failed. The elevators and ladders on the dams aren't sufficient. They don't let enough fish through, plus there are too many small dams up and down the tributaries, all of which need to be removed in order to fully restore the system. But even if we fixed the river, the salmon are still in trouble because we haven't fixed climate change. The Connecticut River salmon swim at the southern edge of the species' natural range. In a warming climate where we expect species ranges to shift northward, you don't want to be among the individuals occupying the southern part of your species' range.

But it's not simply that the river water is getting too warm for salmon to survive. Much of the problem is out at sea. The complicated and poorly understood dynamics of the salmon's marine habitat seem to have been intractably altered. All salmon from New England up through northern Canada come together to feed and overwinter in the North Atlantic. There, circulating water is driven by the interaction of cold, fresh water carried in by the Labrador Current, which mixes with warm saline water brought up by the Gulf Stream. It's a complex system, and small changes can have a big impact. In a warming sea, it seems that changes in the plankton on which the salmon feed, and possibly in the abundance of predators, has made these places—the Labrador Sea and the Grand

Banks—less hospitable for the salmon to feed and find winter refuge. Thus, no matter how far we restore the rivers, Atlantic salmon populations are declining everywhere.

Although it failed at its goal, the salmon recovery effort wasn't a complete waste. Restoring the rivers for the sake of salmon helped a lot of other species that also depend on clean, connected water. Today, when the small shadbush trees bloom, we can once again find hundreds of thousands of shad migrating upstream.

TIGER BEETLES

In a giant concrete tank where salmon once swam laps, Rodger now sits in front of stacked cases of miniature beach habitats built for tiger beetles. I'm reminded of the catastrophe that enveloped another of Rodger's experiments back in graduate school. One afternoon, he meticulously checked that each of the dozens of federally threatened northeastern beach tiger beetles the team had been raising all summer were fed, safely burrowed into their holes in the sand, and closed into their respective containers. He then sealed them into the environmental control chamber—a refrigerator-sized unit that precisely maintains perfect temperature and humidity—and went home. But overnight the brand-new unit went haywire, raising the temperature to over 120°F. The next morning Rodger found shelves of toasted larvae, months in the making, the entire captive population of this protected species. That was years ago. For the current project, Rodger brought on an engineer to build their own environmental control chamber, with remote monitoring.

In his new lab, Rodger is perched on a stool, lanky limbs on a wiry frame, sporting a green down vest over a patterned sweater and round-lensed glasses with thick black rims. He's surrounded by images of Puritan tiger beetles, whose metallic green wing covers are patterned with white around the edges, whose black eyes bulge from their heads, and whose bodies hover atop long legs meant for running across hot sand. Clearly some comingling of styles.

As we catch up on times since graduate school, I fill Rodger in on my book project and ask if he knows why the trees at Rainbow Beach get bigger the further you go from the shore. But Rodger's beetles don't venture into the forest, so neither does he. Still, I think the answer to the tree mystery must be connected to the beetle management.

I lift a large plastic tub off a cart in Rodger's lab and put it on the floor for Juno to inspect. Behind Juno is another cart loaded with crickets and darkling beetles destined to be meals for the tigers. In front of us in the tub are dozens of clear plastic tubes, each the size of a roll of quarters, standing up on their ends. They are half full of fine, slightly damp sand. On the surface of the sand in each tube sits a dark hole just big enough for a grain of rice to slip down. Some tubes have two holes, some have none. Picking up a tube and looking through the clear side, we can see where a hole becomes a tunnel as it worms down the container edge into the sand. Somewhere in that tunnel lurks a young larva. In another couple years, it will be big enough for Rodger to release into the sands of Rainbow Beach.

In nature all you see is the top of the hole—dark, round, apparently featureless—perhaps just the mark where a child stuck a small pencil in the ground and pulled it out. The lack of features around the hole is itself the distinctive feature of a larval tiger beetle burrow. Unlike an ant hole, piled with soil excavated from below and dumped at the burrow entrance, the rim of a larval tiger beetle hole is clean. You'll find no debris on the ground surface for an inch or so in all directions around the hole. Look just beyond this cleared zone, and you may see a miniature hill of soil thrown there by the larva (fig. 5.5). The larva scoots to the top of the burrow, carrying a tiny clump of soil. With a quick flip of her head,

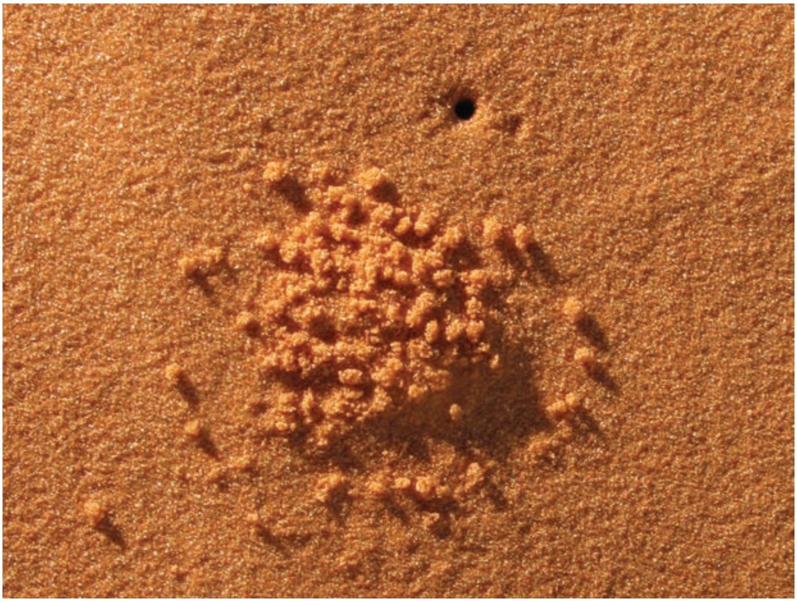


Figure 5.5. Tiger beetle burrow in Coral Pink Sand Dunes State Park, Utah, showing the characteristic beveled edge of the hole and the throw pile.

the soil is sent in an arc over the clear zone and lands neatly in the growing pile an inch or so away. If you are feeling mischievous when you approach an open hole, drop a couple grains of sand down it and see if she flings it back out at you.

Sometimes, if you look closely, you'll notice that the very edges of the open burrow entrance are gently beveled. This is where the larva will rest her flattened head, the same color as the surrounding soil, fitting tightly as it closes the burrow like the lid of a pot. Or perhaps more like a cork in a freshly shaken champagne bottle, with her little eyes peering upward anticipating lunch. From the vantage point of the poor little ant or baby cricket out on a stroll, nothing betrays the trap. The path ahead is free of obstacles, meticulously so. In a flash the ground transforms into a raging tiger, and a tiny life is taken.

Puritan tiger beetles, like the Atlantic salmon, are in trouble. At least with salmon, even if they go extinct in the United States, there are rivers in countries all around the Atlantic Ocean that still support members of the species—in Canada, Greenland, and most of Europe. There are even places outside of their native range where Atlantic salmon have been introduced—the Pacific Coast of the United States, South America, New Zealand, and Australia. But Puritan tiger beetles are found in two small areas: in part of the Chesapeake Bay in Maryland and at a couple sites along the Connecticut River. And Rodger believes that, based on differences in behavior and genetics, these will soon be recognized as two separate species. So really the species I'm looking for on Rainbow Beach occurs primarily on just this and one other little beach along this one river.

Not too long ago Puritan tiger beetles could be found on at least eleven beaches up and down the Connecticut River. And back then it would have been much easier to find them here at Rainbow Beach. What went wrong? I put the question to Tim Simmons, a restoration ecologist who has spent decades managing these critters' habitat for the state wildlife agency. It's mid-winter when I pick up the phone to call Tim. Through the crackle and hiss of the speakers and the interference in the air, Tim explains his long history with the beetles while I sit in my office, staring though my window at the snowpack on the ground.

Outside on the river the frozen surface—a polished skating rink in places, a pile of shattered pieces in others—pops and hisses as it moves impossibly slowly, tugging forcefully at the bank. In spring, the ice disintegrates. Propelled by floodwater, a truck-sized block crashes into shore, scours the vegetation and ground beneath, and moves on. The sun rises, the remaining ice melts, and summer arrives. A fresh scar in the land, devoid of vegetation, records the river's fury last winter. In this sunny little spot where the ice tore up the land, the soil is now warm, dry, and finely textured. A tiger beetle, plump with eggs, runs over to this perfect soil, angles herself upright, and, dancing like a miniature jackhammer, deposits

Figure 5.6. Beach substrates in the tiger beetle burrowing zone on Rainbow Beach. (Juno Charney)

an egg. Over the next two years, a larva fastidiously manages her burrow as she grows. At last she transforms into an adult and explodes out into the sunshine, glimmering with hope.

But life aboveground isn't so easy. As she searches for food and spouses, she is continually interrupted by human children throwing beach balls and oversized men spilling out of their bathing suits looking for somewhere other than their motorboats to relieve themselves. Digging sideways into the warm sand, she constructs a shallow little cave in which she rests and reminisces over her underground childhood. One day, a strange dry fog rolls down from an airplane flying over a nearby cornfield. For the following week she has chills and a sickly feeling in the pit of her stomach, but this passes. Many of her would-be spouses are less lucky.

When it comes time to lay her eggs, she can't find any fresh scars from past winters' ice scour. All around, she is annoyed to find the signs of the unsophisticated bronzed tiger beetles, who seem to be haphazardly procreating in subpar soils, oblivious to the refined and highly selective standards of a Puritan tiger beetle. Eventually, she finds some decent exposed earth in the trampled edges of what Tim Simmons calls the "latrine trail" formed by human beachgoers. As she plunges her butt into the soil, she hopes her little ones find an easier life aboveground than she did. Later that summer, after being buried in six inches of silt left by seventeen feet of floodwater, only a handful of her many larvae are able to dig themselves out and set up ambush for their prey.

What went wrong? A lot of things. For one, a nuclear plant upstream, a series of dams, and a warming climate have raised the temperature of the river such that less ice forms. Though not the only force that creates Puritan tiger beetle habitat, Tim thinks ice was historically important for creating their habitat here on Rainbow Beach (figs. 5.6 and 5.7).

Climate change and the upstream dams have also conspired to create bigger and more frequent flooding of the beach. It's not the existence of the dams per se that's causing the flooding but changes in the timing of when the hydroelectric companies choose to release their water stores. Tim is hopeful that when the power plants renew their operating licenses there will be an opportunity for conservation concerns to help guide future water release schedules. The nuclear plant, too, has been shut down, alleviating another stress on the river. The climate, on the other hand, seems hell-bent on delivering increasingly severe deluges.

Boaters partying on the beach do create some habitat for larvae by disturbing the soil, as sort of a stand-in for ice scour. However, because people on the beach are so disruptive to the adult beetles, Tim believes that beachgoers on the whole are a net drain on the species. That's not even counting the people who are intentionally attacking the beetles. Twenty-five years ago two dentists and a lawyer, who on the side were hobby tiger beetle collectors, went to Rainbow Beach and collected every single beetle they could find. Perhaps we should just close the beach to people. If the

Figure 5.7. (a) Ice scour along a small river, (b) ice jam on the Connecticut River, and (c) ice chunks close to the shore on the Connecticut River.

beetles had vertebrae, Tim thinks that would happen. But bugs, even federally endangered ones, don't hold enough political clout to close even a section of a popular public beach.

Decades ago Tim began fighting against the tiger beetles' enemies. He and his team tried to artificially create habitat for Puritan tiger beetles, swarming the beach with rakes, tilling machines, and bare hands. Mimicking the work of giant blocks of ice, they scoured the land, ripping up vegetation and soil to create perfect sites for larval tunnels. But the successes were always short-lived. The beetles like to live right at the back of the beach, near the forest edge. But every time Tim would create a perfect nesting spot, creeping vegetation or floods would ruin his team's work within a few years. Beach-going people kept coming and harassing the adults. Sometimes Tim would be dowsed with pesticides from the nearby fields. However he tried to help, the fight for tiger beetles on Rainbow Beach was always an uphill battle.

At the core of the problem, rivers are naturally dynamic. Tim realized that his team was, as he put it, "trying to manage static conditions on a place that wants to be violently dynamic. That's a lesson that habitat managers have to learn—usually the hard way." Rainbow Beach has never been and never will be static. The sands and vegetation are constantly changing. Where the tiger beetles want to nest this year won't be the same as next year. The problem is that so much of the river has been impacted by humans, there aren't a lot of other places left for them to go.

CATCHING TIGERS

As the field season approaches, Rodger's team gears up to catch tiger beetles. The plan is to have the adults lay eggs in the safety of the lab, free from predators and competitors, where Rodger can fatten up larvae and ultimately release the offspring back into the wild. I stop in one afternoon to hear a pep talk by Hal Weeks, who is sharing the success story of the Oregon chub—a little fish that depends on the backwaters in wildly meandering rivers in the Willamette River Valley. Humans, with their habit of overtidying things, found these rivers and simplified the system by straightening channels and controlling floods. This effectively eliminated chub habitat, pushing the fish onto the federal endangered species list. Hal and others went about restocking the fish into remaining habitat, working with farmers to protect populations, and convincing the department of transportation to stop spraying near critical waters. After twenty years of work, the fish was deemed "recovered" and taken off of the endangered species list.

A few days after Hal's presentation, carrying a crew of Puritan tiger beetle volunteers, a federal motorboat drops us off on Rainbow Beach. Standing at the water's edge, I distribute maps, a GPS, a compass, and printouts of this chapter's image to the students and volunteers. Turning the map upside down and then right side up again, they're having trouble figuring out why the GPS seems to be putting us on the wrong shore. We eventually solve the map puzzle and then head off to practice catching tiger beetles. Today we're only catching the common species, so that when the rare beetles finally emerge in a few weeks, we'll have made all our mistakes with something not so precious.

As we wander near the back of the beach, I duck quickly into the trees to search for Juno's hat, which we left here last year. It was next to a big wooden display kiosk erected years ago to tell visitors about the endangered beetles. As I enter the woods, I'm disoriented. The saplings Juno had posed next to on our previous visit are flattened to the ground—presumably by the ice jams and floods this winter. The odds of finding his hat look grim.

I muse over my own cherished hat—from the Telluride Bluegrass Festival—that I left on an island off the coast of Florida. Like debris in the water, a flood of memories washes past me. That hat came to me during a mid-college road trip, Operation Monkey Storm, not long after my friends and I were evicted from the Alamo for playing croquet in the courtyard. I insisted that we visit Colorado's Great Sand Dunes, a place that I had fallen in love with at seven on a family road trip, mirroring a trip my dad had taken as a child. My dad had allowed his poky stubble to grow into a proto-beard while my brother and I lost a little metal Band-Aid tin full of model airplanes in the shifting sands of the Colorado Dunes—then returned and miraculously found the tin. After the dunes, Operation Monkey Storm headed to Telluride, where I bought the hat.

For years after Operation Monkey Storm, I dipped that hat into every river I encountered. In a little ceremony, I'd scoop water to all the cardinal directions, then end with one big scoop over my head, letting the water run down my back. The Russian River, the Missouri, the Mississippi, the Connecticut, the Columbia, the Rio Grande, the Saint John, and countless little creeks in between. The hat took on a pungent smell, like mildew and snakes, but always stayed with me. When my dad was dying, I placed the hat on the floor of the room, scoop-side up. Somehow I felt that all the sacred river energy would either flow out into the room and help, or that the hat would soak up whatever sacred energy was floating in the room to save for later. I can't be sure, but I think it helped in some way.

Several years later, I was with Liz Willey and Mike Jones—my turtle friends—out on an island off the coast of Florida searching for turtles with my threadbare hat. The island had been made by Calusa Indians thousands of years before, entirely out of discarded sea shells. At the time that it was made, the mound of shells may well have been connected to the mainland before sea levels rose and turned it into an isolated island.

On that island, I found myself in a thicket of barbed wire cactus—a maze of long, spindly arms that swung through the air with two-inch spines. The spines kept going right through my layers of clothes and flesh until they landed with a thud against my bones. Several tips broke off in my fingers. Two years later, hiking on Stewart's Island off the southern tip of New Zealand, one of those spines reared its bloody head from my thumb, taunting me. I had no tweezers, and it slipped back in, where I can still feel the lump to this day.

I found a turtle in that Florida thicket, but when I emerged, I realized my hat was gone. Despite searching, I couldn't find it. A year later Mike and Liz returned to the island without me, hoping to encounter the hat while they searched for turtles. But it remained lost.

In the woods behind Rainbow Beach, I find the wooden kiosk. It's covered with flyers about the tiger beetles and carefully worded messages imploring visitors to respect their habitat. But it's also completely overgrown by trees. Hidden back here, there's no way any beachgoers would ever see the board or get the message.

Two years after I lost my hat in Florida, Mike and Liz returned with our friend Derek. About to board the motorboat for the return home, Derek decided to make one more quick run out after a turtle. A few minutes later he returned to the boat. In his hand was my hat. Or what was left of it after rotting in the Florida Everglades for two years—primarily the brim, the spider-like network of seams, and a few pins and porcupine quills I'd stuck in it over the years.

Clinging to these memories as they slip past feels like scooping water with only the skeleton of my hat. How does the philosophy go? I can never dip my toe in the same river twice because it's a different river from moment to moment? I never die because I am a different "I" from moment to moment—or rather, I am constantly dying and being reborn in each moment? The river and I don't exist as discrete things but are merely two overlapping heaps of moving parts?

Staring into the forest behind Rainbow Beach, I suppose Juno hasn't lashed his soul as tightly to his hat as I did to mine. It's probably been washed far downstream. Maybe we should just go back to REI and buy a new one. Turning my back on the forest, I return to practice catching the common tiger beetles.

On a sunny July day a couple weeks later, I return with a different federal team. This time, the beach is teeming with real, live endangered Puritan tiger beetles. I belly-crawl through the sand trying to capture portraits before they flit away. Hanging out on damp sand near the water, the beetles in my lens crawl with their bellies also near the ground to stay cool. Then I find one in the hot, dry sand. Perched atop a four-inch dune, the beetle fully straightens its six long legs, stilting its body as far as it can away from the radiating heat below. Classic tiger beetle behavior. This is how they have adapted to hot, sandy microclimates. My camera clicks once, then the beetle flits away.

A bit further up the beach, we find a Puritan tiger beetle approaching a dead wood turtle, not far from sandbar willow—all three species listed under the state's endangered species act. I text a picture of the turtle to Mike, who has been following hundreds of individual wood turtles for decades, keeping careful track of each one's idiosyncratic life. Often, when you find a wood turtle around here, it's one that Mike knows well. This one, it turns out, isn't one of his.

FOREST EDGE

I wonder, is saving one species at a time really going to get us where we need to be? Rather than going about conservation one single beetle at a time, protecting whole systems often seems like the most sensible approach. After all, there are over 100,000 species of insects in North America, an unmanageable number. The number of discrete habitat types is much smaller. But sometimes single-species approaches are all we can do. For one thing, some of our most powerful conservation laws are the various federal and state endangered species acts. These laws don't recognize endangered ecosystems in the same way that they recognize endangered species. Ideally, we can focus on umbrella species—that is, species whose protection necessitates the protection of entire unique systems. The target species becomes a crutch to advance a broader conservation mission. And, ideally, we can use other proactive measures to protect valuable systems.

When Rainbow Beach was originally purchased as a conservation area, it wasn't for the Puritan tiger beetle—nobody even knew the beetle lived here. It was actually for the forest behind the beach. This is a rare example of floodplain forest. Silver maple. Cottonwood. Boxelder. These are wetland trees that particularly love rich riparian soils. But riparian forests are under threat. There aren't many left, and the ones that are tend to suffer.

Assembling images for this chapter, I realize I don't yet have a good picture of the smallest trees in the small-to-large gradient. So I dress my scale bar in his orange-and-white shirt, black shorts, and a fresh haircut, and we head back out to Rainbow Beach.

On this visit we're accompanied by Joe Rogers: geologist, river ecologist, and the town's assistant conservation planner. Joe, who stands at six feet, six inches, folds himself into my car, and we drive along the runway of a small airport, bounce on dirt roads through a vast plain of cornfields, and park at a rusty metal gate shrouded in poison ivy. Joe thought he had the key that would allow us to drive right up to the edge of the beach. He doesn't. Instead, we duck under the gate, drop down a short slope, and land in another flat cornfield.

For the next half mile, we fight our way through eight-foot cornstalks. Joe strides ahead, lost in the sea, and I feel like I'm drowning amid the crashing sounds of corn leaves slashing at my ears. Juno clings to my torso, shielding his face from the leaves' serrated edges, and I worry about what pesticides the corn hurls at us. When I'm almost ready to give up, we arrive at the western edge of the forest. On the far side of this forest waits Rainbow Beach. As we stand with the corn behind us and the forest in front of us, we hesitate. We are staring at a tangled wall of blackberries, bittersweet, and poison ivy supported by a frame of boxelders. If we tear a hole through this wall, will it be easier to walk in the forest interior? There is only one way to find out.

Forest edges are rarely inviting. Often a vertical curtain of vegetation seals off the forest perimeter. Outside the forest, something—lawnmowers, cattle, water, rock outcrops, asphalt—prevents woody shrubs from growing. Inside the forest, shade limits the growth of shrubs. Right at the edge, however, there is plenty of light and nothing to prevent the growth of woody stems. The plants respond by filling in the space with leaves—it's almost like the top of the forest canopy turned on its side.

In the fabric that forms edge curtains, sometimes the species are harmless enough: forest shrubs like spicebush and mountain laurel; native North American vines like trumpet creeper and grape; and the saplings and side-shooting branches of the canopy maples, oaks, and pines above. But many of the species can be downright threatening: multiflora rose, whose thorns, curved like sharpened cat claws, are quick to draw blood and tear clothes; poison ivy, whose oils once turned my legs into two long cuts of seared steak requiring steroids to heal; blackberries, whose prickers are not as menacing as rose thorns but can still tear at my jacket and inflict pain on my skin; and a whole suite of invasive species like bush honeysuckle, bittersweet, wisteria, and tree of heaven that threaten our native ecosystems.

To appreciate the forest, you've got to get past the edge. It's deep inside that the true nature of a forest reveals itself. It's in the forest interior that the shrub density is usually thin enough that it's easy to walk and see the grandeur of the trees. Here in the interior the forest is beyond the reach of the extra sunshine, the extra wind, the noise, and the pollution that pours in from the edges. It's beyond the reach of many of the exotic species, which are often concentrated at the edges because that's where the birds, attracted by the higher density of berries and bugs, pooped out the exotic seeds. The interior is beyond the reach of the predators that live out in the field beyond the forest and will venture only a short distance into the forest edge to feed. Many of our sensitive species—small salamanders, skittish birds, delicate ferns—can only survive deep in the forest interior, hundreds of feet from the edge. That's why, as a conservationist, I fight to protect big patches of forest with low perimeter-to-area ratios.

TERRACES

Carefully slipping around poison ivy, Joe, Juno, and I enter the riparian forest. Immediately, the ground drops us down a short slope to another lower level. This is the third shelf we've encountered on the system of floodplain terraces: we started on the plain of the airport, then we stepped down into the cornfield, and now we are down where the riparian forest grows, about fifteen feet below the airport level. Why, I ask Joe, are there terraces along rivers? Whether it's a big river or a small creek through the woods, the water is often flanked by land formed into the shape of a giant staircase.

I understand that each terrace represents a former floodplain of the river—that's the level that the river used to be at thousands of years ago. And I know that the river has been working hard to cut down through the layers of sediment dropped at the bottom of the glacial lake. This down-cutting is given extra speed because, after the glaciers melted away, the continent lifted upward, free of the heavy burden of ice. The river, responding to the uplifted land, is driven to cut ever faster down into the underlying rocks and soil. So, naturally, the current floodplain level will be lower than previous floodplain levels. But why are there discrete steps? I imagine a gradual process of uplifting land and down-cutting water. Wouldn't that produce a continuous slope from the airport down to the riverside?

"It turns out," Joe suggests, "things don't happen gradually, things happen episodically . . . big change happens during big events." For a long time the river might calmly meander back and forth at one level. But then an enormous flood arrives, quickly reshaping the landscape. Braving the storm, gawkers might drive to the edge of the river and marvel at how the top of the water is now thirty feet higher than normal. But beneath the surface the bottom of the river might also be suddenly much lower than normal. The force of all the rushing water mines away tons of old sediment in a flash, carrying it out to sea. The flood recedes, and now the river suddenly finds itself sitting on a new lower level, having abandoned its old floodplain as a terrace up above.

Or, in a similar vein, perhaps the river is slowly cutting downward, and then in a big storm suddenly shifts sideways to a new position where it resumes downcutting. Such a start-and-stop migration can explain a series of staircases.

These explanations aren't too different from what the geology textbooks say. But most textbooks seem to suggest that the different terrace levels indicate larger-scale periods of stability and change. That is, for a while everything is stable, and the river forms a nice flat floodplain. Then there's a prolonged period of change—glacial rebound, tectonic uplift, falling sea level, or a climatic shift—which causes the river to start cutting down until another period of geologic stability occurs. The textbooks point to paired river terraces, frequently found to symmetrically flank a river to indicate the old floodplains during periods of stability.

I suppose that's plausible, but . . . I don't know. Despite being backed up by over a hundred years of literature on terraces, that explanation doesn't feel terribly satisfying. It still seems like, at the scale we're talking, the downcutting should be a gradual process.

Tekla Harms, my former geology professor, suggested another, satisfyingly simple explanation for terraces—an explanation published back in 1909. I visited her this year looking for answers, and she unrolled a big map of the valley on her desk—made of old USGS topographic sections that had been taped together. The current river ran down the center of the map, surrounded with Tekla's notations. On the inside bend in the river, she pointed out topo lines marking a series of low undulations called "scroll-bars"—remnants of past positions of the beach fronts as the river migrated. Tekla then traced her finger along a broader set of contour lines that she'd long ago highlighted on the paper map. East of the current river position, these tightly clustered lines ran parallel to each other as they snaked up the map. They indicated a long, low ledge of soil—the outermost river terrace. The flat land above, just east of the ledge, was the bottom of the old glacial lake. It remained more or less as it was when the lake drained 12,000 years ago. Sometime in the past the meandering river had made its way just to this ledge, cutting through the old lake bottom as it moved eastward. Then, on a whim, the river decided to wander back to the west side of the valley, leaving the terrace behind.

Time passed, and as the river meandered through the valley, it cut deeper downward. Its floodplain got lower and lower—yes, gradually. Then a curve of the river swung to the east again, back near that first terrace, although, by chance, it didn't reach all the way to the old terrace. Instead it shifted back to the west again. Because so much time had passed between the two times the river found itself on the east side of the valley, the level of its floodplain was substantially lower the second time. Thus, the second terrace it cut was at a lower level. The steps in such terraces simply indicate the time that passes as the river swings back and forth in the valley bottom.

The beauty of this explanation is that we don't need to invoke external agents or particular conditions. Terraces simply arise from the intrinsic nature of meandering rivers. But then would terraces on either side of the river be paired? Well, according to recent computer simulations, yes. Because often the river meanders in such a way as to cut off terraces on both sides of its active channel before it has much time to cut downward.

Beyond not understanding terraces, I also never fully understood why floodplains are so flat. I know that water wears down a landscape, and water sits flat on the land—so the level to which it cuts will be flat. But I failed to understand that water also flattens by filling—in the same way that the clay slurry in our basement experiment settled into the deepest spots of our plastic tub to create a horizontal surface. If you look at the profile of the bedrock underneath the Connecticut River, it's anything but flat. Strip away all the soil, and there's a dramatic landscape of peaks and valleys down there. There are places where bedrock still protrudes in the river and spots where you could dig for over 200 feet and hit nothing but muck. It's just that the river and glacial lake in their turns came along and filled in all the holes. Now all we see on top is the flat surface good for farming and landing planes.

RIPARIAN FOREST

Inside the forest, Joe, Juno, and I find a dark, tangled magic. There are few shrubs—mostly big trees above nonwoody vegetation. But making forward progress toward Rainbow Beach is still not trivial. We crawl under and over huge fallen trees. The land gently undulates up and down, and in the muddy low-lying clearings that recently held water, it is easy to navigate. But in other places the wood nettle is thick and chest high, forcing me to hold Juno up above my shoulders so that he clears the nettles. The nettles bite at my elbows, and when we move too quickly, the thicker needles along their stems pierce through my pants. Soon my skin is marked with itchy white welts. Though Joe's arms tower above the nettles, his pants are much thinner than mine, and together we yelp at the stings.

Still, I love wood nettle. You only encounter it in very specific types of places—moist, dark, rich. It's a good native species that supports local wildlife and reminds me of shady streamside forests of my childhood. Legend has it that a little sting from nettle each year even helps with arthritis. As a kid, I would occasionally run through the center of nettle patches just to experience the thrill of the short-lived stings. Today, however, my increasingly pained skin is happy when we find a seven-foot-tall thicket of Japanese knotweed smothering everything beneath it in darkness. There we crack hollow knotweed stems beneath our boots as we plunge ahead.

Despite walking hundreds of yards, it feels like we never really get far from an edge. Everywhere we go in this forest there are signs of disturbance—recent floods, sometimes carrying damaging blocks of ice, have ripped away at the inhabitants. Into the light-filled gaps created by these disturbances come invasive species—knotweed, bittersweet, garlic mustard, catalpa, and more. Sometimes it's the floodwater that's brought the species in. Some landowner may have thought she was helping the environment upstream by cutting down a knotweed patch, but the cuttings she left on the bank were carried by the water to this spot in the forest, where they sprouted roots and started a new colony.

Few riparian forests remain, and those that do are suffering. They suffer because, like this one, they are small and frequently disturbed. Bounded on one side by cropland, on the other by a river, this is just a thin fragment of the riparian forest that previously covered most of the floodplain terraces. Once riparian forests up and down the river were connected to each other and to vast contiguous forests into the uplands. Sensitive forest dwellers could easily roam long distances without leaving the safety of the trees. Now this small patch isn't connected to anything and is assaulted by edges on all sides.

In truth, it's a miracle that this forest is here at all. I wonder how it slipped through hundreds of years of agriculture. The flatness of the land, combined with rich soil and a lack of big rocks, makes for extremely valuable farmland. It's rich and rock-free, in part because we're sitting on the old clay-settled bottom of the glacial lake. But the soil is also renewed in every flood. The rushing floodwater surges over the riverbank, spilling across the land. Then it stops. While water within the river channel keeps rushing down to the sea, the water up in the floodplain stands still. The stillness of the water after the flood is what allows the nutrient-rich clay particles to fall out and settle across the land, replenishing the soil.

Eventually, Joe, Juno, and I, traipsing up and down over the old forest-covered scroll-bars, reach the south end of Rainbow Beach, where the shore is just a thin strip of mud. We wander northward, and the beach widens with every step. We tread across strange long runners from invasive reeds creeping across the sand. Soon tiger beetles flit away from us, and we stop to admire the drag marks where the beavers have cut willows and brought them back to the river to feed. We chat with a family of boaters about the beaver that chewed off the hoses on their boat one night.

When we reach the spot where Juno and I landed with Julia months before, Joe and I swear never to walk in again: next time, we're taking a boat. After gathering up all of our courage, we begin the long trek back to the car, trying a different route this time. On our way out, Juno makes up a song, "On the Other Side of Rainbow Beach." We pass a troop of college students scattered in the trees amid clipboards and measuring tapes taking notes, learning all that they can from this rare, changing forest.

MEANDERING

Julia, Juno, and I roll up our measuring tapes and head back to the canoe. We walk across the sand—Juno taking pictures of a fish skeleton that he wants to include in the book, and Julia and I discussing tiger beetles. When we get to the shore, we unpack our lunch and maps and talk about the site. Julia picks up the GPS and scowls. The maps and her intuition are offering conflicting signals. The GPS seems to be saying we're on the wrong bank. It's messing with her sense of direction. I know the feeling.

Sense of direction is a funny thing. Sometimes, once it's set, it's hard to undo. One of my first introductions to this valley was when I arrived here on a bus driving west from the Atlantic coast. We exited the interstate and drove east over the bridge that looks out to Rainbow Beach. The bus was driving eastward just before it dropped me off in town. But, having just come from the coast, my body felt that we were still headed west. From then on, my gut instinct in this area was that east was west and south was north. It took me decades of intentionally watching the sun track across the sky to rewire my brain—and still parts of that instinct remain.

Rely too much on technology, and you never develop a sense of direction to begin with. The summer I chased Jefferson salamanders across the Berkshires I had thousands of vernal pools programmed into my GPS and trusted its guidance as I drove back and forth across the county visiting up to ten random sites a day. I've seen almost every part of the Berkshires and have many fond memories of forests and amphibian-filled ponds that I've tromped through. But I have no idea where any of these places are, or how to find them again, other than digging up my old GPS coordinates. When I drive through the Berkshires today, I am frequently surprised as I turn the corner. In front of me is a familiar place associated in my mind with a nearby wetland, but because I never developed a map in my head of where these places are, I never know which site I'll see next.

One of my favorite tools to hand to the *Field Naturalist* students was a little compass I kept on my watchband. My mom gave it to me, but for some reason about half the time it would point exactly 180 degrees in the wrong direction. Some weeks it would be right, but other weeks north was south. The students, of course, didn't know this. With the sun shining down on the landscape in front of them, they had to decide whether to trust their senses or the technology. They already knew not to trust me. I can still feel the wounded glare Grace shot me when she finally figured out the compass trick.

While Juno digs in the sand, Julia and I look across to the muddy cliff on the far side of the river. Clay holds the vertical wall together. It's a classic cut-bank in a meandering river. Up in the mountains, where the rocks are barely weathered, there's not much clay to hold things together. Those fast-moving rivers carry and deposit lots of large rocks and gravel, which don't hold their form. When a river cuts through a gravel bank, it will usually collapse into a low pile. Under such conditions, you tend to get braided rivers made of networks of crisscrossing channels. But on the gentle slopes of the lowlands, where the rivers carry mainly fine particles and there has been plenty of time for weathering to produce clay from granite, you get lazy meandering rivers.

Once the river starts to bend, the bend gets progressively more curved. The water slamming against the outside bank cuts further and further into the clay. Meanwhile, on the inside of the curve, the water is moving at its slowest and drops loads of sand. In this way the whole river creeps into its curve, with an expanding sandbar and a retreating cutbank. Eventually, the bend gets so extreme that the river practically loops back onto itself. And then it actually does loop back onto itself. The river breaks through a final wall and a whole bend is just abandoned. An oxbow, a boomerang-shaped lake slowly filling with sediment, stands as a tribute to an old bend in the river. There are plenty of them on the maps in front of us (see fig. 5.4).

We think of the land as stable, but it's not. Especially not near water. In love with the power and beauty of water, we build along the banks of rivers and oceans expecting nothing to change. When the power of water frustrates us, we build concrete walls and earthen berms to keep the water from moving. We wreck the water's beauty along with the upstream and downstream ecology. Ultimately, the water will keep fighting back. Accepting change is a hard lesson to learn.

With time, this bend, too, will become just another oxbow. But not exactly where we're sitting. The beach must first travel further east. It's that marching of the sand that vexed Tim Simmons—as the tiger beetle habitat steadily crept downriver, off of the land owned by the state and onto the private land of neighboring farmers.

Sitting on the beach, I pull out some historic maps and a piece of clear plastic—a transparency sheet from old overhead projectors. With a 2012 satellite photo behind the plastic, I trace the current banks of the river with a black marker and put a black star where we are sitting. Then I shift the plastic to a map from 1990 and retrace the riverbank with a blue marker. Then I do the same for a 1962 map with a green marker. And finally I trace the river on an 1862 map using a red marker (fig. 5.8).

And there it is. In 1962 the little black star is sitting on the opposite bank. That's about when the USGS made the topo maps that the GPS is using. The GPS has our location on Earth right—it's just that the river has moved more than 500 feet eastward over the past forty-five years.

Figure 5.8. Rainbow Beach in (a) 2018, (b) 1990, (c) 1962, and (d) 1885. Site location is indicated by the black triangle and the 2018 river position is indicated by the green shape superimposed on the images. (a–c: Google Earth; d: USGS)

Roll the clock all the way back to the 1860s, and none of the riparian forest was even on the map—all of that land was created in the last 150 years. That's why the forest is here—the farmers originally did cut down all the forest, but then new land grew in at a lower, swampier, difficult-to-farm terrace, and the forest was left to grow.

Landscapes look so stable and permanent. But even on human timescales things change. The shifting Colorado Sand Dunes swallow our childhood treasures, rising sea water engulfs the shell-mound islands of the Calusa Indians, Earth's crust rebounds from the lost weight of glaciers, meanders cut terraces down into the riparian landscape, the shifting river leaves undulating scroll-bars behind in the forest, ice jams scrape the soil, trees near the eroding edge of the cornfield fall into the water, abandoned hats are washed downriver, and the kiosk at the edge of Rainbow Beach is gradually overgrown by trees.

As the beach we're sitting on moves east, the forest is chasing it. The edge of the forest, with the youngest trees leading the charge, advances onto the sand where the Puritan tiger beetles like to burrow.

And that's why the biggest trees are farthest from the water—because the land itself is oldest there.

MAJOR LESSONS FOR INTERPRETING A LANDSCAPE

- How is the shape of the land changing over time? How fast, and by what means?
- Consider any rare species or targeted management for conservation at your site. Go on to your local regulatory agency's website and look through its maps and guides.
- Where are the habitat edges, and how are they structuring the species assemblages?

(overleaf)

Figure 6.1. Large or small, for every pattern there is a process to be discovered.

6. Chemicals

A SHORT TRIP AROUND THE WORLD

I'm not a morning person. Intellectually, I understand that mornings are wonderful—cool air, sparkling dew, singing birds, yadda yadda. But my body sees it differently. I live for night. I guess that's why I study salamanders instead of birds. On road trips, I limp my way through the daylight, straining to stay awake while the sun drags my eyelids down. But once the sun sets, I get a burst of energy and can drive without stopping until the gas runs out. Today I have no choice but to be on the road at 5:00 AM if I am going to catch this field site. Last night I would rather have taken the kids for a long walk through the woods, dimly lit by a crescent moon. Instead we went to bed extra early, leaving the moon high in the sky, so that I could rise now at this decidedly un-amphibian hour, alone.

Low tide is in an hour and a half, and there are 103 miles of pavement between me and the water. Plus I still need to park, unload my gear, drop my boat in the water, and paddle out to the site. Canoe on the roof, I race south. But it's not just the coast that interests me today; this is also a geologic pilgrimage.

Flying past my window are rock faces that were blasted from the hills when the road was cut. Reddish mudstones jut out of the highway median, arranged in flat slabs that are stacked and tilted. In my mind I see the fossil footprint from this rock layer displayed on the floor of the local natural history museum. Next to the display a sign invites Alder and Juno to crawl around in the track itself, pretending to be dinosaurs.

Two hundred million years ago, when this mud was wet on the valley floor, a real dinosaur walked casually along. Her left foot landed here, stayed for less than a second as she moved her right leg forward, then the left foot lifted and, with the sound of squishing mud, she was gone. Impossibly, that instant was permanently recorded. The track captures a tiny flicker of life. It's not so much a description of the animal's build, diet, growth, or ecology—though some of that can be guessed at from the track. What fascinates me is that the track records a personal moment in her story.

At that moment thoughts were in her head. Perhaps her eyes were looking to the left at a friend. Her ears heard splashing in the river nearby. Her belly rumbled from a recent meal. Two rocks clanked together in her gizzard. A pterodactyl shadow approached. In a snap the moment was absorbed into the quadrillions of other moments among the trillions of creatures among the billions of years of our planet. Could she have hoped, or cared, that, after the sun had set and risen seventy billion more times, somehow against all odds that singular moment in her life would be hardened in stone, adorned with decorations, and admired by generations of children?

Dinosaurs aside, after an hour of driving, it's been a fairly tame trip from a geologic perspective. I've been more or less driving south along the center of the rift valley, passing essentially the same sorts of rocks that characterize the northern portion of the valley.

I pass dark, jagged formations of basalt—remnants of the lava flows that filled the spreading rift valley and formed the mountain at Bark Hollow. The road crosses red-brown sandstone—an arkose related to the one at Bark Hollow, but this one, the Portland Arkose, is the famous "brownstone" used to build townhouses in New York City. All these rocks—the arkose, the mudstone, the basalt—are familiar native rocks that were formed here on Laurasia, the supercontinent containing North America, Europe, and Asia 200 million years ago.

Suddenly, the landscape shifts. In just a few minutes, I leave Laurasia behind. The road undulates up and down. Approaching the crest of each hill, I anxiously peer out of the front window to see the upcoming cliff, slowing down as my gaze lingers on the passing rocks. Sometimes I'm able to snap a few blurry, tilted pictures, shooting from my hip through the splattered side window. It seems that each cliff face holds an entirely new set of rocks.

I see dark blocks bisected by three-foot-wide stripes of white. I see gray wavy lines. I see golden flaky layers. I see light gray lenses inside dark gray masses that are streaked with red rust. I see tilting, I see folding, I see intrusions. The patterns stream by in rapid succession, each rock face bringing a completely new story. But all the rocks bear the telltale signs of metamorphism—these rocks were subjected to great heat and pressure, which transformed them physically and chemically.

These metamorphic rocks are the violent scars of continental collisions. These rocks are remnants of the things themselves that glommed on to the front of our continent, like the bugs on my windshield. Several independent landmasses, known as terranes, have been crushed, fused, and swirled together here.

Complex sets of gray schist and gneiss out my side window belong to the Taconic (or "Bronson Hill") island arc. Resembling Japan, this serene volcanic island chain once sat off our coast 450 million years ago. I then drive over rocks that began as sedimentary layers deposited on the floor of the ancient Iapetus Ocean before being thrust onto our continent and metamorphosed into gneiss. Next I'm on to two other ancient landmasses: the Putnam-

Nashoba island arc and the microcontinent of Avalonia. That last landmass, Avalonia, is the most significant.

GONDWANA

Toward the end of our trip around the world, Sydne and I found ourselves as special guests at the grand opening of the Salamander Conservation Center in the mountains of Taiwan. Sitting next to the emissary from Bhutan while aboriginal children danced in red capes in front of us, I tried to fit in by tucking my hair under my hat and patting down my beard—neither of which had been groomed or trimmed in five months. Out of everywhere we'd been in the world, Taiwan was by far the hardest place for us to navigate. Luckily, the salamander biologist Kuang-Yang Lue from the National Taiwan Normal University took us under his wing for a couple days and drove us down to the ceremony at Shei-Pa National Park.

In the afternoon Dr. Lue hiked us along a ridge trail through a misty forest. The trees—dark, gnarled silhouettes in the fog—were mainly red cypress, an endangered Taiwan endemic in the same genus (*Chamaecyparis*) as eastern white cedar and Port Orford cedar, which grow along the east and west coasts of the United States. Where the trail approached the mountain edge, the wind blew a brief opening in the mist, and we glimpsed a vast expanse of ridges and valleys. Walking a few steps further, I noticed a promising looking rock near the trail—about the size of a large book—sitting on undisturbed ground in such a way that it could have held a hiding place beneath it. I lifted the rock.

Beneath the rock sat a salamander, gray and wide-mouthed, grinning up at us (fig. 6.2). She was about as thick as my thumb and speckled with light blue. If this had been the Berkshires, she could easily have been mistaken for one of the members of the unisex-

Figure 6.2. (a) Guanwu salamander in Taiwan, (b) unisexual salamander in Massachusetts, (c) eastern red-spotted newt in Massachusetts, and (d) common newt in the Netherlands.

ual salamander complex. But this was the endangered Guanwu Formosan salamander, a Taiwan endemic with populations so small that Dr. Lue believes inbreeding was to blame for the asymmetrically shorter toes on her right foot.

After Taiwan Sydne and I stopped for a few days in the Netherlands before heading back to the United States. There, a Dutch herpetologist, Richard Struijk, graciously dragged me in the pouring rain through muddy ponds filled with common newts. People often ask me what newts are, assuming they are something related to, but different from, salamanders. Newts are definitely a distinctive group, but newts are indeed members of the salamander order. In fact, out of the ten families of salamanders, newts are members of the one family named Salamandridae, which includes the species *Salamandra salamandra.* (There is even a subspecies named *Salamandra salamandra salamandra*.) This is the type species after which the whole order of salamanders is named. It doesn't get any more salamandery than that.

Richard taught me how to spot the newt eggs, which were laid singly at the tip of underwater grass-like leaves. The giveaway was that the last half inch of the leaf had been folded over to protect the egg. I wondered if this insight might help me find eggs of newts back in the United States.

Later in the week Sydne and I walked through a Dutch outdoor sculpture garden whose paths were lined by beech trees. With their smooth, light gray bark and Crayola-green spring leaves, these trees felt no different from the beech trees of New England. The European beech in this sculpture garden, like the beeches of China and Japan, are in the same genus (*Fagus*) as American beech.

Beech, cypress, salamanders. These all share something in common. As Sydne and I bounced around the Southern Hemisphere during the prior five months, we hadn't seen any of them. Instead of salamanders, we saw side-necked turtles, a distinct evolutionary branch of turtles that occurs throughout the Southern Hemisphere and whose members hide their heads by folding their necks over to the side rather than retracting straight back like the storybook turtles of the North.

Instead of the "regular" beech we're used to, in Argentina we hiked through huge, dark montane forests of *southern* beech (*Nothofagus*)—trees in a different family than the northern beech (fig. 6.3). A few weeks later we hiked through similar forests of

Figure 6.3. (a) Southern beech forest in New Zealand, and (b) southern beech in Argentina.

southern beech in New Zealand. And, while our plane was crossing the southern Pacific Ocean, flying within sight of Antarctica, we read that paleoecologists have collected fossil pollen of southern beech trees from that ice-covered continent, remnants of the ancient Antarctic southern beech forests.

As Sydne and I experienced, Europe, Asia, and North America share species and higher taxonomic groups in common. Likewise, different sets of species are shared among the world's southern continents. Lots of taxa follow these same basic patterns. Why?

It goes back to plate tectonics. Today the Atlantic Ocean separates populations of European and American salamanders, allowing them to diverge along distinct evolutionary trajectories. But that hasn't always been the case. Europe, Asia, and North America all derived from the supercontinent of Laurasia. Back when these landmasses were connected, beech, cypress, and salamanders could move back and forth across the supercontinent. Even after the spreading North Atlantic Ocean finished separating Europe and Greenland fifty million years ago, occasional land bridges across the Bering Strait would have still allowed for some exchange.

Just as salamander ancestors casually strolled between Canada and Europe in the past, an analogous mixing occurred among today's southern continents—who once formed the supercontinent of Gondwana. Five hundred million years ago—before salamanders had even evolved—Africa, Antarctica, South America, Australia, and New Zealand were all part of that gigantic landmass. Eventually, Gondwana would join up with Laurasia to form Pangea before everything splintered apart again. But even during the days of Pangea, when the landmasses were all united, there may have been an environmental barrier to north-south movement. The equator bisected Pangea, and the equatorial climate would have been markedly different from the climates further north or south. This likely deterred Gondwanan and Laurasian species from crossing over. Ultimately, it was across the unions forged by Gondwana that southern beech, side-necked turtles, and a whole variety of Southern Hemisphere specialties dispersed.

Of course, the world's biogeography isn't all so simply divided between north and south. There is, for instance, a distinctive set of snapping-turtle-sized trilobites whose fossils can be found along the margins of Europe, New England, eastern Canada, and northwest Africa. From these fossils geologists deduced that somewhere around 480 million years ago a chunk of Gondwana broke free and drifted off toward Laurasian landmasses, carrying its unique species along. This little Gondwanan chunk was the microcontinent of Avalonia.

And here I am, near the end of my morning road trip, in Avalonia. Within two hours I've gone from North America to Africa, from the land of salamanders to the land of side-necked turtles. It's true that land animals probably hadn't even evolved when Avalonia left Gondwana. And it's also true that 150 million years after Avalonia turned its back on Gondwana, all the world's landmasses reunited in the supercontinent Pangea, squishing Avalonia in the middle and allowing some species to disperse across the continental borders. But still, it feels biogeographically potent to now be

Figure 6.4. Saltwater cordgrass, with *Field Naturalist* students spotting birds in the salt marsh.

standing on a chunk of original Gondwana when essentially all of my life, save for a brief honeymoon, has been strictly Laurasian.

TO THE MARSH

At last I reach the water. Forgetting about rocks, this spot is a Mecca of its own, well worth the pilgrimage for any inhabitant of our valley (fig. 6.4). In rapid succession a cormorant, a Cooper's hawk, and a great blue heron fly past me over the water. A blue crab tiptoes across the bottom of the boat launch, partially obscured by the red surface reflections of my canoe that now floats in the water. Standing on shore, I give the canoe a hard push and jump onto the stern all in one motion. I sidle down into my seat as the boat and I drift away from the mainland.

Figure 6.5.
(a) Greater yellowlegs, and (b) tracks near where I landed my canoe in the marsh.

We cut across a channel as wide as a six-lane highway to a flat, grassy expanse on the other side. As the canoe and I approach, snails crawl across a flat mud shelf near the waterline, and I see tracks of a shorebird that I guess to be greater yellowlegs—they have the classic “game bird” foot morphology with three straight toes toward the front and one barely registered nub out the back (fig. 6.5).

Working our way a bit north, we find the mouth of a little meandering creek, about the width of a two-lane road. The tide is just barely beginning to come in, and this slight current helps move us up-creek. Bands of colors line the banks. Two-foot-high mud walls, dark brown, display exposed roots and a network of holes. On top of the mud walls stand erect grasses, three feet tall, dingy yellowish at the base and bright green on top. When your eye is at exactly the right level, a thin white stripe of salt cuts high across the grasses, marking the top of a very high tide.

We round a bend and find a tiny inlet off of the creek, just wide enough to squeeze the front of the canoe into. Behind the inlet is a long, straight channel lined with *Phragmites*—common reed. Fiddler crabs flee across the muddy banks, diving down holes as the canoe wedges in. I scramble up the steep mud slope, clinging to tall grasses and scattered logs to keep from sinking, wrestling to keep my boots from being sucked into the muck. Once I'm up the bank, the land is flat and firm. Next I drag the canoe up, hauling it a dozen yards over land and lashing it to a big piece of driftwood. High above me I catch the white-and-black markings of a flapping osprey.

It's a beautiful morning out here, despite the lack of salamanders. It's not the sun or the bedrock that keeps salamanders away; it's salt. Put most salamanders in salty water, and osmosis will suck water out of their bodies, right through their sensitive porous skin. Out of around 700 salamander species worldwide, only about a dozen have adaptations that allow them to tolerate brackish water—and they do so by raising their internal saltiness to compensate for the increased saltiness of their environment. But today the primary vertebrates here with me seem to be birds—the last lineage of the dinosaurs. A great egret, bright white in the morning sun, now skims across the grass, gliding downward for a landing (fig. 6.6).

As I wander through this flat expanse, patterns begin to emerge (figs. 6.7–6.9). The plants are not uniform. There are patches of red, green, yellow, brown, and tan. There are sections where the vegetation is tall, short, and even absent altogether. Some of the species seem to swirl together, like a van Gogh sky. Occasional straight lines cut long gashes through the canvas.

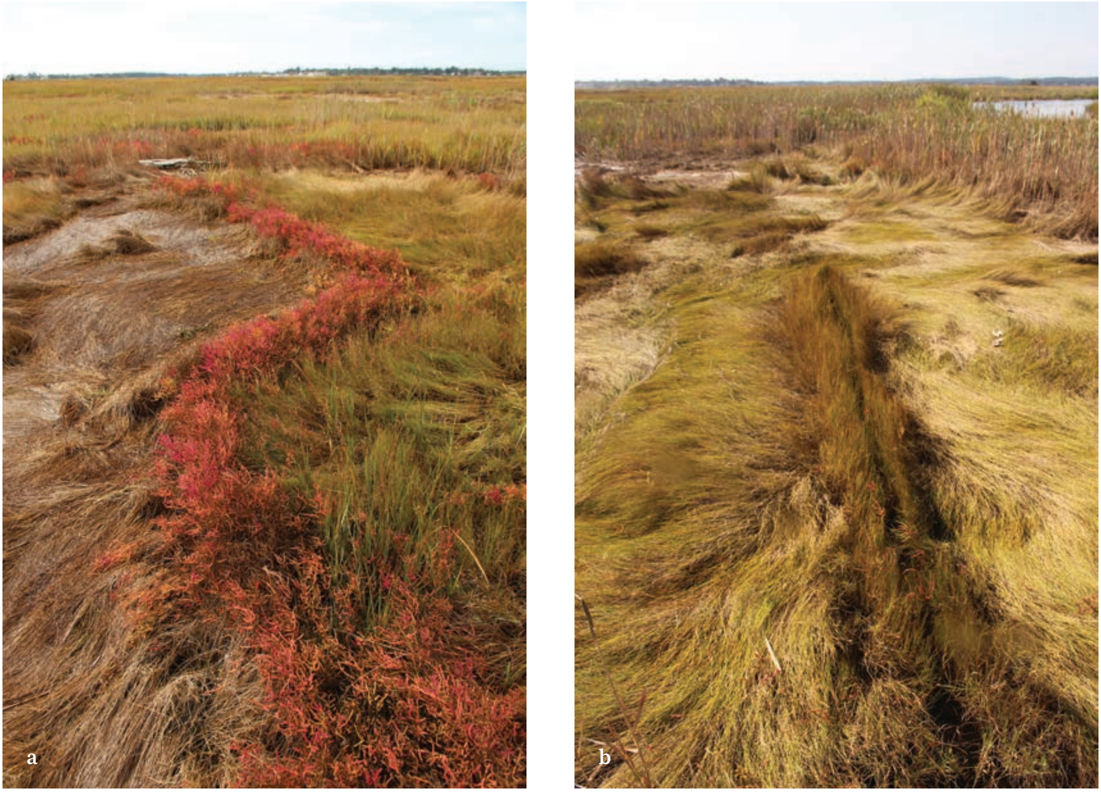
The burning question in my mind today is, "What causes these patterns?" I've come with two words in my head, "zonation" and "disturbance," but the theories hinted at by these pieces of jargon don't seem to fully capture what I see here (fig. 6.1).

The plants are not uniform, and they're also not random. For

Figure 6.6. Greater egrets and snowy egrets in the marsh.

the most part, I'd call them "clumped." Whether or not things are arranged in a random fashion tells us something about the processes at work—so it's useful to develop an eye for randomness. If you look at a little patch of the night sky, say, right around the North Star, the arrangement of stars is basically random. But if the patch of sky you're looking at includes the Milky Way, other galaxies, or star clusters, then you'll notice a clumpy distribution of stars. Like cows at watering holes, things that are clumped have some affinity for each other and so tend to cluster together.

If things tend to avoid each other, they will also be nonrandomly distributed, but in the opposite way from clumpy distributions. They will be evenly spaced, or overdispersed. Consider trees in a forest—trees don't want to grow too close to other trees, so they tend to be spaced just far enough apart to let their neighbors grow. On the bottom of a pond, frog tadpoles will often clump together as they munch down dense patches of algae. In the same pond, the carnivorous salamander larvae will be evenly spaced along the bottom, each defending her own little hunting ground.



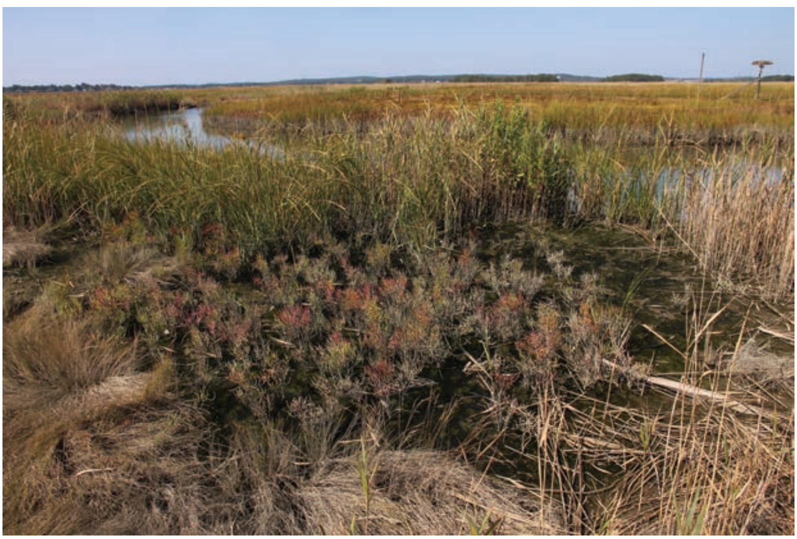


Figure 6.7. Patterns in the marsh: (a) wavy lines, and (b) straight lines with changing vegetation height.

Figure 6.8. A muddy patch in the marsh.

Figure 6.9. Aerial view of the chapter site showing many patterns.

As an inlander, I don't really know much about coastal systems. Luckily, there are only a few dominant species here to keep track of: smooth cordgrass (*Spartina alterniflora*), salt marsh hay (*Spartina patens*), black rush (*Juncus gerardii*), marsh elder (*Iva frutescens*), and common reeds (*Phragmites australis*). These are the characteristic plants of this natural community—the salt marsh. Salt marshes form within the intertidal zone—where the daily fluctuations in water levels alternately submerge the plants and then abandon them to the drying air. And they only form on parts of the coast that are protected from the violent ocean waves.

I look up at the crescent moon in the blue sky and imagine a line connecting the endpoints of the crescent, extending down to the horizon. This is a navigation trick: where that imaginary line hits the horizon is, more or less, south. On the horizon south of here, barely visible in the chapter-opening image, is a thin line of elevated land far in the distance. This is Long Island, a big pile of debris—the terminal moraine—dumped at the end of the glacier that once sat here. As the glacier retreated, it left behind an island of rubble that now protects us here in the Long Island Sound from harsher ocean waves, helping this estuary to thrive.

More than just sheltered by the Sound, this salt marsh is protected from waves by the Connecticut River. We are just inside the mouth of the river, hiding in part behind a mound of fine sediments dumped by the river—the river's delta. The spot where we are standing is part of a much broader estuary—where fresh and salt water mix—extending up the river.

Besides protecting this spot from waves, the mound of sand may have saved the river from development. The shifting sands, continually renewed by the glacial sediments washing out of the Connecticut River Valley, historically made it tricky to navigate big boats into the mouth. So, unlike every other major river in the region, we didn't build a huge port city at the mouth. Instead the estuary was left to function largely intact. Today this whole estuary is officially listed under the international Ramsar Convention treaty as a "wetland of international importance," supporting critical breeding ground for many fish, birds, and other creatures.

Salt marshes are often lauded as the most productive ecosystem on Earth. Per square foot, these plants produce more biomass than anywhere else. I've heard this said a lot, but I've never fully understood it. I'm told it's because there are a lot of nutrients here. But why are there a lot of nutrients here? How did they get here? I need to go track down a biogeochemist who can spell it all out for me.

LUNCH

Hungry, and with many questions on my mind, I head for a huge log—a whole tree carcass that has washed in—to find a seat for lunch. As I walk toward my lunch destination, I wonder, could

Figure 6.10.
Predated crab.

that tree have once grown on Rainbow Beach before the undercutting river dropped it and floated it all the way here? Eventually, anything—stick, stone, hat—plucked by the current up there would have to pass by here. Stepping forward through swirling salt hay, I notice for the second time today an empty broken carapace from a small crab sitting upside down in the grass, far from the water's edge (fig. 6.10).

Above me a monarch butterfly drifts along—one more in a steady drumbeat of monarchs that have been passing overhead all morning. One at a time, with long minutes in between, the orange flecks in the blue sky are all heading in the same south-southwest direction. Using their hardwired ability to tell compass directions from the sun, how many will make it to the wintering grounds 2,500 miles away in the forests of southern Mexico? Did any of these individuals flying over me start their lives in the milkweed plants growing in my yard a hundred miles north? How do caterpillar-sized bites of leaves possibly contain enough energy to justify such an enormous journey?

Figure 6.11. Gull pellet with crab parts.

I reach the log and have a seat, trying to avoid the many white streaks and splats painted on by birds. Wedged into a crack in the wood is an irregular mass, about as big as the end of my thumb (fig. 6.11). Looking closely, the mass holds a mosaic of small, colored, sharp-edged fragments—blue, brown, pink, lavender, orange, gray, yellow—mixed with a few pieces of grass and coated by a shining layer of mucus. The fragments have the same speckled texture as the crab carapace I stepped over in the grass. In fact, these fragments may be the missing parts of that very same crab.

Earlier this morning a gull plucked the crab out of the shallow water and flew it over to the flat, low grass. There the gull flipped the crab and swallowed the choicest bits, including much of the underside shell and a few stray pieces of grass. The crab bits slipped down the gull's throat into the first part of her stomach, where digestive juices started breaking down the meat. Then the meal traveled to the gull's gizzard, where the sandpaper walls, assisted by small rocks stored just for this purpose, further pulverized the crab. But some of the hardest parts of the crab refused to be broken down. These hard fragments were compressed into a tight ball and pushed back up. The gull, standing on this log, pumped her neck, shook her head, and puked up this pellet.

Despite the prevalent belief that only owls make pellets, making pellets is a normal part of eating for most birds. Indeed, many other dinosaurs made pellets as well. It's just that owl pellets are particularly good for school children to dissect. Owls, having weak digestive juices and the tendency to eat their prey whole, often expel pellets from which you can reconstruct the entire prey skeleton. Plus, because of their size and charisma, owls make large pellets that are easy to find, easy to work with, and easy to get excited about.

PESTS

Perhaps the pellet was made by the same gull that now shifts nervously, eyeing me from the tall wooden nesting platform behind me. Similar platforms are scattered all across the marsh. They are intended not for gulls but for osprey. Osprey, the giant raptor whose wingspan can reach almost six feet. Osprey, the graceful flier who hovers in place with bent wings, high above the water until it spots a fish, then dives in for the kill. Osprey, the specialized hunter who sinks her talons into the meal, gripping on with uniquely barbed foot pads and reversible toes, then angles the load aerodynamically forward as she thrusts the still-wriggling fish through the air. Osprey, the globally abundant species that very nearly went extinct.

It was in this very spot where, sixty years ago, Roger Tory Peterson first documented the collapse of the osprey populations. Spurred on by the work of Rachel Carson, Peterson and his disciples ultimately traced the osprey decline to the popular insecticide for which Paul Hermann Müller won the 1948 Nobel Prize. In 1935 Müller started his search for the perfect weapon against insects. In 1939, after trying 349 failed chemicals, he finally placed a fly in a cage with DDT. The fly died. DDT went on to international fame, reducing populations of pest insects and helping in the fight against diseases like yellow fever and malaria. Crops, livestock, people, houses, and wetlands worldwide were all dusted with DDT.

Here on this estuary, as on many other estuaries, DDT was sprayed indiscriminately from low-flying planes in the middle of the twentieth century. The target was the salt marsh mosquito, whose larvae are specially adapted to live in the salty standing water that collects in small pools in tidal marshes. This aggressive mosquito bites both day and night, carries diseases such as Eastern Equine Encephalitis, and can fly up to forty miles from her breeding ground to badger inlanders who never set foot near the coast.

DDT worked wonders on the salt marsh mosquito. And globally, DDT worked wonders on many other mosquitos. By 1961 DDT had been used to eradicate malaria from thirty-seven countries, including from the United States.

But the DDT miracle turned out to be short-lived. In large tropical countries abounding in mosquitos, a tiny fraction of the mosquitos happened to have genetic mutations that allowed them to survive encounters with DDT. While most mosquitos crumpled and died around them, these mutant mosquitos thrived and multiplied. In evolutionary terms DDT exerted a new selective pressure, and the mosquito populations adapted. Having lost much of its potency, DDT could no longer be relied on as the ultimate cure for the disease epidemic. It was the overuse of DDT that caused its loss of potency—had we been more selective about which mosquitos we targeted for spraying, resistance would have evolved much more slowly in mosquitos, and perhaps we would have had better long-term success in eradicating malaria.

Though DDT's effectiveness waned, the chemical compound itself persisted. It clung to the small particles of clay and sand in the soil. It worked its way into the sediment layers. It was consumed by the microscopic plankton floating in the water column. Inside the plankton, DDT clung to the creatures' fat, even as other food byproducts were expelled. Filter-feeding clams and fish consumed these DDT-laced plankton. Again, DDT clung to the fatty tissues of the clams and fish, becoming ten times more concentrated as it refused to let go. The DDT then took another step up the food chain when bigger predatory fish and omnivorous crabs feasted. Once again the DDT became even more highly concentrated.

At last seagulls and ospreys swept down and ate the crabs and big fish. These top predators, with concentrations of DDT hundreds of times higher than the concentrations of DDT in plankton, suffered. Their cognitive functions declined. Their immune systems declined. Their reproductive abilities declined. And, most obvious to human observers, their eggshells thinned to the point that they cracked too early.

In 1940, 400 ospreys nested here in the Connecticut River estuary. By 1970 there were only 16. DDT and the equally toxic compounds that it breaks down into, DDE and DDD, can last for many decades out in the marsh, poisoning not just the birds but all the big fish and mammals high on the food chain. Erecting nesting platforms, conducting scientific studies, and lobbying politicians to ban DDT, a handful of ecologists like Roger Tory Peterson, Rachel Carson, and Paul Spitzer fought to save the osprey. And they succeeded.

By 2010 there were once again over 450 ospreys breeding here. Staring at these nest platforms in front of me, I wonder, did Roger Tory Peterson—inventor of the field guide, leader of the twentieth-century environmental awakening, muse of the global birdwatching movement, Presidential Medal of Freedom recipient, two-time Nobel Peace Prize nominee, and self-described "hermit who lives up in the woods"—personally erect these very ones?

It's important to keep in mind that Rachel Carson and other environmental pioneers never sought a complete ban of DDT—nor has it ever been completely banned. Rather, the point is to use it wisely and selectively so that its potency is maintained. Where a serious public health risk exists, most agree that DDT should be used. But instead of spraying it across every cornfield, residential garden, pasture, and swamp, spray it inside houses and at targeted breeding sites in malaria-prone areas. And instead of relying on DDT as the only answer and a magic solution, look to the other tools in our toolkit. Use a variety of insecticides, consider new technologies like the genetic engineering of mosquitos and fungi, and rely on old-fashioned approaches, like eliminating standing water where mosquitos breed.

FARMING

Long before DDT was popularized, people were fighting to eliminate mosquito habitat from this salt marsh. Regularly spaced ditches, dug in long lines throughout the marsh, allow fish to swim up and eat the mosquito larvae living in marsh-top pools. More to the point, these ditches act like reverse irrigation to drain the water out of the pools so there's nowhere for the mosquitos to breed. Normally, at low tide, water stuck in the middle of the marsh would have to percolate sideways through hundreds of feet of marsh to get back out to the open water. That's a slow process and would hardly begin before the tide came back in again and refilled the pools. But if every spot on the marsh is at most a few feet away from an open trench, the water rapidly drains away. The water table drops, and pools no longer sit on the surface. Mosquito larvae dry out. But so do the plants.

Although the vast majority of the ditches in northeastern salt marshes were dug as a part of the economic stimulus policies in the 1930s, nominally for the control of mosquitos but really just to create jobs, some parts of these marshes had been cut with ditches for hundreds of years. And it wasn't all about mosquitos. Hay made of various salt marsh grasses—salt hay—is a prized commodity. Livestock love the salty taste, and seventeenth-century colonists would graze their cattle on salt marshes to cure sick animals. Farmers learned early that draining water from the marsh helped improve conditions for growing, harvesting, and grazing of salt hay. Today, more than 90 percent of the marshes in southern New England are striped with ditches.

If I'm really going to talk about the salt hay economy, I don't want to just read and write about it. So I recently ventured out to my local garden store and asked for a bale of salt hay. The old gardener behind the counter informed me that their salt hay comes from Boston's North Shore, where it's not a National Seashore, and so farming there is still legal.

Salt hay has a high value, the gardener told me, because it lasts years longer than regular hay before it rots, and, most significantly, it won't introduce weeds to the garden you're mulching. All bales of hay contain errant seeds from the grasses, clovers, asters, and other plants swept up in the bale. But the plants in the salt hay bale require salty conditions to sprout and thrive. The various salt grasses, the sea lavender, the seaside goldenrod, and the seaside aster pose no threat to my inland garden.

A burly staff member walked me out back to the shed where a forklift held a few of the treasured bales. Little dark seeds protruded from the bundle, and I recognized them from the salt marsh. Priced at $14.99, $3.00 more than a regular bale of hay, I bought one. Driving away, the sun in my car warmed up the bale, releasing a thick briny smell into the air. At home Juno and Alder were thrilled by their new present, which they decorated with flags, pretended was a horse, then smelled long and hard to see if they could pick up the scent of the coast.

WAITING

I finish up my lunch on the log, but I'm in no hurry to move. I arrived at low tide, and now I really want to see high tide, which isn't until 3:00 PM. I've seen the marsh at its driest, and now I want the tide to roll in and soak me and everything around me, lifting my canoe off of the dry land. To have this experience, there's nothing left to do but wait.

It strikes me that as I've revisited my field sites for this book I've always been in a hurry. I'm working on a deadline to capture images and write a story before the seasons slip past, all while finishing up languishing academic papers and attending to the needs of my two children. If I sit back and take my time to do anything, a swarm of guilt, like a million salt marsh mosquitos just waiting for me to stand still, will bear down on me.

It's the typical pace of modern life. I raced out to Bark Hollow. I squeezed in quick visits to Maggie's Forest. I ran through the Great Swamp. I paddled hard by Rainbow Beach. Having been to each place before, I already knew the patterns I'd come to document, and I just needed to snap some pictures and get out of there. If I'd been living life at such a pace years ago when I first visited those sites, I never could have found the stories in the first place. To learn the unexpected, you've got to sit back, open your eyes, and let the patterns talk to you. I wonder how many new patterns I missed this year as I raced through the sites? Wasn't this whole project really just an excuse to experience nature at the pace I enjoy?

Here the tides are out of my control, so the guilt doesn't land on me. Happy at blaming the moon, I pull out my ukulele and strum a few chords. Hours pass, more birds and butterflies fly over, but not much else happens. High tide should be coming soon, but still the water doesn't seem to be anywhere near me.

My mind wanders to the crescent moon that was peeking though the trees last night before I tucked the kids in. And then it hits me. In my haste to assemble my gear and find a window in my life long enough to slip down to the coast, my planning had been negligent. I should have taken the kids on that moonlight wander in the woods after all. Sitting here on this log, my feet aren't going to get wet today.

LIFE EXPLODES

I get up off the log and wander over to the edge of the ditch to see if the water is still rising. I poke some tiny sticks in the mud at the waterline and then wait a few minutes. The sticks are now an inch down from the waterline. Indeed, the water is still creeping, ever so slowly, up into the marsh.

Although not much has changed back by the log, there are definitely big changes over here by the ditch. All the creatures have come to life. I see fish chasing blue crabs under water. A tiny flat crab crawls under my boot. Ghost shrimp race back and forth (fig. 6.12). The fiddler crab holes are now completely under water. Moon jellies drift by.

As I witness this explosion of life, it's clear that salt marshes really are extremely productive. The banks of the ditch seethe with crustaceans. I try to form the analogy between this marsh and the upland forests I'm used to. Instead of earthworms and millipedes on the forest floor, it's crabs and shrimp. Instead of oaks and pines, it's cordgrass and reeds. Is this place really so different from Bark Hollow?

Well, at Bark Hollow the plants are duking it out over calcium and magnesium. As the mountain rocks break down, these elements and a host of other macro- and micronutrients infuse into the forest soil where the roots fight over them. But almost as fast as the nutrients emerge from the rocks, the spiteful rain pours down and whisks away the calcium, magnesium, and anything else it

Figure 6.12.
Ghost shrimp.

can carry. Full of nutrients, water seeps through the ground, tumbles along tiny surface rivulets, creeps into streams, cascades into pools, and rushes into a small river that at last joins a large river. And where does that river lead? Here.

It's quite the pilgrimage that each nutrient atom has taken to get here from the uplands to the sea. Tumbling down the waterways, an atom of phosphorus spirals between two lives. Sometimes she floats freely as a dissolved phosphate, rushing down with the current. Then some organism gobbles her up, and our phosphorus atom lives for a while bound in nucleic acid, ATP, or another molecule. As she is passed from critter to critter, she doesn't move far downstream. Then she's excreted, or her host dies alone, and she returns to a free-floating life, headed for the sea before being captured by another creature. She's not alone. Nitrogen, carbon, sulfur, calcium, magnesium, potassium, iron, chlorine, and many more nutrients spiral downstream alongside her.

As I stand in this marsh, these nutrients swirl around me at the edge of the ocean. The ocean is the repository for all that's leached from upland soils. That's why it's so salty. And that, it suddenly hits me, may be why the salt marsh is so productive. The roots have access to the vast stores of nutrients washed down to the ocean—not to mention the nutrients deposited with the river-borne muck trapped by the tangled marsh. These are the nutrients that water stole from all the mountains, hills, and valleys in the other chapters of this book.

As I watch ghost shrimp float up and down in the ditch, I'm aware of the three-dimensionality that water provides life. Along every submerged stem in the marsh is a fleet of microscopic organisms—algae, bacteria, fungi, protists, viruses, and decaying matter—the periphyton. This layer forms a little factory that efficiently recycles local wastes and captures nutrients as they float by. This supports the plants and provides nutrients up and down the stems in a way that wouldn't be possible along the stem of a plant on land.

Why aren't land plants surrounded by such active living coats? For one thing there aren't as many nutrients floating in air as there are in water. But mainly it's because if these periphyton organisms tried living on the stem of a sunflower, they'd dry out. Of course, *water*. The most important nutrient. Second only to shelter on the list of survival priorities. It's needed for photosynthesis. It's the way we move molecules inside our cells and throughout our body. It's the basis of all life.

Sure, calcium and magnesium help determine which plant species grow on which patch of land, but they don't really have a big effect on the overall productivity of the land. Water, more than all those other nutrients, is the factor that most limits the growth of plants on land. Water itself is the reason marshes are so productive.

At last I think I get it. Of course this is one of the most productive ecosystems on Earth—it's rich with water and mineral nutrients stolen from the uplands. I guess I won't need to track down a biogeochemist after all. But I still need to come back here—under a different moon.

TIDAL FORCES

I look over to the part of the marsh where Olivia choreographs the other *Field Naturalist* students in an impromptu dance about the tides. One student is the moon, one student is the sun, and one student is Earth. Oh, and it's Halloween, so the moon and Earth happen to be wearing appropriately colored animal suits—tiger orange moon and blue bunny Earth. The outstretched arms of the Earth-student reaching toward the moon are meant to be the tidal swell in the oceans. As the Earth-student spins on his axis, his arms stay aimed at the moon-student slowly tracing her own orbit.

The yellow sun-student also exerts a tidal pull on the Earth-student, though only about one-third as strong as the moon's. When the students are standing in a line, the tidal arms reaching toward the moon are also aimed right at the sun. This is when the pull is the strongest, and thus the tides are the highest. At these times the moon is backlit by the sun, and Earth sees a new moon. When you look to the sky and see the moon near the sun, looking like just a little sliver—which my seven-year-old self decided was the "snag" of the fingernail I'd thrown out the window on our family road trip—tides will be extreme.

This all seems intuitive—that every time the moon passes overhead, a high tide will follow as the moon pulls the waters upward. But that's only half the story: generally, there are two high tides every day, not one. One of these high tides is on the opposite side of Earth from the moon. You can picture two bulges in the oceans on opposite sides of Earth circling daily. The Earth-student really needs to have his two arms always projecting in opposite directions from each other—one to the moon, one away.

Though the moon's gravity pulling water up toward it seems easy to believe, I find it hard to believe that there's a tidal force pushing water up on the opposite side of Earth. Professor Kannan Jagannathan recently set me straight on this, declaring, with a grin, that "tidal forces are real, whereas gravitational force is not real," at least according to Einstein's theory of relativity.

To understand tides I traveled back to my old college physics department. I was aiming for 10:00 AM, to catch an old tradition wherein the department faculty and staff come together to sip coffee and trade stories. The first thing I noticed was that the smells hadn't changed. I cut through the newer biology building, still packed with the scent of modern finishing materials that I had expected to fade years ago. (Is it the linseed oil in the linoleum flooring, some glue in the wood laminate, or some other composite material?) Then I passed into Merrill, the old brick behemoth that houses physics. Merrill smells of stone dust from the walls and greasy vapors emanating from a massive underground mechanical room whose door is often ajar, inviting mischievous undergrads like me to sneak through like a stowaway on a military submarine.

Morning coffee is held in the machine shop, where I once fashioned aluminum screws and clamps to help measure the electric dipole moment of the electron. I opened the door to the machine shop and was overpowered by its familiar oily smell. I found the machinist, Dan Krause, alone with the coffee. When I was an undergrad twenty years ago, Dan had already been there for decades. Now retired, his red hair had turned white and thin, but he still had the familiar habit of smoothing his hair by slowly running his two hands in synchrony from his forehead over his scalp and down the back of his head.

I asked Dan why no one else was at coffee. With his hands he mimicked texting on an imaginary iPhone and said that everyone is now so busy communicating on their devices that no one wants to sit and chat. Dan then lamented that even the new machinist, though superb, tends to program instructions into a computer rather than manually steer the metal lathes. In the sea of old machines, one smell not still in the air—in part because I'd stayed up until 4:00 AM cleaning it off of every surface in a corner of the lab—was the exploded beer bottle I'd tried to cool with liquid nitrogen one evening.

At last I found the open office door of Professor Jagannathan, affectionately called Jagu. In a red-and-white plaid shirt, Jagu's lanky frame was hunched over his little MacBook. I hadn't told anyone I was coming, and he sprang to life when he saw me.

Imagine three parts of Earth: the water in the ocean on the point closest to the moon, the solid body of Earth, and the water in the ocean on the point farthest from the moon. The water on top of Earth sloshes around, but Earth itself moves as one big rock. To simplify things, Earth itself can be represented by a point right at the center.

The force of the moon's gravity is strongest in the places that are closest to it. So the water closest to the moon is pulled more strongly toward the moon than Earth itself. This explains the high tide when the moon is overhead—all the water on the moon-side of Earth rushes and squeezes over trying to get closer to the moon and piling up underneath it.

On the far side of Earth, the moon is pulling more forcefully on Earth itself than on the water. In essence the water is staying still as the moon rips Earth further away from underneath. On the moons of Jupiter, this tidal ripping force is so strong that it powers massive volcanoes and earthquakes. Near black holes, it can shred stars into spaghetti.

But that explanation, as Jagu tells me, only works if you're someone like Isaac Newton who believes in gravity. If you are in an elevator, freely falling through a bottomless shaft, you wouldn't experience gravity. Hold out your left hand and drop a stone. It won't seem to fall. Instead, the stone just floats in front of you. You, the stone, and the elevator are all falling toward the center of Earth together. That's why Einstein says gravity isn't real: your experience of it depends on your perspective.

Still falling, now reach out your right hand and drop a second stone. Both of those stones are now falling toward the center of Earth. If you draw a line from each stone to the center of Earth, they won't be exactly parallel. There will be an ever-so-slight angle between them. As you and the stones fall together, look very carefully, and you will see that the stones will drift toward each other as they travel their separate paths.

This effect doesn't depend on your perspective. Whether you are standing on the thirteenth floor waiting for the elevator, or you are hurtling to your death with the stones, you will see that the stones are getting closer to each other. The difference in gravity experienced between two places—between the stone in my left hand and the stone in my right—is what Einstein calls the tidal force. In Einstein's theory of gravity, only these tidal forces exist, and they describe the geometry of space-time itself, which is warped in the presence of massive bodies like Earth and the moon.

So then. If you are Earth, holding the Atlantic Ocean in your left hand and the Indian Ocean in your right hand, with the moon high over the Atlantic, what do you feel? Every part of you is pulled toward the moon; however, because the moon is on your left, that hand is pulled moonward more strongly than your right. Floating freely in space, you don't actually feel the moon pulling your body at all, just as a skydiver doesn't feel Earth pulling her downward—she just falls. But as a celestial body holding an ocean in each of your hands, what you do feel is your left and right hands getting stretched apart, as if pulled in opposite directions. You feel the *difference*. The tidal force. The force that powers volcanoes on the moons of Jupiter. The piece of gravity that Einstein believed in. You feel your two handfuls of ocean pulled out away from the core of your body—and this is the reason that two tidal bulges rise up on either side of Earth. And this is the reason that each day on the marsh brings not one, but two high tides.

This is the simplified version of the tides. To be precise you have to add in the sun—whose tidal forces are weaker only because the sun is so much farther away from us than the moon, so the difference in gravity from one side of Earth to the other is much smaller. And beyond the sun, there are all the complexities of our shorelines, underwater topography, the latitudinal change in the moon's orbit around Earth, and other factors, like the lag between when the moon is overhead tugging at our waters and when the tides actually catch up to us many hours later. Travel the globe and you will find that these contributing forces vary widely from place to place.

When my friend Chelsea was working in Antarctica, she experienced just one high tide per day. When Sydne and I were rescuing whales in New Zealand's Golden Bay, I remember the tides rushing in like a fast-moving wall. In Canada's Bay of Fundy, daily tidal fluctuations can be over fifty feet because the moon's orbit matches the natural frequency of waves sloshing through the bay and connected waters. Like pushing a child on a swing, mother moon pushes child water through the swing bay with perfect timing to reach huge heights. Complexities abound. But in general, if you look up at the moon, you can make a reasonable guess about how the tides will behave.

THATCHED ROOF

After explaining the tides Jagu invited me to lunch with the other faculty, but I had to run off to meet Charley so we could teach an animal tracking course. As I walked back through the familiar smells in the physics hallways, I wondered what others thought of the smells emanating from me that last summer I worked in the lab. No one ever complained, but, that summer, I slept half a mile into the woods behind Charley's house in a shelter known by the Algonquian-derived word "wigwam"—a word that in some contexts has been used in a derogatory way but in its strict sense refers to a particular architectural form framed by saplings (fig. 6.13). I committed to a completely rustic sleeping experience—I left matches, flashlights, and all other electronics in the physics lab or in my car. I used friction to start all my fires under the cooking stone. I bathed only in the tiny stream nearby.

Often I would get out of the physics lab after dark and have to feel my way through the woods to the wigwam. One moonless night was so dark I couldn't see my hand in front of my face. The only light came from the occasional glowing fungus on branches lying on the ground. I crept along in bare feet, using my ears as much as my soles to follow the trail. Because the leaves on the trail were compacted, the sound of crunching was often the first sign that I'd made a wrong step. But the wigwam was about 200 feet off of the trail, on the far side of a small hill. I blindly abandoned the trail where it seemed right and stumbled through the forest.

After a long time away from the trail, I finally caught a whiff of the wigwam. Smokey, musty, unlike anything else in the forest. I put my nose in the air and walked upwind toward the scent. When the scent got weaker, I would turn toward where it was stronger. If you could see smells drifting off of an object, the plume would look like an expanding cone. Animals find the source of a smell by zigzagging back and forth working their way up the cone.

Decades ago entomologist Jeff Boettner used to rear spongy moths in his laboratory, and he worked so closely with them that the spongy moth pheromones stuck to his clothes and got into his system. For many years afterward, Jeff smelled like a spongy moth, and free-flying spongy moths would seek him out. Standing in line at an ice cream stand one day, Jeff caught a glimpse of a lit-

Figure 6.13. Wigwam (sapling hut) insulated with common reeds.

tle moth on the other side of the street searching for a mate. The moth was downwind from Jeff. It flew first to the left, then to the right, slowly making progress upwind. He decided to have a little fun with the unsuspecting people around him. Beckoning with his finger, Jeff whistled loudly as if the moth was his dog, and he called out, “Come moth! Here mothy moth!” The people watched, wide-eyed, as the moth steadily advanced until it was right on top of him. Then he clapped his hands loudly and said, “Enough!” His hand claps mimicked the sound of a predatory bat and the frightened moth flitted away. Then Jeff called him back. “I’m sorry mothy, you can come back. Come back mothy!” And the moth came back. Again, Jeff clapped the moth away, and then again, he called the moth back. The slack-jawed ice cream eaters were stunned.

Working my way toward the smell of the wigwam that night, I didn’t quite succeed. At some point the smell was so overpowering, I couldn’t tell which direction it was coming from. Moth antennae are shaped like old-fashioned radio antennae and, like the independently smelling nostrils of dogs, are built for telling the direction that a smell comes from. My nose isn't. Exhausted, I lay down and slept in the leaves. A few hours later I woke up to a forest flooded by moonlight. There was the wigwam, fifteen feet in front of me.

A Woodsy Club project, the wigwam stood about eight feet tall and was about ten feet in diameter. Over a few weekends we bent saplings, peeled bark from a fallen basswood, and dug an underground vent to feed the fire. It was covered with a foot-thick shaggy layer that gave the wigwam an endearing look and that was the source of its distinctive smell. This gray-brown fur was harvested from a roadside wetland next to our local Target and, like traditional thatched roofs around the world, was made entirely of common reed, *Phragmites australis* (fig. 6.14).

Reeds act as an invasive species, and as we cleared several truckloads of the brittle stalks from the Target wetland, we hardly made a dent in the population. After we were done the wetland looked like the same dense monoculture of reeds as when we started. For the last 150 years, reeds have been invading wetlands across North America, altering the dynamics and crowding out native species. But common reeds are a native species. They are found on every continent except Antarctica and have been here in North America for at least 40,000 years—which is the age of Pleistocene sloth scats found full of reeds.

Although common reeds are native to North America, not all members of a species are the same. For instance, among rare California tiger salamander, a few invasive genes are spreading rapidly throughout the state. These genes, which originated from Texas salamanders imported for their quality as fishing bait, transform the salamander into an aggressive predator taking over wetlands and gobbling up other amphibians. Similarly, in common reed the recent takeover is blamed on the introduction of a European form

Figure 6.14. Common reeds invading an inland wetland.

of the species—although some botanists deem these as two distinct species. Before this introduction our native reeds were somewhat rare and grew at low densities mixed with other species. The invasive strain is stronger, taller, faster-growing, and more adaptable than our native strain. It has spread rapidly. When you see a wetland filled with reeds, it usually is a sign that a wetland is ecologically degraded, like in the Target parking lot. But very occasionally you find the native reed still meekly growing as it once did.

ZONATION

Lost in thoughts, I'm still standing out in the salt marsh waiting for high tide. In front of me is a cluster of what I think may be the native reed, mixed in with marsh elder. Compared to invasive reeds, these reeds are smaller, have redder stems, and grow more sparsely. This reed cluster is concentrated along the edge of the drainage ditch that runs down the center of our chapter-opening image—this is one of the many ditches dug for the purposes of mosquito control or hay farming.

What is this ditch doing to the marsh?

With our salt marshes so extensively assaulted by ditchdigging and hay farming, there's something really remarkable happening—or not happening. In most cases if you go dig up a forest or start farming a prairie, you're going to end up with a lot of species that weren't previously growing there. Some will be the crops themselves—wheat, corn, rye, potatoes. Others will be ubiquitous invaders taking advantage of the new early successional habitat—lamb's quarters, red clover, common plantain, dandelion, and so forth. But in these salt marshes that's not happening. Every plant that I find here seems to be a native species that's lived on this marsh for thousands of years. And in all, there really aren't that many different types of plants growing here.

In a way, the reason that there are so few plants here is the same reason that there are so many. That is, there are few *species* of plants, but many *individuals*—making for a very productive ecosystem with very little plant diversity. It's a pattern you see in many places. While increasing diversity often corresponds with higher productivity to a point, when you get to the extremes of productivity, sometimes you arrive back at something closer to a monoculture. There's a lot of debate among ecologists about when, whether, and why such patterns exist. But one explanation is that the richest environments are also the hardest to tolerate. In such conditions only a few species figure out how to survive, and those that do thrive. Here on the salt marsh, it's the abundance of water and nutrients that makes this place rich—and difficult to tolerate.

I like drinking water, but I can't survive more than a minute or so at the bottom of a swimming pool. Similarly, without special adaptations plants submersed under water will starve for oxygen. Additionally, the bacteria that grow without oxygen in waterlogged soil have a tendency to release chemicals like hydrogen

Figure 6.15. Cordgrass, like many salt-adapted plants, excretes salt crystals through glands on its leaf.

sulfide, organic acids, and soluble forms of manganese and iron, all of which can build up under water to levels that are toxic to plants. And if the water then recedes and the soils dry out again, when these toxic chemicals react with oxygen in the air, they produce a whole new suite of toxic compounds that can further injure the plants.

I also like the electrolytes in Gatorade, but I wouldn't survive drinking only salt water. For a plant dunked in the ocean, the high concentration of sodium and chloride ions can wreak havoc. While chlorine is a micronutrient, needed in small amounts by plants, there's just way too much of it in the ocean (fig. 6.15). The osmotic pressure from the saltiness makes it hard for the roots to soak up water, despite being surrounded by water. Similarly, these ions will interfere with the uptake of other essential nutrients like nitrogen. What's more, the chlorine ions will enter the cells and break down basic metabolic processes by reacting with enzymes and proteins.

Thinking like a salamander, it's bad enough trying to imagine adapting to salty ocean water, but, given a few million years and enough motivation, we could probably figure out how to raise our internal concentration of salts to match the ocean environment. But now you want us to switch rapidly back and forth between environments? One minute we're deep in cold salty ocean water. Then the tide recedes and we're surrounded by brackish river water. Then suddenly we're exposed to the dry air and the hot sun. Any water that's left nearby starts to evaporate and the saltiness spikes. And then once again we're plunged back into deep water. Twice a day we're to handle the fluctuations in salinity, temperature, soil waterlogging, and changing current directions? No thank you.

And one of the most extreme things about northern salt marshes is the freeze-thaw cycle. Expanding ice crystals have the power to break rocks, push glacial till up through farm fields, and certainly to tear plant flesh. It might not be so bad if the ice formed once at the beginning of winter and then melted in spring. But twice a day the plants are dunked back in the water where the ice melts away, and then twice a day the plants are again exposed to the power of ice-crystal formation right down to their cores. These freeze-thaw cycles are why mangroves—the woody equivalent of salt marsh grasses—can't survive at high latitudes.

So back to my first question in this chapter: What creates the striking visual patterns of a salt marsh? If you Google it, you're bound to quickly encounter the word "zonation." Simply put, there are different ecological zones within a salt marsh, and different plants grow in different zones. There's the low marsh zone that is flooded every day by the rising and falling tides. There's the high marsh zone that is flooded only occasionally on extremely high tides. And then there are all the intermediate levels along this gradient. Moving from the lowest marsh up to the highest marsh in order, you pass through zones dominated by smooth cordgrass, salt marsh hay, black rush, and finally marsh elder.

At the core, zonation is caused by the fact that tides are harsh. Each species in the salt marsh has developed some level of tolerance to these harsh tidal conditions, and it doesn't like to be pushed beyond its limits. Imagine clearing out all the plants and then planting the species in the zones lower than the zones they belong in. Try planting salt marsh hay where cordgrass normally grows, black rush where salt marsh hay normally grows, and marsh elder where black rush normally grows. All the plants will die.

The unforgiving nature of the tidal zone explains why so few species grow here. It explains why, after being dug up and farmed, the marshes aren't covered with corn and clovers. And the specialization of these plants for particular tidal zones explains why a bale of salt hay at the garden store is worth a few extra bucks.

In our experiment with moving salt marsh plants around, now imagine moving the species to the zone higher than where they belong. Because they've now moved from a harsh environment to a gentler environment—at least from the perspective of terrestrial organisms—all the plants will live. If we plant cordgrass where salt marsh hay normally grows, it will grow just fine. That is, assuming we removed all the salt marsh hay first. The cordgrass *will* die if we just plant it in amid the salt marsh hay. The reason is that the cordgrass invests more of its energy in dealing with the harsh tidal environment and less of its energy competing with neighbors for space.

Less worried about the tides, the salt marsh hay, meanwhile, builds thick robust root systems that outcompete any cordgrass for the nutrients in the dirt. The same is true for each zone transition on up into the uplands: plants in the lower zone are more tolerant of harsh conditions, whereas plants in the higher zone are better at competing for nutrients.

Although there are a lot of nutrients here, they're not unlimited. In the uplands nutrients were less limiting simply because water was even more limiting. But here, with plenty of water, nutrients—particularly nitrogen—are generally the limiting factor for productivity.

So to add another twist to our experiment, imagine fertilizing the marsh so much that nutrients are no longer limited. Then the ability to compete with your roots won't matter. The most important limiting resource to compete for will be sunlight, and since cordgrass is taller than salt marsh hay, the cordgrass will invade and take over the salt marsh hay zone.

And what does the ditch do? It lowers the water levels, dries out the marsh, and shifts the zones. Cordgrass zones are invaded by salt marsh hay and then black rush. That's why ditching helps the farmers—since those latter two species are the more valuable crops.

Right at the edge of the ditch the effect is dramatic.

When turbulent tide water surges over the lip of the ditch, it slows down and drops any sediments it was carrying right at the ditch edge. This creates a little mound that runs parallel to the ditch. Often this natural levee is built on top of the mound of peat and mud that the Civilian Conservation Corps ditchdiggers of the 1930s dumped from their shovels as they dug. The result is a little spot of very high ground that supports high-marsh plant species at the edge of the ditch, even when the ditch runs through the middle of the low marsh.

And that's why we see a cluster of reeds and marsh elder at the edge of the ditch in the center of this site. Once established on the ditch edge, the reeds can then build the ground up even higher with their extensive root networks. Spreading clonally through sideways runners, the reeds will then creep down and send up new shoots in zones that would normally be intolerable. Still connected to life support from their parent shoots, these new shoots survive, building up their roots and raising the marsh height to a tolerable level, like that of the high marsh.

On this particular day the wimpy tides aren't getting anywhere near the high marsh. To see the whole of the marsh flooded, I'll need to come back in ten days—when the moon is full.

RETURN

Ten days later I'm back. This time Charley, Julia, and Juno are in the canoe with me. Within a minute of landing on the marsh, Julia spots a tiny speck on a glasswort. Glasswort is a funny succulent with stubby round limbs almost like those of a wee cactus. This season much of the glasswort is turning red and grows in little clumps here and there. The speck that Julia spotted on one of the glassworts looks like a miniature dried twig, smaller than a grain of rice (fig. 6.16). Charley and Julia spring into action photographing and collecting. Looking around, the glassworts are covered with these tiny grains of rice. Why all the excitement? They're the larvae of a case-bearing moth, a group of moths that build tiny houses out of silk and found debris. It is likely that this particular species hasn't been documented in the United States before.

Over the past few years, Charley and Julia have been photographing, collecting, and raising hundreds of leaf-mining insects, along with some stem miners. As larvae, these insects live inside of plants, digging tunnels through the flesh. Charley and Julia's home is overflowing with plastic bags and vials stuffed with leaves that house immature moths, flies, sawflies, and beetles. Some are in their refrigerator. Some are in their dark basement. After they dug up whole arrowwood plants to raise tiny, new-to-science bark-

Figure 6.16. Larva of a case-bearing moth that mines the leaves of glasswort.

mining moths, the four-foot-tall potted shrubs sat in their kitchen enclosed in hand-stitched sacks for when the moths emerged and started flying around. When they travel, their car is packed full of living specimens.

Leaf miners tend to be host-specific: each insect species prefers a particular plant species, genus, or family. But these creatures are poorly understood. Generally, if you find a leaf miner on an uncommon plant, there's a good chance it's an undescribed species. That's how Charley and Julia have discovered dozens of new species over the past few years. Want to find a new species? Go somewhere with uncommon plants and look for leaf mines, then plunk the leaves in a Ziploc bag and mail it to Charley and Julia to figure out.

Over the next hour on the salt marsh, in addition to the case-bearing moth, we find a leaf-mining moth in marsh elder that is almost certainly a species new to science, a stem-mining fly in salt-marsh aster that is either a new species or a species never before associated with this plant, a shore fly whose larval stage has never been described by scientists but seemed to be living on the aster Charley collected, and an aphid on sea lavender that Charley has seen in two other places and may be a new species.

As the four of us wander, admiring the patterns, the tide rises high. At last the tide washes over everything. It gets too deep for Juno's boots, and he starts walking around barefoot. It looks refreshing. Inspired, I do the same. Instead of sweating in boots and wool socks, now my feet feel the silky grasses under the cool water.

I point to a pair of dark, reddish lines that cut across the marsh, about five feet apart from each other. They are rows of glasswort. Charley and I debate the significance of the lines. Though Charley and I advertise ourselves as professional trackers, it's Julia who says they are the tracks from where someone drove across the marsh years ago. As soon as she says that, it seems so obvious: the pair of lines continue hundreds of feet into the distance.

So why is the glasswort growing in the tracks? The vehicle created low spots in the marsh—two long ruts in which water pools. At low tide the rest of the marsh is dry, but water still sits in the ruts, evaporating. Water vapor floats off into the air, but the salt stays behind, making the remaining water in the rut saltier and saltier. And because the soils remain waterlogged, the roots are continually starved for oxygen while the anaerobic bacteria are busily producing toxic compounds. Conditions in such areas become so toxic that only the most specialized salt marsh plants can survive, and often no plants at all. Glasswort is a specialist of such conditions. I wonder how many years these lines will last.

Of course, glasswort didn't evolve just for tire tracks (fig. 6.17). A host of natural disturbances can pave the way for glasswort. Somewhere on the marsh a raft of dead leaves from last year's grasses settles in a pile, smothering the vegetation. In another spot a block of winter ice freezes to the marsh, then a storm surge lifts the ice, ripping away the marsh surface. Elsewhere a voracious flock of geese tears up a patch. In all these patches the dominant marsh grasses are killed back, exposing bare dirt. There, glasswort seeds arrive, and the plant thrives until the clonal grasses creep back in and take over again.

When the grasses have been killed by a disturbance, their roots rot away, and this often leaves a hole in the marsh. Or, sometimes, the disturbance itself scours a hole. As in the tire tracks, water may pool here, and the soils may become waterlogged and toxic. In the center of the depression, the toxicity may be too much even for glasswort to handle. This leaves a large dead zone, which might become a permanent, self-sustaining feature on the marsh, known as a panne. Although the center of a panne might be devoid of vegetation, the edges are the most diverse places on the marsh—at least from a plant perspective. Sprinkled around the bare dirt is a sea of wildflowers. Red-stemmed glassworts are joined by purple flowers of saltmarsh false foxglove, pink flowers of sea milkwort, blue flowers of Carolina sea lavender, the tiny white flowers of seaside plantain, and several other species that grow in pannes and disturbed areas of the marsh.

Sometimes the levee formed at the side of a drainage ditch may ironically act to trap surface water right at the ditch edge, forming a little pool that supports panne species. Indeed, in the center of our site, a little red patch of glasswort suggests such a ditch-side formation. But pools of water, which might breed mosquitos and slow down hay balers, were exactly what the ditches were built to eliminate. And in general they succeed. The ditches crisscrossing this marsh have lowered the whole water table and mean that

Figure 6.17. Glasswort in a salt panne.

high-diversity pools and pannes are much rarer here than they used to be. If you drive far up the coast into Maine, where fewer ditches were dug, you'll find many more pannes with much higher plant diversity. Perhaps as sea level rises, the water table in this southern New England marsh will rise too, and pannes will once again flourish.

Unfortunately, the more likely scenario is that the whole marsh will disintegrate in the rising seas. In this way the future might look a lot like the past; 20,000 years ago the salt marshes of New England didn't exist. How did they arise? Our marshes begin with cordgrass. At the leading edge of the marsh, cordgrass builds the marsh by trapping sediment in its roots and stems. Cordgrass is thus the engineer responsible for creating the habitat on which the other marsh species depend. Back when the continental glaciers were melting away, whenever pioneering cordgrass would begin to establish at the water's edge, the rapidly rising seas would push it back inland, leaving behind a marshless coastline. Then about 4,000 years ago, the rate of sea level rise slowed enough for cordgrass to keep pace. Ever since, cordgrass has flourished—expanding New England marshes upward and outward. In response to the slowly rising sea, cordgrass built up deep layers of peat beneath its roots. In this way cordgrass extended the area of the marsh inland as the rising waters slowly inundated the coast; simultaneously, cordgrass stretched the marsh out toward the sea with an expanding bed of peat. In areas where cordgrass was successful in building peat layers up to the high tide level, the drier conditions allowed salt marsh hay to then take over, adding on its own layers of dense peat. Today most of the marsh surface is dominated by salt marsh hay and other higher-zone species.

Salt marsh hay, with its cowlick swirls that typify our coastal marshes, now appears poised to vanish from this landscape. Marsh development all depended on the sea level rising at a slow enough rate for the grasses to keep up. With modern climate change, the pace of sea level rise is accelerating to rates not seen for thousands of years. In response, salt marsh hay zones are reverting to cordgrass, and cordgrass zones are washing into the ocean as the marshes simply disappear.

But compared to 20,000 years ago, the marshes do have one advantage: they're already here. Because the cordgrass doesn't have to start over from scratch, some scientists believe that certain well-positioned marshes may find a way to survive and even thrive under these new conditions by growing upward faster and migrating inland. That is, if human-erected walls don't get in the way of marsh progress.