11

Wild Things

A group of sea otters laze at the edge of Elkhorn Slough. They float on their backs in the steel-gray water, paws folded against their chests, gazing at the small boat steered by ecologist Brent Hughes of the University of California–Santa Cruz. Hughes has documented a profound shift in the slough's ecology, triggered by the otters. Sea otters were nearly driven to extinction by fur hunters in the 1800s, and were gone from Elkhorn Slough for a century. In 1984, when the first sea otters recolonized, Elkhorn Slough's once bountiful eelgrass beds had dwindled to a few small, scattered patches. Now, more than thirty years after the sea otters' return, expanding eelgrass beds grow lush beneath the water's surface, the dense leaves sheltering juvenile fish and feeding an array of invertebrate grazers.

The slough, on the central California coast, is one of the most severely polluted estuaries on the planet. Artificial fertilizer applied to 2.69 million acres of farmland in the neighboring Salinas Valley runs into its waters. The excess nutrient load causes eutrophication. It also fuels the growth of epiphytic algae that thrive on the surface of eelgrass leaves, blocking the sunlight the grass needs and smothering whole beds.

The problem is common in estuaries around the globe, which receive heavy loads of nutrients from rivers draining polluted watersheds. Seagrass meadows filter contaminants from water and prevent coastal erosion in addition to acting as nurseries for fish and invertebrates. These crucial habitats are disappearing. The global distribution of seagrasses has decreased by 29 percent over the last 140 years, and 58 percent of the surviving seagrass meadows are in decline.[1] Nutrient pollution of coastal waters had long been thought to be the main driver of this trend. But in Elkhorn Slough, the eelgrass has made a remarkable comeback even as pollution loads continued to climb. The mechanism of this welcome ecological shift was unknown until Hughes demonstrated that sea otters are the key (Fig. 11.1).

He began to put the pieces of the puzzle together when he went diving in Tomales Bay, an unpolluted estuary to the north. The eelgrass in Elkhorn Slough was lush and green despite intense pollution; in Tomales Bay, where there are no sea otters, the eelgrass was a dull brown, smothering under epiphytic algae. Hughes noticed another difference: The sea slugs, invertebrate grazers that feed

Figure 11.1 Sea otter in Morro Bay, California. Sea otters have been found to have a powerful positive impact in the highly polluted ecosystem of Elkhorn Slough. Photo by Mike Baird.

on algae, were much bigger and more abundant in Elkhorn Slough. “Here they’re like mutant monsters,” he says. He began to wonder if he was seeing the result of a trophic cascade—a chain reaction in which predatory sea otters benefited seagrasses.

Sea otters were thought to be gone from California until a small colony of survivors was discovered on the Big Sur coast in 1938. Under strict protection, the otter population has gradually expanded. When otters entered Elkhorn Slough in 1984, they found a bonanza of easy prey: abundant crabs. The crabs feed on invertebrate grazers like sea slugs and amphipods (shrimp-like crustaceans), which devour the epiphytic algae that can otherwise smother eelgrass. During the otters’ long absence, crabs had become dominant and grazers declined, allowing epiphytic algae to thrive in the polluted water.

“The sea otter is a model top predator,” notes Hughes. “They eat 25 percent of their body weight daily.” Otters need the calories because they lack the blubber that insulates other marine mammals—and due to their voracious appetites, otters can have a major impact on the numbers of their prey. They make very convenient study subjects, because they bring their food to the surface where it can easily be observed. An army of citizen volunteers has been tracking the eating habits of the otters since they returned to Elkhorn Slough; the data show they feed heavily on crabs. When Hughes looked up historical data on otter populations and the expansion of eelgrass beds in the slough, “the pattern matched like a hand in a glove,” he says.[2] He and his colleagues confirmed the trophic cascade hypothesis using laboratory experiments and predator-exclusion cages in parts of the slough.

Hughes was surprised by his discovery. He’d spent much of his graduate education studying algae and had been mentored by scientists who believed that bottom-up forces, like changes in temperature and nutrient concentrations, were the principal explanation for the global decline of seagrasses. Because it wasn't what he was primed to see, "it took a lot to recognize the impact of otters," he says. The trophic cascade in Elkhorn Slough is a classic case of top-down regulation of an ecosystem—where the balance is shifted by interactions among predators, grazers, and plants.

The otter population in the slough continues to climb. "We keep thinking the slough is at carrying capacity," says Hughes, "but the otters keep surprising us." Every eelgrass bed in the slough continues to expand as otter numbers grow. When Hughes and his colleagues use cages to exclude otters from an area, the eelgrass inside the cage gathers a load of epiphytic algae and declines.

During the past five years, otters began to haul out in salt marshes at the slough's edge. Mother otters find the marshes particularly useful as a safe place to leave their pups while they hunt. Few predators capable of taking a pup lurk in the shallow waters of the marsh. There are now generations of otters in the slough who've never swum in the open ocean, once thought to be the species' only natural habitat. Though its waters are murky with human-generated pollutants, Elkhorn Slough now offers a window into the ways of sea otters before European settlement.

A parallel case, illustrating the role of top predators in protecting seagrass beds, has been documented at the edge of the North Sea, on the west coast of Sweden. There, nutrient pollution has steadily increased at the same time that overfishing has led to a steep decline in the population of adult cod, once the major marine predator in the region.[3] More than 58 percent of local seagrass beds (*Zostera marina*, the same species that grows in Elkhorn Slough) have been lost since the 1980s.[4]

On Sweden's Baltic coast, the water is also polluted and eutrophic, and cod stocks have been depleted over the past twenty-five years. Yet there has been no significant decline in seagrass beds. The critical difference lies in the food web of each region. Sweden's North Sea coast hosts an abundant array of small predators, including grass shrimp, gobid fish, and shore crabs, which feed on grazers, releasing epiphytic algae to thrive and smother the eelgrass. In the Baltic, small predators are scarce, grazers are abundant, and the eelgrass survives.[5] Experiments with fertilization of eelgrass beds show that nutrient loading does not cause a bloom of epiphytic algae where grazers are present. Instead, grazers become more abundant, devouring the algae as fast as it can grow.

The results of studies in eelgrass beds in Chesapeake Bay, led by Emmett Duffy of the Virginia Institute of Marine Sciences, echo the Swedish findings. In some experimental plots the number of amphipods, small crustaceans that are dominant grazers on epiphytic algae, was lowered by using carbaryl insecticide. In others, artificial fertilizer was applied. Added nutrients caused a six-fold increase in growth of epiphytic algae, reducing eelgrass growth by 65 percent.[6] Where natural grazer populations were present, they controlled algal growth, and fertilization actually increased eelgrass biomass. The presence of small predators, including fish and crabs, lowered populations of grazers, increased biomass of algae, and inhibited growth of eelgrass.

"What we found is similar to what's been shown in Elkhorn Slough," says Duffy. "The system we looked at had three levels: small predators, grazers, and algae. Hughes went up one more level, with the addition of otters as an apex predator. Depending on the structure of the food chain, the presence or absence of predators may have different impacts on the plants."

Elkhorn Slough presented a rare natural experiment in the return of a lost top predator; the situation in the North Sea, with the decline of cod at the same time that nutrient pollution increased, is a clear parallel. In many other ecosystems, it's more difficult to nail down the shifting balance among predators, prey, and the plants that form the foundation of ecosystems. The Chesapeake, for instance, hosts multiple species of predatory fish, many affected by overfishing, but detailed data on their role in the eelgrass ecosystem don't exist.

Duffy is lead researcher on an international project studying bottom-up and top-down forces affecting eelgrass throughout its range. The Zostera Experimental Network (ZEN) is conducting standardized experiments in eelgrass beds at fifteen sites scattered across the Northern Hemisphere. Researchers tested the effects of nutrient fertilization and of reducing the population of crustacean grazers. The results surprised Duffy.

"We found no effect of nutrient loading alone on the amount of algae," he says. "We did see bottom-up control of amphipods, the small animals that eat the algae. They're more abundant in areas with higher nitrogen loads. That means you do have bottom-up control, but the increase in biomass passes through the algae, and is realized at the level of the animals feeding on it."

The ZEN study also examined genetic diversity within eelgrass beds and species richness of grazers. More genetically diverse eelgrass hosted more small grazers, and more diverse grazer communities seem better able to control algal growth. The findings underscore the need to protect biodiversity in a human-dominated world.

"We've learned over the last two decades that changes in top predator populations, on land and sea, can have a pervasive influence on the rest of the ecosystem," notes Duffy. "We want to have clear water and healthy seagrass beds and marshes. Large predators are very vulnerable to human impacts, and losing them can trigger the loss of these habitats."

The long-held assumption that coastal habitats are shaped only by bottom-up influences arose from classic studies of salt marshes on Sapelo Island, Georgia, done by Eugene Odum and his colleagues in the 1950s and 1960s. Odum focused on the role of physical factors, including temperature, salinity, and the availability of nutrients, in shaping marsh productivity, and saw grazers as having little effect. The idea that only bottom-up forces affect salt marsh ecosystems became a scientific dogma, and was applied to seagrass meadows and mangrove forests as well as marshes.[7]

The first evidence countering the bottom-up model came in the late 1980s, when salt marsh began to disappear from the shore of La Perouse Bay in Manitoba. Robert Jefferies of the University of Toronto documented the process, caused by grazing of large flocks of lesser snow geese on their breeding grounds. The geese grazed salt marsh plants to the ground, then grubbed into the soil to devour the roots, transforming the landscape to barren mud.[8] The habitat change has been longstanding, because evaporation increases in the open mudflat, making the environment too saline for marsh plants to recolonize. This marsh loss in subarctic Canada was driven by human-caused habitat change far to the south. While many of the temperate zone salt marshes historically used by migrating geese have disappeared as a result of coastal development, the lesser snow goose has flourished during its winter migration by feeding in agricultural fields and on golf courses, which are heavily fertilized.[9] Brian Silliman, now at Duke University, and his one-time advisor Mark Bertness, of Brown University, have pioneered studies that show the devastating impact of smaller, less obvious grazers on salt marshes—an effect that can be intensified by nutrient pollution. In one early experiment, Bertness and Silliman fertilized plots of salt marsh on Sapelo Island and compared the growth of areas with and without herbivorous snails. They found that fertilized marsh plants also attracted hungry insects. "About two years in, we went out to the marsh and saw that our experiment was over," remembers Bertness. "Every single one of the fertilized plots had been completely devoured by grasshoppers."

Over the last fifteen years, both Bertness and Silliman have documented a dramatic role of nutrient pollution in intensifying the impact of grazers on salt marsh. When nitrogen is abundant, marsh plants incorporate it into their leaves, producing soft, nutritious foliage that's irresistible to grazers. The researchers have witnessed an intense response from a variety of grazing animals, ranging from insects and snails to cattle in an ongoing study in Chile.

"Fertilize a spot on the marsh and the cattle are so intent on getting to that area that they'll knock cages over, stick their heads through barbed wire," says Bertness. "There's marsh grass all around, but they want the fertilized stuff."

The phenomenon appears to play an important role in the die-off of salt marshes, which has wiped out more than 250,000 hectares[10] of marsh habitat along the Atlantic and Gulf coasts of the US. "The heavy flow of nitrogen and phosphorus into these marshes from upstream cities and farms can trigger a chain reaction that leads to intense overgrazing by marsh herbivores," says Silliman. Native snails alone can devastate tracts of nutrient-enriched marsh plants if predators are not there to control their numbers.

Silliman first became interested in the role of marsh grazers when he noticed a native snail, the periwinkle, feeding on green stems of cordgrass in a Virginia salt marsh. Periwinkles feed mainly on standing dead cordgrass and detritus, and so had been thought to have little influence on cordgrass growth. Silliman discovered that by rasping away at live shoots of grass, the periwinkles created and maintained wounds that were invaded by fungi. In effect, the snails injure the cordgrass in order to farm these edible fungi. In 2002, Silliman published a study that tracked a wave of snails as it denuded a once-healthy tract of cordgrass in only eight months. The periwinkle's major predators—the blue crab and the diamondback terrapin—had been hunted into scarcity, allowing the snail population to expand. "The plants have never seen the kind of increases in nitrogen we're giving them now," says Silliman, whose work has focused on marshes in the southeastern US. Coastal woodlands once absorbed much of the excess nitrogen, but as development accelerates, the woods are cut down and nitrogen availability in marshes skyrockets, increasing by 200 to 300 percent.

Seagrass meadows and salt marshes are among the most effective natural filters for nutrient pollution. The thick growth of plants in these habitats slows the flow of water, causing organic material to settle to the bottom, where some of the carbon and nitrogen becomes locked in the sediment. They also have an unparalleled ability to remove nitrogen, the main nutrient of concern in marine waters, from the ecosystem. Denitrification, the bacterial process that transforms biologically available nitrate into N_2 gas, removes large amounts of nitrogen from coastal ecosystems. Work by Michael Piehler of the University of North Carolina has shown that more than 75 percent of the nitrogen load carried to Bogue Sound, North Carolina, by polluted streams is released to the atmosphere through denitrification. The process occurs at much higher rates among structured coastal habitats, like seagrass beds, salt marshes, and oyster reefs, than in barren mud.[12] Even small strips of remnant salt marsh can make a real improvement in denitrification rates.[13]

The runaway pollution caused by use of artificial nitrogen fertilizers threatens coastal ecosystems around the world. The array of life supported by dwindling marshes and seagrass beds is under serious threat. That reality is clear in Elkhorn Slough, where the return of lush eelgrass has failed to guard against other impacts of extreme nutrient pollution. In a recently published study, Hughes and his colleagues found that low levels of dissolved oxygen make the slough toxic to young fish, impairing its historical function as a nursery for marine life.[14] The result has been a significant decline in the population of commercially fished species, including English sole, in the open waters outside the slough.

"We need less nutrients and more intact top predator populations," says Hughes. "Given the intensity of human land use and population growth in many coastal watersheds, reducing nutrient pollution will be difficult. Restoring food webs may be the key to ecosystem survival."

At a lush south Florida marsh, an alligator lunges off the bank, triggering a mighty splash that sends a startled heron into flight. Mobs of white ibis and roseate spoonbill pluck their prey from the water or sift it from the mud. Brian Garrett, wildlife coordinator for the South Florida Water Management District (SFWMD), steps on the brakes as a handful of wood storks flush away from his pickup truck. The birds' lanky, bald-headed bodies transform to soaring grace as they circle above us.

This industrial habitat, created to filter pollutants out of the runoff from sugar and dairy farms upstream, is one of the Stormwater Treatment Areas (STAs) managed by the South Florida Water Management District (SFWMD). (See Chapter 10.) A recent study found that bird populations in the 57,000 acres of STAs are more abundant and diverse than those in found in adjacent natural marsh.[15]

The findings are part of a new wave of research on the wildlife ecology of constructed wetlands, critical habitats in a world where many natural wetlands have been destroyed. Thousands of manmade wetlands now treat sewage effluent and contaminated runoff from city streets and farm fields worldwide. These wetlands are most often designed to improve water quality, not to nurture wildlife. Yet creatures from coyotes to snails inevitably exploit the rich habitats they create. Depending on the circumstance and the species, constructed wetlands may represent a lifeline or an ecological trap—a place that lures adults to breed but is deadly to their young.

Tyler Beck, now a biologist with the Florida Wildlife Commission, studied bird populations in and around the STAs as a graduate student at Florida Atlantic University. He found that bird density in the artificial marshes was thirty-eight times greater than in nearby natural wetland, while species richness was four times higher. This result was no surprise to him after his first visits to the STAs. In addition to the relatively obvious birds, remote, motion-activated cameras have caught images of the endangered Florida panther and of abundant coyotes and feral hogs. Thousands of people come to the STAs each year to bird-watch, and hundreds more line up to hunt ducks and alligators. “Our study put down on paper what anybody can see with their own eyes out here,” Beck says.

The STAs are part of a massive effort to restore the ecology of the Everglades, an expanse of sawgrass marsh, cypress swamp, and coastal mangrove forest that once encompassed 4.8 million acres in south Florida.[16] About 700,000 acres of the northern Everglades, at the edge of Lake Okeechobee, were drained to create farmland in a frenzy of canal-building that began in the early 1900s. Before this grand re-engineering of natural flows, a sheet of shallow, clear water ran south

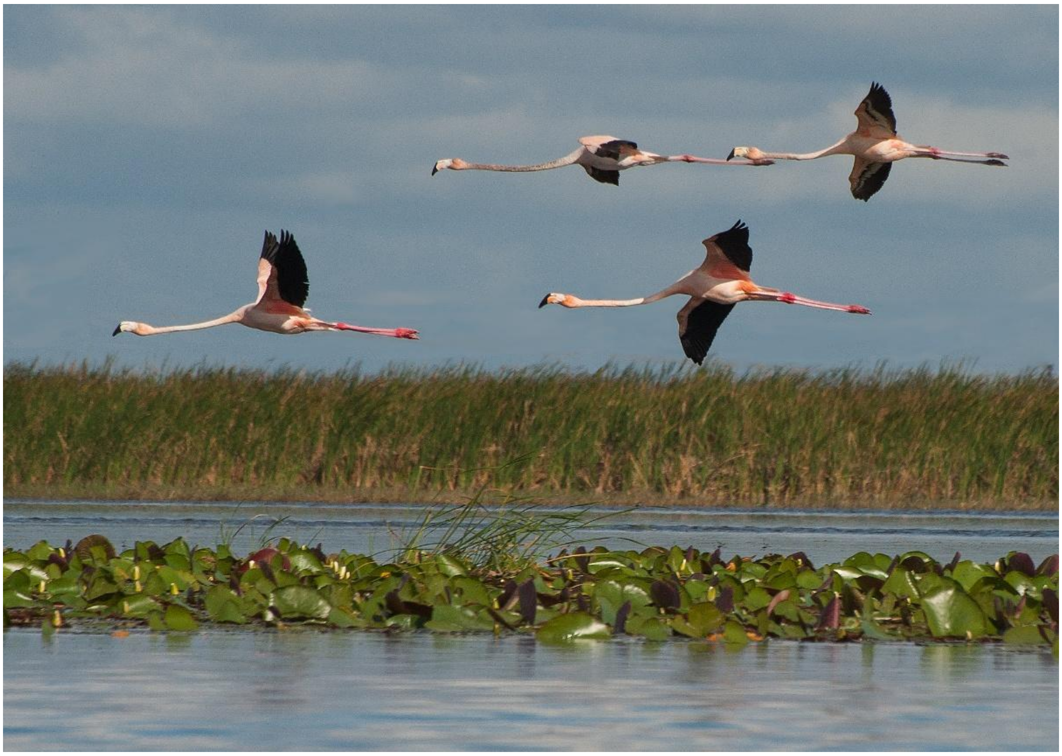

Figure 11.2 American flamingoes at a Florida Stormwater Treatment Area. Photo courtesy South Florida Water Management District.

from Lake Okeechobee across the tip of the Florida peninsula, sustaining sawgrass marshes adapted to low-nutrient conditions—which the conservationist Marjory Stoneman Douglas famously named “the river of grass.”

By the 1970s, Lake Okeechobee was choking on heavy loads of nutrients that ran off sugar fields and dairy farms. Blooms of algae fueled by high phosphorus levels have at times covered as much as 153 square miles—about twenty percent of the lake’s surface. Such explosions of algal growth can pump toxins into the water, or drain it of oxygen, killing fish and aquatic invertebrates. The lake was suffering from a bad case of eutrophication. The polluted water flowed downstream into remaining native wetlands, creating an explosion of cattail, which thrives in nutrient-rich water, outcompeting sawgrass and reshaping the ancient Everglades ecosystem. The shift in vegetation affects everything from tiny invertebrates in the bottom muck to hawks cruising above the marshes, which have a hard time locating their prey amid the tall, dense stands of cattail.

In the late 1990s, as part of a settlement in a federal lawsuit over violation of water quality standards, SFWMD built six stormwater treatment areas at the interface between heavily fertilized agricultural land and protected native wetlands. Much of each STA consists of thick stands of cattail, which not only thrive in nutrient-laden water but excel at knocking down phosphorus levels. Cattail stems slow the flow of water, allowing phosphorus-rich sediment to settle to the bottom. The plants also take up nutrients to fuel their own growth. Farther downstream in each STA are areas kept clear of cattail so that submerged plants—like guppy grass (*Najas guadalupensis*) and muskgrass (*Chara* spp.) can flourish.[17] These underwater plants absorb more of the phosphorus load. The STA systems remove 60 to 80 percent of the total phosphorus, achieving a major improvement in water quality, though nutrient loads remain higher than those in the pristine, pre-development Everglades.[18]

Bird populations are dense in the STAs because the nutrient-rich waters there fuel an intensely productive ecosystem, while the cattail stands filter out enough of the excess nutrients to prevent the worst symptoms of eutrophication (Fig. 11.2). American coots, small black-plumed, white-billed birds, form particularly abundant flocks. Beck calculated that 8 percent of the total American coot population is now wintering in the STAs—which implies that these artificial habitats may be altering the overall distribution of some North American water birds. The STAs have also become ground zero for the invasion of the purple swamphen, a showy species introduced from Asia, now flourishing alongside the native coots and gallinules.

The STAs support rare birds along with the common and the invasive. The snail kite, an endangered subspecies that lives only in Cuba and the Everglades region, has a sharply curved bill adapted to pry the flesh of native apple snails from their shells (Figs. 11.3 and 11.4). The kites prey almost exclusively on apple snails—including invasive species of apple snail introduced to Florida. They need relatively open wetlands, where they can see their prey as they cruise over the water. For this reason, stands of cattail make poor kite habitat.

Yet there’s enough open water in the STAs that kites are a common sight, flying low with their heads tilted down as they search for prey. Beck, who is now the

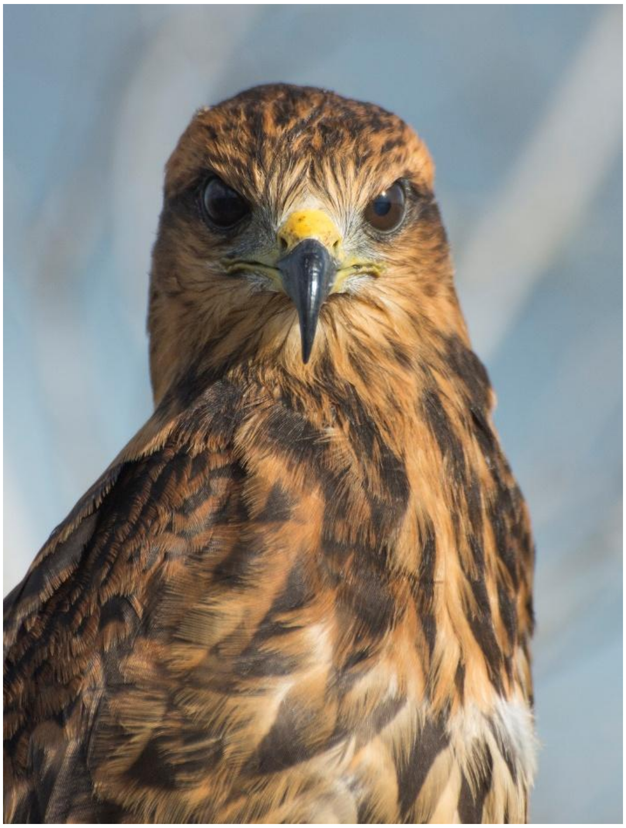

Figure 11.3 A young snail kite. An endangered species that lives only in Cuba and the Everglades region, the kite preys on apple snails. The birds breed successfully in the south Florida STAs. Photo courtesy South Florida Water Management District.

snail kite conservation coordinator for the Florida Wildlife Commission, notes that a University of Florida research team recorded one hundred active kite nests—a record number—in the STAs during 2014. The number of nests varies from one year to the next. Based on data through 2016, Garrett estimates that a total of 140 successful nests have raised chicks in the STAs since the kites were first found nesting there in 2010.[19] That's a significant contribution to the survival of a bird whose total US population is estimated at only 1,200 individuals.

Though water levels shift—deeper in the summer rainy season, shallower in the dry of winter—the STAs are kept flooded year round to maintain the plants that work to cleanse the water. Permanent water is good for apple snail populations, and for snail kites too. This is far different from the undisturbed Everglades, however, much of which dried out for months at a time before the drastic re-plumbing of south Florida. Garrett and other managers work to control water levels in the STAs during the months when black-necked stilts are breeding. These elegant wading birds, which stalk through the water on slender, bright-red legs, nest on the surface of muddy pond banks. An uncontrolled flood could wipe out hundreds of stilt chicks.

The threatened wood stork is also adapted to the ancient rise and fall of water in the undisturbed Everglades. A stork feeds by probing with its bill in murky water: Its jaws snap shut with lightning speed when the bird senses a fish. The

Figure 11.4 Apple snail shells from a Stormwater Treatment Area. Photo by Sharon Levy.

species traditionally feasted in small pools where fish concentrate when wetlands dry out in winter, making the stork's hunt-by-feel tactic more effective. The massive re-engineering of south Florida's water flows has hit wood storks hard, eliminating the seasonal changes that shaped the birds' survival strategy. We saw several storks on our tour of STA 5/6, exploiting the abundant small fish there. Still, the long-term survival of the US wood stork population will likely require major changes in the plumbing humans have imposed on south Florida, to allow a rebirth of seasonally dry wetlands—a habitat the STAs cannot replace.

Every September, thousands of sandpipers and stints arrive at the edge of Port Phillip Bay, near Melbourne, Australia. They gather in numbers seen nowhere else on the Australian coast. Exhausted from their long migration—many of these tiny shorebirds breed as far away as northeastern Siberia or western Alaska—they settle in for some serious eating. At low tide, they spread out on the mudflats at the bay's edge, probing into the muck with their sensitive bills. The bay mud is a rich source of small invertebrates, made even richer by discharges from the Western Treatment Plant (WTP), which for decades has handled the sewage generated by millions of people living in Melbourne. Long-term discharge of treated sewage has given the bay's nearshore ecosystem a nutritional jolt, enhancing the growth of algae and the small creatures that feed on it, creating a feast for hungry shorebirds.

The WTP has a distinction unique among wastewater facilities: It's recognized as the centerpiece of a conservation site of international importance under the Ramsar Convention on Wetlands due to its intense use by water birds. In addition to helping feed large numbers of native Australian shorebirds and migrants from the far north, the plant contains a series of sewage treatment lagoons, some of them built as long ago as the 1930s, which have become critical habitat for waterfowl.

Unlike the STAs in south Florida, lagoons at the WTP lack emergent plants like cattail. Called waste stabilization ponds, these open-water systems are seen by some experts as the simplest, least energy-intensive means of treating sewage, and are widely used in the developing world.[20] In the lagoons, bacteria break down organic compounds, while algae and zooplankton flourish on the nutrients in the sewage. The WTP is the world's largest array of wastewater stabilization ponds; the second largest is in Nairobi, Kenya.

Many Australian ducks and geese breed at ephemeral wetlands in the continent's interior, which dry up at the end of the wet season. In the dry months, the birds head to the coast, seeking refuge and food in permanent wetlands. More than a third of southeast Australia's original coastal wetlands have been lost to draining and development. The treatment lagoons at the WTP are reliably flooded with high-nutrient water, booming with algae and aquatic invertebrates. High nutrient loads in most of the ponds have kept them empty of fish, leaving the bonanza of food available to birds.

Recent studies by Christopher Murray and Andrew Hamilton of the University of Melbourne have found that wastewater treatment ponds, at the WTP and elsewhere in southeast Australia, host more abundant and diverse bird populations than remaining natural wetlands.[21] "Over a period of 22 years, we found significantly more species, and higher numbers of birds, in wastewater ponds," explains Hamilton. Like south Florida's STAs, the treatment ponds attract birds because of their intense biological productivity, fed by the high nutrient levels in polluted water.

In a single day of observation at Pond 9, a 109-hectare segment of the Lake Borrie lagoon system at the WTP, Hamilton has counted as many as five thousand pink-eared ducks,[22] striking birds that sport zebra-striped plumage and hold their long, lobed bills just under the surface to filter plankton out of the water. They swim alongside large flocks of teal, shovelers, grebes, and swans; Hamilton has recorded up to twenty thousand birds at a time on Pond 9. Perhaps the most dramatic example of a species that relies on habitat at the WTP is the blue-billed duck, a diving bird that forages for invertebrates on pond bottoms. In 2002, when the world population of this duck was estimated to be about twelve thousand individuals, more than thirteen thousand were counted at the WTP. The plant has also hosted twenty-five thousand hoary-headed grebes at a time, dwarfing recorded numbers at any other Australian wetland.[23]

This mind-boggling abundance does not represent normal conditions in a natural wetland. “Waste stabilization ponds support a very different type of community when it comes to the balance between numbers and diversity of various species,” notes Hamilton. “They’re great for water birds, but not for amphibians and arthropods, which need emergent vegetation . . . Because we’ve lost so much natural habitat, we’re happy to have a place like the Western Treatment Plant, a sort of a McDonald’s for water birds.”

These treatment wetlands, and the birds that use them, exist on the knife edge between artificial abundance and the deadly effects of eutrophication. In the series of interconnected ponds used in waste stabilization systems, the first one or two ponds will be anaerobic, the free oxygen drained from the water by the decomposition of heavy loads of organic matter. In these extreme conditions, anaerobic bacteria digest pollutants, but few aquatic creatures survive. Farther along in the sequence, where the water is cleaner, aerobic ponds support abundant food for water birds. Murray and Hamilton have documented the highest abundance and species richness of water birds in the aerobic ponds at the cleaner end of treatment systems, both at the WTP and in the Goulborn Valley, a major agricultural area in Victoria.[24]

Port Phillip Bay remains surprisingly healthy despite long-term discharges from the WTP and other sources in sprawling metropolitan Melbourne. An intensive study of the bay’s ecology[25] explains this happy accident. The bay is shallow, and its waters remain clear. Sunlight penetrating to the bay floor allows microalgae to flourish on the bottom. Thick mats of benthic microalgae capture nutrients before they can escape back into the water column to fuel algal growth there, which would cloud the water.

Meanwhile, the bottom-growing algal mats feed a diverse community of invertebrates—several hundred known species—that live in the sediment. These small creatures burrow through the sediment, mixing organic forms of nitrogen into the muck. The nitrogen that isn’t held in the sediment is transformed to N_2 gas by bacteria and diffuses up through the water and into the atmosphere.

A model of nutrient cycling in the bay created by scientists with the Commonwealth Scientific and Industrial Research Organization, Australia’s national science agency, predicted that continued nutrient loading could push Port Phillip Bay over the brink, clouding the water, smothering the benthic algal mats, and killing many species of benthic invertebrates. To prevent this, the WTP was ordered to improve its wastewater treatment, to decrease the amount of nitrogen it released to the bay.

In 2003–2005, activated sludge systems were installed in two of the WTP’s newer treatment lagoons. Some of the older lagoons, including the Lake Borrie ponds, were removed from the sewage treatment process and began to receive fully treated effluent. Ecologists feared that cleaner water would mean less algae and invertebrates for waterfowl to dine on, reducing Lake Borrie’s value as bird habitat. While one Australian law mandated the upgrade to the sewage treatment process to protect Port Phillip Bay, another required that plant managers track and mitigate any resulting impacts on bird populations in the WTP.

To compensate for a possible decline in abundance of shorebird prey in Port Phillip Bay's tidal mudflats, managers at the WTP created shallow "conservation ponds" that provide permanent places for shorebirds to roost and feed, unaffected by shifting tides. Early studies had suggested that filter-feeding birds like the pink-eared duck, which seemed to prefer high-nitrogen waters, might be most affected by the sewage treatment upgrade. Surveys of waterfowl in the first years following installation of the activated sludge plants showed an overall decline in the time birds spent feeding on Pond 9 of the Lake Borrie system—a trend that was most pronounced among bottom-feeding species like chestnut teal, gray teal and Australian shelduck. Birds at the WTP also changed their habits, spending more time on ponds downstream of the new activated sludge plants that had once been too eutrophic to attract them. The numbers of birds in the Lake Borrie system dropped. Managers responded by trying various ways of bringing more nutrients back into Lake Borrie, and ultimately decided to build a new pipeline that will return sewage flows there.[26]

The major changes at the WTP coincided with an epic drought that struck eastern Australia from 1997 to 2009.[27] Many natural wetlands went dry; at the height of the drought, in 2008, aerial surveys found that about 70 percent of all waterfowl in the state of Victoria were at the WTP, sheltering on its reliably flooded ponds.[28]

More recent data show that climate—specifically the drought and its end, which saw flooding of long-dry natural wetlands in the continent's interior—drove many of the variations in water bird use of habitat at the WTP. "In hindsight, having seen how birds rebounded after the drought, I reckon we'd have great difficulty arguing for the major expense of the Lake Borrie sewage pipeline on the basis of bird habitat alone," notes William Steele, senior biodiversity scientist for Melbourne Water, the agency that manages the WTP. The pipeline will likely end up paying its way, as continuing human population growth in Melbourne creates a need for more treatment lagoons. It's a point lesson in the complexities of managing treatment wetlands and the birds that flock to them.

In the US, the federal government has had a policy of no net loss of wetlands since 1989. Under regulations enforced by the US Army Corps of Engineers, those who destroy wetlands are required to create new ones in mitigation. On paper, constructed wetlands have begun to balance out the acreage of habitat lost to ongoing development. Yet research over the last fifteen years has made clear that for wildlife, wetland habitats constructed under the "no net loss" policy often don't replace those lost. The needs of amphibians have often been overlooked, says Christopher Shulse, an ecologist with the Missouri Department of Transportation who spends much of his time monitoring wildlife in artificial wetlands. "Amphibians," he notes, "are the canary in the coal mine."

Wetlands are where frogs and salamandersmate and lay their eggs, where tadpoles grow up and sprout the limbs that allow them to emerge onto land. Many species also need healthy upland habitat—forest or grassland—to survive as adults. So the health of amphibian populations reflects not just the state of a single pond, but also that of the surrounding landscape.

Constructed wetlands in Missouri make excellent habitat for one or two hardy species: Bullfrog and green frog do well in steep-banked, permanent ponds, alive with fish that prey on frog eggs and tadpoles. The widespread creation of farm ponds has extended the range of the bullfrog into hillsides where it was not traditionally found. But for many native amphibians, such ponds are a dead end. "The wetland types credited with reversing the national trend toward wetland loss most often have steep banks, permanent water, and little vegetative cover," says Shulse. "They may harbor plenty of stocked fish and bullfrogs, but most native amphibians can't survive in these habitats."

If they are to work for amphibian conservation, artificial wetlands must become more diverse. Native frogs and salamanders need a range of wetlands, from the ephemeral to the permanent, scattered liberally across a landscape that includes upland habitats the creatures can use in adulthood.

In many urban areas, it has become nearly impossible to find a natural wetland, and the only homes available to amphibians are stormwater retention ponds, built to filter toxins from the polluted water that runs off city streets. Joel Snodgrass, head of the wildlife department at Virginia Tech, has spent years studying amphibians in these artificial habitats. In a study of forest and suburban wetlands in a rapidly developing area of Baltimore County, Maryland, Snodgrass and his colleague Adrianne Brand found that most amphibian breeding activity took place in manmade wetlands, and that these were the only places where tadpoles survived to metamorphosis.[29] Survival of eggs and larvae was highest in ponds that went dry for part of the year.

Keeping native amphibians alive in an urbanizing landscape will mean managing stormwater ponds for their benefit. Just how to do this is a difficult question, since stormwater ponds collect a stew of poisons: metals, nutrients, and toxic hydrocarbons left behind by the steady communal drip of gasoline, antifreeze, fertilizers, and pesticides. One ingredient is zinc, which wears out of automobile tires: An estimated ten thousand tons of zinc was released to US roadways through tire wear in 1999. Snodgrass's group found that wood frog (*Rana sylvatica*) larvae exposed to zinc from tire debris showed decreased hatching success, slowed development, and lower weight at metamorphosis, which may mean their chances of adult survival are reduced.[30]

American toads (*Bufo americanus*; Fig. 11.5) thrive in suburban Baltimore, but the wood frog is vanishing. Part of the problem is that the forest habitat where wood frogs spend their adulthood is dwindling. In his lab, Snodgrass found that habitat loss is not the sole threat. He exposed larval wood frogs and American toads to sediments from Baltimore-area stormwater ponds, contaminated with chromium, copper, nickel, zinc, and road salts. The toads raised in these toxic sediments suffered some impacts: They were smaller when

Figure 11.5 An American toad, one of the few amphibian species thriving in suburban Baltimore, Maryland. Photo by Joel Snodgrass.

they metamorphosed into adults than their counterparts raised on clean sand. None of the wood frog larvae exposed to the toxic sediments survived to metamorphosis at all.[31]

Recent evidence suggests that salt, used to melt ice off roads in winter, is the deadliest toxin for sensitive species like the wood frog. The concentration of road salt in stormwater ponds appears to be a major factor determining which amphibians can successfully reproduce. Stormwater ponds are often located next to remnant forest habitats, which might help the wood frog to hang on if its young weren't dying of salt exposure.[32]

Researchers in Edmonton, Canada, also found evidence that stormwater ponds act as ecological traps. In 2009, they recorded that larval wood frogs survived to adulthood in 100 percent of the natural wetlands surveyed. In Edmonton's stormwater ponds, the figure dropped to 32 percent.[33]

Andrew Hamer, an ecologist at the Australian Research Centre for Urban Ecology, has spent many nights listening at the edges of stormwater treatment ponds in Melbourne, identifying frogs by their distinctive courting songs. In a study relating habitat structure in these manmade ponds to frog survival,[34] his results echoed Shulse's concern that one type of habitat cannot sustain all amphibians. Some species, like the spotted grass frog, mate only in wetlands thick with emergent plants. By contrast, the southern bullfrog makes its love call, a resonant *bonk* like a note struck too hard on a banjo, while floating on submerged plants in ponds with steep, barren banks.

Most of Melbourne's stormwater ponds have been designed to hold water permanently, and they harbor thriving populations of *Gambusia holbrooki*, known on its native turf as the mosquitofish. Introduced from the southeastern US in

1925, *G. holbrooki* has become an environmental disaster in Australia, where it is now called the plague minnow. (Carried around the globe in the false hope of mosquito control, *G. holbrooki* is the most widespread fish on the planet, listed on the International Union for Conservation of Nature's list of one hundred worst invasive species.) The little fish flourishes in polluted water, feeding voraciously on native aquatic creatures.

Though he has heard other native frogs calling in the stormwater ponds, Hamer found that only tree frog, striped marsh frog, and southern bullfrog larvae survived to adulthood in the presence of plague minnows.[35] In Melbourne, as in Maryland and Edmonton, stormwater ponds can act as ecological traps.

The growing body of evidence on amphibian life and death should ultimately lead to changes in stormwater pond management. Melbourne's ponds could be made more amphibian-friendly by altering some so that they dry out for part of the year, preventing the establishment of plague minnows. That kind of habitat diversity has already been accomplished in the Baltimore area, but high contaminant levels remain a threat. Where the goal is solely to treat water pollution, toxins will accumulate at levels that form ecological traps even for the hardiest toad. In those places, barriers might be needed to keep amphibians out.

Finding ways to make stormwater ponds serve as healthy frog habitat will be a complex mission, moving beyond the system's original design as a way of simply slowing polluted water and allowing contaminants to settle out. "We'll have to figure out where the critical thresholds are for pollutant levels, and for combinations of pollutants: metals, pesticides, fertilizers, salts, polyaromatic hydrocarbons," says Snodgrass. "It's a soup of pollutants that's difficult to understand."

Oil sands mining in Alberta, Canada, is producing vast amounts of an even more toxic stew. Separating bitumen from oil sand ore takes 2 to 2.5 cubic meters of fresh water for every cubic meter of synthetic crude oil produced.[36] As a result, large holding ponds full of liquid tailings are accumulating. These oil sands process-affected waters (OSPW) are heavily contaminated with napthenic acids, polycyclic aromatic hydrocarbons, metals, and salt.

Constructed wetlands are part of the plan to restore the blasted landscape left behind by oil sands mining. Thus far a few wetlands have been deliberately built, while others have formed spontaneously. Research on these wetlands reveals both the remarkable resilience and purifying abilities of native plants and the ecological complexities of creating wildlife habitat with heavily contaminated water.

Native sedges can thrive even in the toxic soup of OSPW.[37] Judit Smits, a wildlife toxicologist at the University of Calgary, has tracked the impacts of life in these reclaimed wetlands on birds and frogs. In newly formed oil sands wetlands, wood frog tadpoles suffer delayed metamorphosis—a problem that's linked to effects on their thyroid glands, and that reduces their odds of surviving to successfully reproduce.[38] Their blood contains high levels of cytochrome P450 enzymes, proteins produced by the liver in response to toxin exposure—a sign that precious energy is being diverted from normal growth and development to the metabolism of poisons.

Over time, sunlight and microbial metabolism degrade the organic pollutants, while metals and other toxins sink to the bottom of wetland ponds and are held in the sediment. Seven years in, the worst of the toxic impacts on wildlife fade. Wood frog tadpoles raised in OSPW wetlands more than seven years old do as well as those raised in undisturbed reference habitats.

Smits has studied tree swallows living in nest boxes among reclaimed OSPW wetlands. The birds feed on aquatic insects that spend their larval phase in the wetland itself. Swallows living in new wetlands appear hard-hit by the toxins in their diet. Like wood frog tadpoles, tree swallow nestlings on newly reclaimed wetlands grow slower than those in reference sites and show higher levels of cytochrome P450 enzymes in their blood. In the spring of 2003, when harsh weather triggered a widespread die-off of nestlings, the odds of survival on the most heavily polluted sites was ten times lower than at the control site. Tree swallows on OSPW wetlands are also heavily infested with blow flies; nestlings carried parasitic burdens twice as high as those recorded on the reference site. Some of the toxins in OSPW can impair the birds' immune response to parasites. "On the reclaimed sites," says Smits, "the birds have to use energy to cope with toxicants. So they don't have the resilience or energy reserves of birds living in natural wetlands."

Smits believes constructed wetlands can be a viable way of rehabilitating the post-mining landscape in Alberta. The caveat is that OSPW wetlands will be highly toxic for the first seven years of their existence. "If we want to protect the animals, we have to avoid them getting onto the younger wetlands," she says. "Those areas would need to be fenced off for a few years." So far, there's no requirement that reclamation keep pace with oil extraction, and vast quantities of liquid mine tailings are piling up. Aside from a few wetlands built for research and aged enough to have lost their toxicity, Alberta's oil sands mine areas (1,670 square kilometers were actively being mined or approved for development as of 2013)[39] promise to remain a black hole for wildlife for years to come.

That bleak scene is hard to imagine while walking the trails in the Arcata Marsh. The city's constructed wetlands remain a hotspot for wildlife, hosting large populations of migrating ducks and shorebirds in spring and fall. Mallards, green-winged and cinnamon teal, and Canada geese breed successfully in the summer, and families of river otters play here year-round. But the future of Arcata's popular wetland is now in doubt.

NOTES

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