Chapter 4

Deciphering Amphibian Declines

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In 1973, an Indonesian scientist visiting Australia discovered a nondescript, muddy-brown frog hidden in the streams of the remote, densely forested mountains of southeastern Queensland. The frog attracted a great deal of interest, since it was the first aquatic stream frog known to inhabit the continent. It was unusual in other ways as well. Michael Tyler, an Australian herpetologist, noticed that the frogs would occasionally collect in pools of water in groups of three or four—forming sort of a ring of frogs, touching by the tips of their toes.[1]

But the strangest characteristic was discovered in November 1973, when two researchers in Brisbane were cleaning an aquarium that held one of the frogs. They saw it swim up to the surface of the water and spit out six live tadpoles. They couldn't quite believe what they saw: where could the tadpoles have come from? Perhaps the species was related to a South American frog whose fertilized eggs develop in the father's vocal sacs. But they also noticed a peculiar mass of wriggling bodies under the skin of the frog's stomach. Soon another tadpole was found in the aquarium. Then two more appeared. The researchers finally decided to remove the frog and dissect it. As they reached into the aquarium and grabbed the animal, it flexed backward and opened its mouth wide. As the researchers described in *Science*, "eight juvenile frogs were then propulsively ejected in groups of two or three in no more than 2 seconds. Two further juveniles were ejected after a few minutes and, 30 seconds after the frog had been transferred to preservative, three more were disgorged similarly."[2]

Scientists found that the frog incubated its eggs in the mother's stomach—a form of parental care that was completely unprecedented among vertebrates. That gave the species its common name: the gastric-brooding frog. Normally, whatever a frog swallows would be digested by the stomach's natural chemicals. But somehow this species was able to turn off its digestive enzymes for the six or so weeks it took for the eggs to develop. This was particularly intriguing as it suggested the frog's physiology could hold clues to treating people with gastric ulcers and other stomach ailments. But in 1981, as research was getting under way, the frog suddenly disappeared from the mountain streams where it had once been so abundant. It has not been found again since.[3]

By the end of the 1980s, reports of declines and disappearances emerged from most regions where amphibians were reasonably well monitored.

It was just pure luck that scientists happened to stumble on the gastric-brooding frog in the twilight of its existence. Here was a species humans had been living beside for millennia, yet somehow it had escaped notice. And this creature had a unique adaptation for brooding its young—if we had not actually seen it, we would never have thought it possible. The frog had a lot to teach us, but for some unknown reason, our time with it was cut short.

The loss of the gastric-brooding frog attracted a great deal of attention in the scientific community, largely because it was such an unusual creature. But it turns out that its mysteriously sudden disappearance was not exactly unique to the species. By the end of the 1980s, at least 13 other amphibian species had gone into serious decline or disappeared entirely from mountainous regions of eastern Australia. The southern dayfrog, which had commonly been found in the same areas as the gastric-brooding frog, has not been seen in the wild since 1979. Three other species in southeastern Queensland have declined by more than 90 percent. Further north, in the tropical forests near Eungella, two species declined sharply in 1985; one of them has not been seen since. And in the tropical rain forests of northern Queensland, large-scale declines began in 1989—seven species dipped sharply; four can no longer be found in the wild. All these species were locally endemic: they did not exist anywhere else in the world.[4]

Several hypotheses about Australian amphibian declines have been proposed, but there are no widely accepted, definitive answers. And the mystery spreads beyond Australia. By the end of the 1980s, reports of declines and disappearances emerged from most other regions of the world where amphibians were reasonably well monitored—in North America, parts of South America, and Europe. In Costa Rica's Monteverde National Park, populations of 20 of the 50 native amphibian species have declined or disappeared since 1987. And in California's Sierra Nevada, five out of seven native amphibians have disappeared or declined sharply since the early 1900s. (See Table 4–1.)[5]

As news of the declines began to surface around the world, scientists wondered if they were simply anecdotal accounts that reflected natural population fluctuations. But there were some uncanny similarities—patterns that suggested something more ominous could be taking place. The declines were, in the first place, very rapid. They sometimes involved whole assemblages of species, rather than just one or two. And they were occurring not just in areas that were obviously disturbed, but in some of the world's most carefully protected parks, such as Costa Rica's Monteverde Cloud Forest Reserve and Yosemite National Park in the western United States. These were not the kinds of losses that could be readily predicted—or explained. Something peculiar was happening to *Amphibia*—something bad enough to dis-

Table 4–1. Selected Large-Scale Losses of Amphibians

Location	Species of Concern	Status	Possible Cause
Montane areas of eastern Australia	14 species of frogs, including the southern day frog and the gastric-brooding frog.	Sharp population declines since the late 1970s. Four species are thought to have become extinct.	Parasitic fungus, possibly introduced through international trade in aquarium fish and amphibians.
Monteverde region of Costa Rica	20 species of frogs and toads (40 percent of total frog and toad fauna), including the golden toad.	Disappeared after simultaneous population crashes in 1987. Missing throughout 1990–94 surveys.	Climate change, possibly combined with other factors such as parasites.
Las Tablas, Costa Rica, and Fortuna, Panama	More than 15 species.	Severe declines since the early 1990s.	Chytrid fungus infection, possibly combined with other factors.
Yosemite region of California	Five out of the region's seven frog and toad species—including the mountain yellow-legged frog and the foothill yellow-legged frog.	Severe declines—one species has disappeared entirely, another has declined to a few small populations.	Overall cause unknown. Introduced predatory fish combined with drought-induced loss of habitat contributed to the decline of some species.
Montane areas of Puerto Rico	12 of 18 endemic amphibian species.	Three may be extinct, the others are in decline or at risk.	Unknown. Possibly climate change.
Cordillera de Mérida, Venezuela	Five species.	Sharp declines since the 1970s.	Unknown. Possibly deforestation, floods, roadkill, pollution.
Reserva Atlântica, Brazil	8 out of the reserve's 13 native frogs.	Disappeared or declined in the 1980s.	Unknown. Possibly unusually dry winters, pollution, or a combination of both.

SOURCE: See endnote 5.

tinguish it from the broader tragedy known as the biodiversity crisis.

More than a decade since amphibian declines first emerged as a major scientific mystery, there have been significant advances in our understanding of the issue. While there are still many unanswered questions, there is now little doubt that the problem is real, and that a complex mixture of causes is involved. More important than the many details, however, is the realization that it is not just the loss of frogs and salamanders that should concern us, but what their loss tells us about the state of the environment. Stemming the loss of amphibians will involve changes far beyond the protection of wetlands or forests. It will require fundamental changes in the way we live.

Why *Amphibia*?

The decline of amphibians seems particularly surprising, given that these creatures have been around for about 350 million years and were able to survive three mass extinctions. These events are thought to have killed off approximately half of all animal species, including the dinosaurs that disappeared 65 million years ago. Yet overall, amphibians persisted when so many other groups of organisms did not.[6]

When amphibians first appeared, Earth's terrestrial area was essentially one giant landmass inhabited by plants and insects. Amphibians were the first vertebrates to make the transition from water to land. Somehow, a type of bony fish evolved into a creature that had four legs, could breathe atmospheric oxygen instead of dissolved oxygen, and had a body structure that allowed it to maneuver without the support of water. It was these kinds of traits that laid the groundwork for other classes of vertebrates—such as reptiles, birds, and mammals—to develop.[7]

Since the first amphibian emerged from the water, the class has evolved into three distinct groups (or, to use the scientific term, orders). *Anura*, which includes frogs and toads, is the largest group. The order *Caudata* includes salamanders and newts. And *Gymnophiona*, the least-known group, which are commonly referred to as caecilians, are legless, subterranean creatures that are found only in tropical and subtropical regions of the world. (See Table 4–2.)

Scientists have thus far identified nearly 5,000 species of amphibians—more than the known number of mammals. And compared with other groups of organisms, new species of amphibians are being described at a phenomenal rate—the number of described species is increasing by about 1–1.5 percent a year. And there are still hundreds, perhaps thousands, that have yet to be discovered. Amphibians' collective domain includes every continent except Antarctica, and probably most of the world's major islands. They achieve their greatest variety in tropical and warm temperate forests. The neotropical realm is by far the richest; Central and South America house close to half of the world's amphibian species. But amphibians also live in deserts, grasslands, northern bogs—even tundra, in the case of the North American wood frog, one of four species of North American frogs that can survive in a practically frozen solid state.[8]

Given their durability and ubiquity, the rapid decline of so many species is particularly unsettling. Why are amphibians disappearing now? Many scientists claim that amphibians are important bioindicators—a sort of barometer of Earth's health, since they are more sensitive to environmental stress than other organisms. One trait that gives them this distinction is their "amphibious" nature—the typical amphibian lifecycle is partly aquatic and partly terrestrial. That can make them doubly vulnerable: disturbance of either water or land can affect them. In water, for example, some species have fairly narrow temperature requirements. Some do best in still water; others need flowing water.[9]

And many amphibians are particular about where they will breed. In southwestern California, the endangered arroyo toad does not reproduce well unless it lays its

Table 4–2. Global Distribution of Amphibians

Area	Frogs and Toads	Salamanders	Caecilians	Total Amphibia	Share of World's Amphibian Species
		(number of known species)			(percent)
United States and Canada	90	151	—	241	5
Central and South America and the Caribbean	2,135	248	82	2,465	50
Eurasia and North Africa	103	89	—	192	4
Sub-Saharan Africa	761	—	29	790	16
India, Southeast Asia	745	29	44	818	17
Australia, New Zealand, Papua New Guinea	443	—	—	443	9
Total	4,277	517	155	4,949	

SOURCE: William E. Duellman, "Global Distribution of Amphibians: Patterns, Conservation, and Future Challenges," in William E. Duellman, ed., *Patterns and Distribution of Amphibians: A Global Perspective* (Baltimore, MD: The Johns Hopkins University Press, 1999), 3. For specific boundaries among areas, see page 6.

eggs on the sandy bottom of a slow-moving stream. Some frogs and salamanders will lay eggs only in the shallow "vernal pools" that appear with the spring rains and disappear with the summer heat. This is a kind of evolutionary gamble with the weather: the young are safe from predatory fish in a vernal pool, but they must reach their terrestrial phase before the pool dries up.[10]

Given such preferences, it is no surprise that habitat degradation is the leading cause of amphibian decline. Many amphibians, for example, are forest animals—and the world is currently losing approximately 14 million hectares of natural forest each year, an area larger than Greece. Even when the result is not outright deforestation, logging can devastate amphibian populations. If forests are allowed to regenerate, amphibians can return, although estimates of how long that will take vary; in the southeastern United States, for example, the estimates range from 20 to 70 years.[11]

Consider the logging boom in the U.S. Southeast, where forests shelter one of the world's richest assemblage of salamanders. More than 65 percent of all salamanders belong to a lineage called the *Plethodontidae*, which lack lungs. These creatures breathe through their skin, which must remain moist at all times to facilitate gas exchange or they will suffocate. Plethodontids are consequently extremely sensitive to changes in temperature and humidity. Even selective logging is likely to reduce a population, because it opens up the canopy and dries out the forest floor. In the U.S. Southeast, the logging of mature hardwood forest, the primary salamander habitat, is expected to overtake the hardwood growth rate by the close of the decade.[12]

The Oregon spotted frog has largely disappeared from its historical range in the heavily farmed Willamette River Valley.

Deforestation-induced losses are almost certainly far greater in the tropics, although generally far less is known about them. An extreme case appears to be Sri Lanka. As recently as 1993, the island's amphibian fauna was thought to comprise only 38 species, but a recent five-year survey of the remaining rainforest may have turned up as many as 200 additional amphibian species that are apparently endemic (though these have not yet been formally described, nor has the estimate been published in a peer-reviewed journal). Yet Sri Lanka has only 750 square kilometers of rainforest left; over the past 150 years or so, the island has lost approximately 96 percent of its original rainforest cover. When survey researchers checked the records of naturalists who were exploring Sri Lanka before 1900, they found that more than half of the amphibians mentioned were no longer present. Most of Sri Lanka's surviving natural forests are legally protected, but they continue to dwindle in the face of illegal logging, primarily for fuelwood.[13]

It is true that in many parts of the world, large tracts of new "forests" are being created, but tree plantations do not generally provide an ecological substitute for natural forest. In Florida, for example, approximately 80 percent of the natural longleaf pine forest has been lost over the last 50 years, and the majority of what was cleared has been converted to commercial slash pine plantations. This is considered to be a primary reason why populations of the threatened flatwoods salamander have declined or disappeared in recent decades. The longleaf pine forest was the primary habitat for the salamander, which does not do well in the drier, more uniform conditions of the planted slash pine forest. In South Africa, tree plantations have also come at a cost to local amphibians. The Matatiele wetland near Mtunzini was one of the last remaining natural coastal wetlands in the country and home to more than 25 species of frogs. But when an exotic tree plantation was installed next to it, the water table dropped and the wetland dried up.[14]

Amphibians also depend on many other types of habitat, and unfortunately the grasslands, wetlands, and streambeds of the world are not faring much better than the forests. In California, the conversion of native grasslands to farms and suburban developments is a leading reason for the endangered status of the California tiger salamander—at least 75 percent of the original grassland habitat has been irretrievably lost. And in the United Kingdom, the loss of breeding ponds is a primary reason for the decline of all six native species. Most of the world's rivers are now under the control of dams that cause flooding, scouring, and siltation—the kind of forces that are largely responsible for the disappearance of the endangered Arroyo toad from 75 percent of its former range in California.[15]

Although habitat loss is the leading cause of amphibian decline, it obviously cannot account for the many large-scale disappearances that have taken place in protected areas like Monteverde and Yosemite—places that would seem to be about as close to pristine as possible. And yet the amphibians in these areas are apparently reacting to dramatic changes. But these are changes that are hard to see, or that just do not seem "unnatural."

Toxics are one threat that is difficult to see, and there's no question that amphibians are highly vulnerable to all sorts of pollutants. Because they breathe and even drink through it, amphibians have thin, permeable skin that readily absorbs contaminants. Their eggs lack protective shells and are highly permeable as well. So it is hardly surprising that in heavily industrialized areas, pollution is frequently invoked as a cause for local declines. In some older centers of heavy industry, the pollution is so intense and pervasive that it's a wonder there are any amphibians left to study. Amphibian populations in much of Ukraine, for example, appear to be under attack from heavy metals, pesticides, aromatic hydrocarbons, acid rain, and radioactive waste.[16]

But pollution is taking a toll in healthy-looking landscapes as well. In Britain, the acidification of ponds is a contributing factor in the endangerment of the Natterjack toad. This toad is now nearly extinct in British lowland heath, a habitat that used to support about half the species' population in that country. (The toad is faring poorly in Scandinavia too, but it seems to be in better condition farther south.) California's Sierra Nevada range is losing many of its amphibians, and pesticide contamination could be a factor. The pesticides malathion, chlorpyrifos, and diazinon have been detected in precipitation at altitudes as high as 2,200 meters. The pesticides are not used in the mountains themselves; they are presumably drifting up from the state's heavily farmed lowlands.[17]

Fertilizers, which are used in far greater quantities than pesticides, may be creating problems we are even less prepared to counter. Some amphibians are very sensitive to the nitrogen compounds that typically leach out of artificially fertilized fields. For example, researchers have discovered that tadpoles of the Oregon spotted frog are poisoned by water with nitrate and nitrite levels low enough to pass the drinking water standards set by the U.S. Environmental Protection Agency. (Nitrate and nitrite are compounds that soil microorganisms make from synthetic nitrogen fertilizer.) Many water bodies in the United States contain levels of nitrate that violate government standards. If these are not taken seriously as a matter of public health, it seems unlikely—to say the least—that more stringent standards will be mandated for the welfare of frogs. The Oregon spotted frog has largely disappeared from its historical range in the heavily farmed Willamette River valley.[18]

Pollution, like habitat loss, is thus clearly a major factor in amphibian decline. But even considering both stresses, many declines remain unexplained. Not far from the Willamette valley, in the Cascades Range of Oregon, for example, the Cascades frog and the western toad are disappearing, even though their habitat has not been significantly disturbed or polluted. Researchers have found that these species are the victims of another stress: increased exposure to ultraviolet (UV) light, a consequence of the depleted stratospheric ozone layer, which filters much of the UV wavelength out of incoming sunlight. UV light can damage DNA and even kill cells. Amphibians, with their naked skins and eggs, are particularly at risk. The Cascades species may be losing their eggs to the extra UV exposure.[19]

It is possible that increased UV levels are injuring other amphibians as well, particularly at higher latitudes, where the ozone layer tends to be thinner. Unfortunately, seasonal fluctuations probably increase amphibian vulnerability: in either hemisphere, the ozone layer tends to be at its weakest during winter and spring, a period that overlaps with the egg-laying season for most species. Amphibians at higher elevations could be especially susceptible as well, since the higher you go, the less atmosphere there is to filter out the UV. But researchers have found that not all amphibians are especially sensitive to UV light, nor are all of them exposed to appreciable quantities of it.

Amphibians face another major pressure that, like UV light and pollution, is hard to see. Introduced, non-native species are often in plain view, but because they usually look perfectly "natural," it can be difficult to see them as a threat. Yet certain non-native species frequently prey on amphibians or out-compete them for food. In New Zealand, introduced rats are thought to have caused the extinction of several species of *Leiopelma* frogs. And in the Yosemite region of California's Sierra Nevada, large-scale trout introductions have played a major role in the disappearance or severe decline of five of the region's seven native amphibians. Further south, in California's Santa Monica Mountains, the recent spread of introduced mosquitofish (used widely to combat mosquitoes, but unfortunately they eat more than that) may be depressing local populations of the California newt and the Pacific treefrog.[20]

One invader that frequently injures amphibians is itself an amphibian: the bullfrog, native to the eastern United States. An aggressive, fast-growing species that can reach a length of 15 centimeters, the bullfrog has been introduced into ponds and marshes in many places around the world, as food and fishbait. It is not very particular about where it lives or what it eats. It will try to swallow almost anything it can fit in its mouth—including other frogs. It can also compete aggressively with other species for food. In California, where it was introduced in the early 1900s, the bullfrog may have contributed to the declines of several species. In South Korea, where it was imported for food in the early 1970s, the subsequent loss of native frogs and other small creatures inspired a government-sponsored anti-bullfrog campaign, with hunting contests and bounty prizes.[21]

Another organism that is apparently lurking in many forests and swamps may be consuming far more amphibian species than bullfrogs or trout do. In the mid-1990s, an unknown pathogenic fungus was found to be infecting frogs in Costa Rica, Panama, Australia, and the United States. Researchers in these places discovered the pathogen separately, but as they began to compare notes they realized that they were dealing with the same suspect.

Between 1993 and 1997, Karen Lips, a herpetologist studying amphibians in Costa Rica and Panama, discovered several dead and dying frogs at her research sites—a rare find, since dead frogs are usually snapped up quickly by scavengers. During this same period, she also observed population collapses in several species, and in five out of the seven Panamanian streams she monitored, frogs simply vanished altogether.[22]

Meanwhile, in Australia, researchers were beginning to wonder if an epidemic disease might be responsible for the series of declines and extinctions that occurred along the east coast of the country in the 1970s and 1980s. As with the Central American declines, the victims were stream dwellers and had succumbed very rapidly—traits suggestive of a highly virulent, waterborne pathogen. When researchers compared skin samples from Panamanian and Australian victims, they found them infected by the same type of organism: one or more fungi of the phylum *Chytridiomycota*. That came as a surprise, since chytrid fungi are common pathogens of plants and insects but had never before been reported to attack vertebrates.[23]

In the United States, the fungus was first noticed in 1991, when it started killing captive arroyo toads in California. In 1996, the toads' disease was identified as the chytrid fungus, which has since been found in the wild in various places around the country. In Illinois and Maryland, it has been encountered as an apparently benign infection of stable frog populations: the infected animals seemed perfectly healthy. But in 1999 and 2000, wildlife officials in the U.S. Southwest discovered the fungus in lowland leopard frogs outside Phoenix, Arizona, and in boreal toads near Denver, Colorado. In both cases, they found large numbers of dead and dying animals. Both species have been in sharp decline, and the fungus has become a prime suspect.[24]

Scientists are now wondering how many other declines the fungus might explain. Could it have been behind some of the older die-offs—events later marshaled as evidence for global amphibian decline? In many parts of the world, scientists are uncorking old specimen bottles, and in a few cases the chytrid has turned up. In Colorado, the chytrid has been found in a few preserved leopard frogs from the 1970s. It has also been detected in museum specimens of the Yosemite toad and the Northern leopard frog, collected from the California Sierra Nevada and the Colorado Rockies, respectively, during the 1970s when both species were in decline. In Australia, it has been traced back to 1978—to a treefrog collected in southern Queensland.[25]

In the mid-1990s, an unknown pathogenic fungus was found to be infecting frogs in Costa Rica, Panama, Australia, and the United States.

Even though our understanding of the fungus has grown tremendously in the last few years, there seem to be more unanswered questions now than ever before. For one thing, scientists do not yet know if there is more than one new species of fungus. Nor do they know how it kills its victims. It may suffocate them by causing their skin to thicken (amphibians breathe partly through their skin), or it may produce toxins. And there are plenty of other questions. Where, for instance, did it come from? It may have been widespread for a long time, and only recently detected, or it may have had a restricted range but recently spread to new regions of the world, where it is finding new host species.[26]

If the chytrid has been expanding its range to such distant parts of the world, what could be moving it around? Some herpetologists think it may have been brought into new terrain on the boots of tourists. Others see a likely conduit in the trade in aquarium fish, and in amphibians themselves. In Australia, some scientists suspect that the chytrid may have been transported across the continent on the skin of an infected frog that stowed itself away in a box of fruit. And once the fungus arrives in an area, there are many ways it could spread: it may be dispersed by local people, for example, or by cattle. It can even be carried by birds and insects.[27]

Another hypothesis is that the fungus could be a well-established pathogen in many parts of world, and that something is upsetting amphibian immune responses, making them more vulnerable to attack. After all, the chytrid is not the only pathogen that has been implicated in amphibian declines. A group of viruses called iridoviruses may have caused the tiger salamander die-offs in Arizona, Utah, Maine, and Saskatchewan. Iridoviruses have also triggered declines of the common frog and the common toad in the United Kingdom.[28]

In Costa Rica, 20 species have declined or disappeared since the late 1980s—including the famous golden toad.

Why so much disease in so many places in so short a time? It is possible that scientists are just finding more disease because they are getting better at looking for it. Or it might be evidence that some widespread stresses are throwing amphibian immune systems out of kilter.

By the late 1990s, evidence for one such stress turned up in Costa Rica, where 20 species have declined or disappeared since the late 1980s—including the famous golden toad. Working on the initial hunch that the declines may have had something to do with the weather, a group of climatologists and biologists led by Alan Pounds, head of Monteverde's Golden Toad Laboratory for Conservation, found strong evidence that the reserve's cloud forest is losing its clouds. According to the researchers, local sea surface temperatures have risen since the mid-1970s, and that has tended to push the cloud bank higher. The mountain tops are bathed in the clouds less frequently, so the forest is now somewhat drier. This might account for the amphibian losses. The theory is corroborated by bird observations: some lowland, "cloud-forest-intolerant" birds have moved upslope, into areas they had never occupied before. But the golden toad lived on top of the range and had nowhere to go.[29]

It is possible that the changing climate led to the toad's demise, but some scientists see another, more ominous possibility in the team's findings. Climate change could be "overlapping" with disease: the stresses of a changing climate could make amphibians more susceptible to infection. It is possible the fungus haunts Monteverde as well. Maybe the Monteverde declines are the result of a kind of synergism between the pathogen and the warming seas.

Climate change and spreading disease: both of these forces have a global reach and they could overlap in a number of ways—either simultaneously or in sequence. A change in the moisture regime, as at Monteverde, or a change in water temperature might weaken amphibian immune systems. Warmer water might also affect a pathogen's virulence, or its capacity to move from one animal to another. Warmer air temperatures might increase the range of insects that carry it.

Infections are likely to combine with other types of stress as well. Excessive UV exposure, like climate stress, could suppress amphibian immune systems. So could some forms of pollution. And some diseases appear to have been spread through the introduction of infected game fish like trout; in such cases, a new predator overlaps with a new disease.[30]

Other overlaps are also cause for concern. Consider, for example, non-native species. Organisms that are successful invaders are often capable of tolerating very disturbed conditions. If some kind of disturbance injures the native amphibians but does an invader no harm, then the latter may gain a level of dominance it might not otherwise have achieved. In the Ural Mountains of

Russia, this mechanism has apparently allowed the introduced lake frog to displace some of the natives. The lake frog seems to tolerate industrial pollution much better than the natives do, so the local frogs have been hit by a pollution-invasion overlap. In the Yosemite region of California, a combination of introduced trout and a five-year drought is considered to be responsible for the decline or disappearance of several species. The trout reduced the amphibians' ranges to isolated patches, and that increased their vulnerability to the drought that hit the area from 1987 to 1992.[31]

Overlapping factors may also be partly responsible for the recent rash of amphibian deformities—although there is no evidence that suggests a relationship between deformities and the declines. In some places where deformities have been observed, scientists believe the cause is a kind of parasitic flatworm called a trematode. As the trematode is often carried by snails, there may be a connection between nutrient-rich waters (for example, water receiving runoff from agricultural areas) that attract snails and trematode infections.[32]

Habitat loss, pollution, UV exposure, non-native species, disease, and climatic instability—those are the stresses that we know or suspect are killing off so many of the world's amphibians. Perhaps there are other, as yet unidentified stresses as well. But a simple inventory like this, dismal as it is, still does not adequately represent the threat because it does not account for the overlap factor. Unfortunately, we have virtually no idea what the overlaps will eventually do.

Beyond the Declines

The loss of amphibians demands our attention not just because we need to know why these animals are dying, but because we need to know what their death will mean. Amphibian decline itself is a form of environmental degradation, since amphibians play critical roles in many ecosystems. Given their sometimes secretive and inconspicuous nature, it is easy to underestimate their importance. Many species are only seen in large numbers when they are breeding or emerging from streams or ponds after they have developed from their aquatic to terrestrial stage. And in many parts of the world amphibians stay buried in forest soils or desert sand for several months at a time—waiting out unfavorable weather.

Despite their cryptic nature, amphibians sometimes outnumber—and may even collectively outweigh—other classes of vertebrates in many temperate and tropical woodlands. In Shenandoah National Park, in the southeastern United States, the Red-backed salamander has been found at densities as high as 10 per square meter. Since the park is a hotspot for salamander diversity, each square meter could well contain other salamander species too. In a New Hampshire forest, scientists found that the total mass of salamanders alone was more than double the mass of birds (even during the birds' peak breeding season) and about equal to the mass of small mammals.[33]

Because they are so numerous, amphibians play key roles in many aquatic and terrestrial ecosystems. As tadpoles, they devour vast quantities of algae and other plants. A Marsh frog tadpole, for example, can filter algae out of about a liter of water each day. In some small lakes and ponds, amphibians may be the most important animal regulators of algae and other plant growth. Algal growth is itself a primary regulator of aquatic oxygen levels; the more algae a body of water has, the less oxygen it is likely to have.[34]

Increased algal growth has already been

observed in parts of the world where amphibians have declined. In Ecuador, for example, algal growth rose in the streams where a species of poison dart frog was once abundant. Karen Lips noticed the same phenomenon following the disappearance of several frog species from her study sites in Central America. This kind of subtle ecological change is presumably occurring in many streams and ponds around the world.[35]

On land, amphibians play an important role as consumers of vast quantities of insects and other invertebrates. Some species also eat small reptiles, birds, and mammals. A study of the Blanchard's cricket frog in Iowa concluded that a small pond population of 1,000 frogs would consume about 4.8 million insects and other arthropods per year.[36]

The loss of amphibians could mean the loss of potential cures for many common ailments.

The pest control benefits of amphibians have long been recognized. A *Farmer's Bulletin* of the U.S. Department of Agriculture from 1915, for example, contained a paper entitled "The Usefulness of the American Toad" by entomologist A. H. Kirkland. After examining the stomachs of 149 toads, Kirkland determined that "injurious insects" such as gypsy moths, tent caterpillars, and may beetles made up 62 percent of the toads' total diet. In one stomach he found the remains of 36 tent caterpillars; in another, 65 gypsy moth caterpillars. He estimated that over 90 days a single toad could consume nearly 10,000 noxious insects. It was Kirkland's hope that toads could receive better protection and use as a natural pesticide in farms and gardens. At the time, the toad's most formidable threat, according to Kirkland, was the "small boy."[37]

Today amphibians get little more credit than they did in Kirkland's time, even though their usefulness is now much more evident. In the 1970s and 1980s, for instance, India and Bangladesh were exporting large quantities of frog legs to Europe, the United States, and Japan as a culinary delicacy. These harvests were intensive enough to virtually empty many large marshes of their frog populations. As the frogs disappeared, the insect populations exploded. Crop damage increased and there was a rise in malaria infections. Frog exports were banned in India in 1979. In Bangladesh, a ban was passed in 1990, after farmers realized that it was cheaper to protect frogs than to buy pesticides. Unfortunately, however, there is still a substantial frog smuggling operation in the region.[38]

In addition to their role as consumers of algae and insects, amphibians also support the many different types of animals that prey on them. They are important in the diets of many birds, mammals, reptiles, and freshwater fish. Some bats and snakes live exclusively on amphibians. In California's Sierra Nevada, for instance, there is a type of garter snake that depends on three of the local amphibian species, two of which are in serious decline. If the garter snake goes into decline as well, that could affect the predatory birds that depend on it. The fate of raptors may be bound up in the fate of frogs.[39]

In both aquatic and terrestrial food webs, amphibians often play an important role in energy transfer and nutrient cycling. Some scientists refer to amphibians as important "conveyor belts" of energy through the ecosystems in which they occur. Compared with birds and mammals, amphibians are much more efficient in converting food into new tissue, so a substantial amount of the energy that enters an ecosystem through photosynthesis passes through amphibians, who then are eaten by foxes, snakes, and owls. Some studies have found that amphibians can also be a much better source of protein than birds and mammals. A predator would be better off eating a pound of frogs rather than a pound of mice. And given their dual roles—aquatic juvenile stage and terrestrial adult stage—amphibians are often an important "nutrient bridge" from water to land. Through them, the algae that might otherwise suffocate a pond becomes a part of the terrestrial fauna.[40]

But the role of amphibians is often far more subtle and complex than food web dynamics might suggest. Consider, for example, the tiny frogs that live inside the tank bromeliads in the Brazilian Atlantic forest. Bromeliads are a type of plant common in tropical American forests; most of them look rather like the rosette of leaves on the top of a pineapple, and most of them are epiphytes—that is, they live in trees instead of rooting directly in the soil. The rosettes of tank bromeliads have an especially large central cavity that holds a pool of water in which many different organisms can live. Some of these "arboreal ponds" are quite substantial; one species of tank bromeliad can hold as much as 30 liters of water. But each pool is isolated from all the others, and many of the inhabitants are strictly aquatic. An effective dispersal mechanism is therefore essential to the survival of these communities, and this is the role that the frogs play. Researchers studying these communities in the Atlantic forest have found a host of little animals—from crustaceans to various types of worms—attached to the skin of bromeliad-dwelling frogs. Apparently, the frogs are moving these creatures from one bromeliad to another. The bromeliads grow and die, but the community as a whole might remain stable because of the frogs.[41]

The loss of amphibians could also mean the loss of potential cures for many common ailments. Amphibians are an incredibly diverse group of organisms that we know relatively little about. We do know that they are living chemical factories; amphibians produce all sorts of powerful compounds, or they concentrate compounds found in their prey. This characteristic is frequently a form of defense. Because amphibian skin is thin and permeable, it offers little physical protection from attack or infection. So protection is often chemical instead. Many species produce antibiotics and fungicides. Some produce powerful poisons, which they advertise to predators with their bright coloring.[42]

These chemicals are a medical treasure, as many traditional cultures have recognized. Pulverized toads, for example, have been used in traditional Chinese medicine for a variety of ailments. And while traditional remedies doubtless vary greatly in their efficacy, modern chemistry is substantiating the power of many of the raw materials. Epibatidine, a compound with powerful painkilling properties, was discovered in a skin secretion from a small, brightly colored Ecuadorian frog known as *Epipedobates tricolor.* Today, U.S. pharmaceutical giant Abbott Laboratories is developing a synthetic compound related in structure to epibatidine that is 200 times more powerful than morphine and does not have that drug's negative side effects, such as constipation, respiratory failure, addiction, and resistance to the desired painkilling effects. Clinical trials of the compound are under way. If it fulfills expectations, the epibatidine analog would be a major advance for medicine—improving the lives of millions of people suffering chronic pain.[43]

Another frog of interest is a large green treefrog that is used in an extraordinary hunting ritual practiced by Indians in the Amazon Basin. The Indians create "hunting magic" by applying a secretion scraped from live frogs to self-inflicted burns on the arms or chest. Following a coma-like sleep, the hunters awake and find they have increased stamina and keener senses. Research on compounds from this frog have yielded several novel compounds that are able to lower blood pressure, reduce pain, and provide antibiotic effects. One compound interacts with a variety of receptor systems and has provided new insights into how the brain's message-reading receptor systems work. Whether or not these compounds are responsible for the "hunting magic" properties experienced by the Amazonian Indians remains unknown.[44]

We have yet to learn even the most obvious lessons from some of these creatures. The wood frog is able to tolerate temperatures low enough to turn up to 65 percent of its body water into ice. It produces some sort of natural antifreeze to keep the remaining water liquid, but how does this system work? And what might we have learned from the gastric-brooding frog if it had not disappeared from the rain forests of Australia? This and other secrets are now beyond reach.

Reconceiving the Science

It has been more than 10 years since the prospect of global amphibian decline first attracted widespread scientific attention. We now understand some species and some localized areas very well. We have discovered that a whole complex of threats, such as nitrogen pollution, climate change, and disease, is involved. But there are still some major gaps in our understanding of the issue.

To begin with, there is an incomplete picture of what is at stake. As eminent herpetologist William Duellman recently noted, "the amphibian faunas of many parts of the world remain essentially unknown, and the faunas in many other regions are far from completely documented." In South America, nearly one third of the amphibian species were discovered in just the last two decades. And new species continue to be discovered at a rapid rate. The parts of the world that contain the largest numbers of undiscovered amphibian species include the mountainous regions of South America and Southeast Asia and the islands in the Indo-Australian Archipelago (Sulawesi, Sumatra, and the Irian Jaya part of New Guinea). In New Guinea, the current estimate of the number of amphibian species is 200, but herpetologist Michael Tyler believes the total is probably twice that. The tropics may harbor thousands of amphibian species not yet known to science.[45]

In part, the gaps in our knowledge stem from the enormous geographical mismatch between the research capacity and the creatures themselves. Canada, for example, has plenty of amphibian specialists, but not a single endemic amphibian. On the other hand, Mexico, like most tropical countries, has a vast amphibian fauna and only a few herpetologists. Although a good deal is known about the amphibians of the United States, Western Europe, Costa Rica, and Australia, there is limited understanding of those of South America, Asia, or most African countries—places that house some of the richest diversity of amphibians in the world. (See Table 4–3.) And among the tropical species already identified, many are in the literature only by virtue of their orig-

Table 4–3. Major Known Hotspots of Amphibian Diversity

Hotspot	Total species	Share endemic	Portion of original area still intact	Amphibian diversity per unit area
	(number)	(percent)		(species per thousand square kilometers of remaining intact natural vegetation)
Tropical Andes	830	73	25.0	2.6
Mesoamerica	460	67	20.0	2.0
Chocó-Darién-Western Ecuador	350	60	24.2	5.6
Atlantic Forest Region	280	90	7.5	3.0
Sundaland (western half of the Indo-Malayan archipelago)	226	79	7.8	1.8
Indo-Burma	202	56	4.9	2.0
Madagascar and Indian Ocean Islands	189	99	9.9	3.2
Caribbean	189	87	11.3	6.3
Brazilian Cerrado	150	30	20.0	0.4
Western Ghats and Sri Lanka	146	80	6.8	11.7
Guinean Forests of West Africa	116	77	10.0	0.9
Mountains of South-Central China	85	60	8.0	1.3
Philippines	84	77	8.0	3.5
Eastern Arc Mountains and Coastal Forests of Tanzania and Kenya	63	52	6.7	31.5
Mediterranean Basin	62	52	4.7	0.6

SOURCE: Russell A. Mittermeier et al., *Hotspots: Earth's Biologically Richest and Most Endangered Terrestrial Ecoregions* (Mexico City: CEMEX, S.A. 1999), 34, 42, and 50.

inal descriptions; in such cases, virtually nothing is known of the animal's ecology or even whether it still exists.[46]

In many parts of the world, amphibian research is frequently constrained by a lack of funds—but not generally by a lack of interest. Consider the dire situation in Bangladesh, where amphibians were widely abundant up until a few decades ago, although today most species are threatened throughout the country. Amphibians in Bangladesh are being decimated by habitat loss, exposure to pesticides and fertilizers, and commercial exploitation. Some species are even being ground up for poultry feed. Yet researchers still have a very tenuous understanding of the country's fauna. As biologist Sohrab Sarker watches the amphibians of his country disappear, he bemoans the lack of funding for field studies. "Amphibians in Bangladesh are not studied scientifically," he says, "there are many species that still need to be investigated and identification of some specimens has been held up due to lack of relevant literature."[47]

From Canada to New Zealand, a growing army of volunteers is canvassing the world's swamps and forests, searching for amphibians.

In Ecuador, there is a similar need for additional research. A little frog called the jambato used to be so common you could find it in the backyards of Quito. But the last time a jambato was seen alive was in 1988. Perhaps the frog fell victim to a fungus, possibly the chytrid, but no one knows because there is no money to do the research.[48]

An article in an April 2000 issue of *Nature* provides an excellent demonstration of how skewed the research is. It contains the most exhaustive overview of amphibian population trends to date. To produce it, a team of researchers combed through the scientific literature and coaxed additional data out of more than 200 scientists in 37 countries. Of the 936 populations the team managed to cover, 87 percent were in Western Europe or North America, 5 percent were in Central and South America, 2 percent were in Asia, and less than 0.5 percent were in Africa and the Middle East.[49]

Moving into the second decade of investigating amphibian declines, it will be essential to fill the gaps in our understanding and support research and conservation efforts in understudied regions. There is also a need to coordinate research programs, make information more accessible, and build a global amphibian database.

A key organization that has already played a major role in informing many of the world's herpetologists and supporting research efforts in developing countries is the Declining Amphibian Populations Task Force (DAPTF). This was established in 1991 under the auspices of the World Conservation Union–IUCN's Species Survival Commission. It encompasses a network of over 3,000 scientists and conservationists in more than 90 countries and serves as a global "information clearinghouse" on amphibian decline. The Task Force produces the newsletter *Froglog*, which is an important vehicle for communicating updates on research and conservation endeavors from all over the world. Currently, the volunteer scientists who manage the Task Force are compiling a comprehensive summary of the declines and a CD-ROM database of all data available on amphibian populations, declining or otherwise. Both of these will be available in 2002.[50]

In 1999, the DAPTF helped organize a series of amphibian decline workshops in Mexico, Panama, and Ecuador. The organizers hoped the meetings would be the first in a series of efforts to coordinate and build amphibian research in the region. Given the level of participation—the workshops drew in 88 people from 13 countries—that seems like a reasonable expectation.[51]

The Internet is also providing new and speedy ways for researchers to communicate and contribute to global databases. The recently launched Amphibiaweb is a site dedicated to providing information on all the world's known amphibian species. Each species will have its own "home page," including species description, life history traits, conservation status, and literature references.[52]

Acquiring more information will get us only so far. Once the information is collected, it must be used in the most effective way possible. For this, it will be necessary to change the way the science is done. The declines cannot readily be contained in a single field of inquiry. They involve microscopic pathogens and global climate change; they are part of forestry economics and wildlife toxicology. Understanding them will require a much more interdisciplinary, integrative approach than is typical of conventional research. Instead of individual specialists working on problems independently, research programs will have to find ways to focus the efforts of many disciplines into a collaborative whole. Some of the most successful recent work is already moving in this direction—the climate research at Monteverde, for example, or the international investigation of the chytrid fungus.

That idea is beginning to resonate within some major scientific institutions, such as the National Science Foundation, the U.S. government body that is the chief source of federal funds for scientific research. In 1999, the agency awarded $3 million to a team of 24 scientists from fields as diverse as veterinary epidemiology and evolutionary ecology to study host-pathogen relationships as an aspect of amphibian decline. Jim Collins, the Arizona State University biologist who heads the team, explained the challenge this way: "As we went through thinking about how to answer the questions, we really had to think about how we did the science. And how we did the science had to change—it couldn't be just an individual investigator laboring away in an isolated laboratory." Collins emphasizes the need for interaction not just between different biological disciplines, but also with the social sciences and possibly even the humanities. "To understand this problem we have to do a better job of integrating humans into ecological and evolutionary theory," he argues. "The nature of science itself is going to have to change."[53]

But the new research paradigm cannot be just a matter of linking scientists together. Because the problem is so pervasive, science is going to need to build a community of serious amateurs—members of the general public who can become "citizen scientists." A volunteer amphibian monitoring movement is already gaining steam. From Canada to New Zealand, a growing army of volunteers equipped with amphibian identification tapes, field guides, flashlights, pencils, and waterproof notepads is canvassing the world's swamps and forests, searching for amphibians. From schoolchildren to retirees, these people are heading out in evening hours, listening for frog calls, and keeping careful records of what they hear and see.

One of the largest volunteer networks is the North American Amphibian Monitoring Program (NAAMP). The program began in the mid-1990s, and by 1999 hundreds of volunteers were working in 25 states. They are trained to identify their local amphibian fauna and follow a standardized monitoring protocol. The data they collect become part of a global pool of information that is being used to gain a better understanding of amphibian declines. Indicative of the extent of this effort, in Minnesota the program has sold more than 1,000 copies of its amphibian audio tape, and its well-tuned volunteers have covered 150 monitoring routes since 1993. In Maine, NAAMP volunteers monitor 60 routes; Texan volunteers cover 20 routes.[54]

In many cases, volunteers see animals they have never seen before. A participant in a Massachusetts program commented that she had lived in her town for her entire life and "had no idea that each spring hundreds of salamanders crossed through her backyard." Massachusetts volunteers are also involved in identifying vernal pools—the shallow, seasonally flooded wetlands that provide critical breeding sites for many amphibians. Since the late 1980s, local citizens have helped identify a good portion of the 1,200 vernal pools that are now protected by the state.[55]

Another monitoring network is under development in Central America. Modeled on NAAMP, the Maya Forest Anuran Monitoring Project (MAYANMON) was initiated in 1997 to monitor amphibians in the Maya Forest region. Today, the program is a tri-national effort, with sites in Belize, Mexico, and Guatemala. It plans to add additional countries soon. Like NAAMP, this is a volunteer program based on regular, standardized monitoring of numerous sites. The information collected will be critical for the development of baseline data for an area that has not been well studied. Thus far, all participants are biologists, but MAYANMON recently received a grant to train local Mayan villagers who have an interest in monitoring the ecological health of their surroundings. The MAYANMON project is the first of its kind to be undertaken in Central America, and it represents a unique example of international cooperation.[56]

Many European countries have encouraged volunteer efforts to reduce road traffic mortality. Beginning in the 1960s, conservationists initiated programs to reduce amphibian roadkills by informing motorists, installing "toad-crossing" traffic signs, and setting up detours during peak migration times. More recently, drift fences have been used to capture migrating amphibians as they head toward roads. Once the migrants have been detained at the base of the fence, volunteers capture them and ferry them to safety. A "toad patrol" squad at one road crossing in England rescued more than 4,500 toads in just one season. At the same crossing, more than a thousand toads were killed by motorists.[57]

In addition to providing crucial information about population trends, migration patterns, and breeding sites, the new trend in "citizen science" is providing something that may be even more significant. By getting people out into the woods and swamps and attuned to their local fauna, the volunteer programs could serve as a way to capture the public's imagination and develop bigger constituencies for conservation science. Amphibian decline is kind of a case study of unsustainability, touching on all the major environmental issues of our day. It could serve as an important catalyst for change on these issues.

Protecting Amphibians

There are clearly many impressive and promising initiatives under way that bode well for the future of amphibian research. But will the evidence ever translate into sweeping changes in conservation policy? Considering amphibian decline as a political issue, it is almost inconceivable to imagine an international treaty to prevent frog extinctions. Amphibian decline lacks the political "weight" of issues like climate change. True, some countries do have explicit policies protecting amphibians—but these vary greatly around the world, and as is clear from the current trend in amphibian populations, they are not entirely effective.

In the United States, the Endangered

Species Act (ESA) is the only law that provides direct protection for amphibians. Since its inception in 1973, 18 frog, toad, and salamander species—out of 194 identified in the country—have been listed as threatened or endangered under ESA. Species listed under ESA receive special protection, primarily in the form of a "take" prohibition that makes it unlawful for a person to kill or injure a listed species—this can include any significant habitat alteration or degradation that kills or injures the species. Other recovery strategies, such as captive breeding and reintroductions, are also frequently used.[58]

Over 27 years ESA has been successful in rescuing several amphibian species from the brink of extinction. And it has provided many indirect benefits through the protection of habitats—wetlands or forests that are saved for amphibians clearly provide many important services beyond being homes for frogs. But there are also some pitfalls associated with ESA. For one thing, it can take years for the listing to be approved once a petition has been filed. The Santa Barbara County population of the California tiger salamander, for example, finally received permanent listing as endangered under ESA in September 2000—eight years after the listing petition was submitted and 15 years after the species was first recognized as a candidate. In those 15 years, more than half of the population's known breeding sites were destroyed.[59]

Denmark, France, Germany, Luxembourg, and the Netherlands also have legislation protecting all amphibians. But in other European countries, there is no protection. As in the United States, formal protection of amphibian species usually entails some form of habitat protection.[60]

There is one international treaty that provides some specific protection for amphibians. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) controls trade in numerous endangered plant and animal species. (See Chapter 9.) As of 2000, 81 amphibian species were protected under CITES. But the focus of CITES is on restricting international trade, not on providing on-the-ground protection within a country's borders.[61]

As laudable as ESA and CITES are, such species-specific approaches are not enough to slow the current pace of global amphibian declines. Beyond the fact that they apply to just a tiny fraction of the world's amphibian species, these strategies are not effective for several reasons. For one thing, many species are going extinct that are not on any lists at all. They are disappearing in remote areas of the world where the amphibian faunas are not well understood. In addition, many of the declines and disappearances have taken place in just a year or two—far too quickly to do the paperwork for listing under laws like ESA or CITES. And finally, even if species such as these had been protected under an endangered species law, it probably would have made no difference. They already lived in highly protected areas. The Monteverde Cloud Forest is one of the world's premier parks, and home to expert biologists who monitor the local fauna very closely. Aside from a last-ditch effort at captive breeding (which was attempted with the gastric-brooding frog), there was no obvious way these losses could have been prevented by the time they were detected.

Given the magnitude of the threats at play, it is obvious that a species-by-species approach is just not going to work. The problem of amphibian declines is teaching us an important lesson about the way we approach environmental issues in general.

While it is certainly reasonable to argue for more money and research and conservation, and to demand more powerful conservation policies, the painful fact is this: no amount of money or legislation is going to make this problem go away—if it is directed only at this problem. What is happening to amphibians reflects what is happening to the planet in general. If we don't address the underlying reasons for amphibian decline, there is no way we can save these species.

While efforts to protect particular species are important, amphibians show us that what really matters are the initiatives to protect forests, wetlands, and other essential habitat; to reduce the spread of non-native species; to improve farming practices so that farmers don't depend on heavy inputs of pesticides and fertilizers; and to reduce the emissions of greenhouse gases that contribute to climate change. Clearly, the benefits of these changes will be felt far beyond frogs and salamanders. They will have far-reaching impacts on ecosystems and human health in general. Ultimately, the survival of amphibians and other creatures will depend on our willingness to confront the major, systemic environmental issues of our day.