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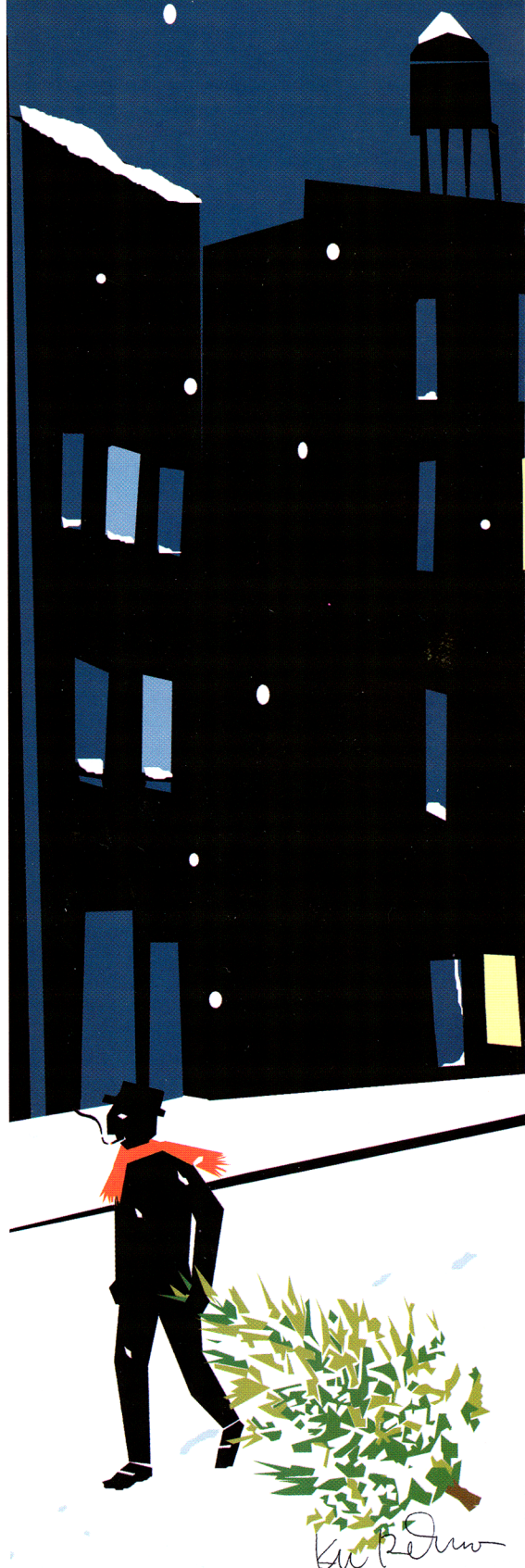
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BUTTERFLY LESSONS

Insects and toads respond to global warming.

BY ELIZABETH KOLBERT

P*olygonia c-album*, generally known as the comma butterfly, spends most of its life pretending to be something else. In its larval, or caterpillar, stage, it has a chalky stripe down its back which makes it look uncannily like a bird dropping. As an adult, with wings folded, it is practically indistinguishable from a dead leaf. The comma gets its name from a tiny white mark shaped like the letter “c” on its underside. Even this is thought to be part of its camouflage—an ersatz rip of the sort that leaves get when they are particularly old and tatty.

The comma is a European butterfly—its American cousins are the hop merchant and the question mark—and it can be found in France, where it is known as *le Robert-le-Diable*; Germany, where it is called *der C-Falter*; and the Netherlands, where it is *gebakkelde aurelia*. The comma reaches the northern edge of its distribution in Britain. This is unremarkable—many European butterflies come to the end of their range in England—but from a scientific standpoint fortunate.

The English have been watching and collecting butterflies for centuries—some of the specimens in the British Natural History Museum date back to the seventeen-hundreds—and in the Victorian era passion for the hobby was such that even many small towns supported their own entomological societies. In the nineteen-sixties, Britain’s Biological Records Centre decided to marshal this enthusiasm for a project called the Lepidoptera Distribution Maps Scheme, whose aim was to chart precisely where each of the country’s fifty-nine native species could—and could not—be found. More than two thousand butterfly enthusiasts participated, and in 1984 the results were collated into a hundred-and-fifty-eight-page atlas. Every species got its own map, with black dots

showing where it had been sighted. On the map for *Polygonia c-album*, the comma’s range was shown to extend from the south coast of England up to Liverpool in the west and Norfolk in the east. Almost immediately, the map became out of date; in the years that followed, hobbyists kept finding the comma in new areas. By

Chris Thomas is a biologist at the University of York who studies lepidoptera. He is tall and rangy, with an Ethan Hawke-style goatee and an amiably harried manner. The day I met him, he had just returned from looking for butterflies in Wales, and the first thing he said to me when I got into his car was please not to mind the smell of wet socks. A few years ago, Thomas, his wife, their two sets of twins, an Irish wolfhound, a pony, some rabbits, two cats, and several chickens moved into an old farmhouse in the village of Wistow, in the Vale of York. The University of York has an array of thermostatic chambers where commas are raised under temperature-controlled conditions, fed carefully monitored diets, and



the late nineteen-nineties, the butterfly was frequently being sighted in the north of England, near Durham. By now, it is established in southern Scotland, and has been sighted as far up as the Highlands. The rate of the comma’s expansion—some fifty miles per decade—was described by the authors of the most recent butterfly atlas as “remarkable.”

measured on a near-constant basis, but, in the spirit of British amateurism, Thomas decided to turn his own back yard into a field lab. He scattered wildflower seeds he had collected from nearby meadows and ditches, planted nearly seven hundred trees, and waited for the butterflies to show up. When I visited the place in midsummer, the wildflowers were in bloom and the

JOOST SWARTE

grass was so high that many of the tiny trees looked lost, like kids in search of their parents. The Vale of York is almost completely flat—during the last ice age, it formed the bottom of a giant lake—and from the yard Thomas pointed out the spires of Selby Abbey, built nearly a thousand years ago, and also the cooling towers of the Drax power plant, Britain's largest, some ten miles away. It was cloudy, and since butterflies don't generally fly when it's gray, we went inside.

Butterflies, Thomas explained after putting the kettle on for tea, can be divided into two groups. The so-called "specialists" require specific—in some cases unique—conditions. Specialists include the chalkhill blue (*Polymmatius coridon*), a large turquoise butterfly that feeds exclusively on horseshoe vetch, and the purple emperor (*Apatura iris*), which flies in the treetops of well-wooded areas in southern England. The "generalists" are less picky. Among Britain's generalists, there are, in addition to the comma, ten species that are widespread in the southern part of the country and reach the edge of their range somewhere in the nation's midsection. "Every single one has moved northward since 1982," Thomas told me. A few years ago, with lepidopterists from, among other places, the United States, Sweden, France, and Estonia, Thomas conducted a survey of all the studies that had been done on generalists that reach the northern limits of their ranges in Europe. The survey looked at thirty-five species in all. Of these, the scientists found, twenty-two had shifted their range northward in recent decades; only one had shifted south.

After a while, the sun emerged, and we went back outside. Thomas's wolfhound, Rex, a dog the size of a small horse, trailed behind us, panting heavily. Within about five minutes, Thomas had identified a meadow brown (*Maniola jurtina*), a small tortoiseshell (*Aglais urticae*), and a green-veined white (*Pieris napi*), all species that have been flitting around Yorkshire since butterfly record-keeping began. Thomas also spotted a gatekeeper (*Pyronia tithonus*) and a small skipper (*Thymelicus sylvestris*), which until recently had been confined to a region south of where we were

standing. "So far, two out of the five species of butterflies that we've seen are northward invaders," he told me. "Sometime within the last thirty years they have spread into this area." A few minutes later, he pointed out another invader sunning itself in the grass—a *Polygonia c-album*. With its wings closed, the comma was a dull, dead-leaf brown, but with them open it was a brilliant orange.

That life on earth changes with the climate has been assumed to be the case for a long time—indeed, for very nearly as long as the climate has been known to be capable of changing. In 1840, Louis Agassiz published "Études sur les Glaciers," the work in which he laid out his theory of the ice ages. By 1859, Charles Darwin had incorporated Agassiz's theory into his own theory of evolution. Toward the end of "On the Origin of Species," in a chapter titled "Geographical Distribution," Darwin describes the vast migrations that he supposes the advance and retreat of the glaciers must have necessitated:

As the cold came on, and as each more southern zone became fitted for arctic beings and ill-fitted for their former more temperate inhabitants, the latter would be supplanted and arctic productions would take their places. The inhabitants of the more temperate regions would at the same time travel southward. . . . As the warmth returned, the arctic forms would retreat northward, closely followed up in their retreat by the productions of the more temperate regions. And as the snow melted from the bases of the mountains, the arctic forms would seize on the cleared and thawed ground, always ascending higher and higher, as the warmth increased, whilst their brethren were pursuing their northern journey.

The last of the great ice sheets retreated some ten thousand years ago, at the start of the Holocene. At that point, the concentration of carbon dioxide in the atmosphere stood at two hundred and sixty parts per million. Give or take twenty parts per million, it remained at that level through the invention of agriculture, the founding of the first cities, the building of the pyramids, and the discovery of the New World. When, in the early eighteenth century, coal-burning began to drive up CO₂ levels, they rose at first gradually—it took more than a century to reach three hundred parts per mil-

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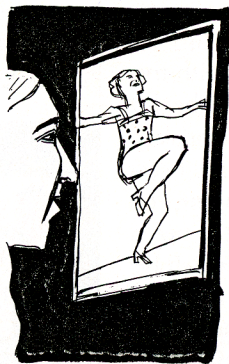


lion—and later, following the Second World War, much more rapidly. By 1965, CO₂ concentrations had reached three hundred and twenty parts per million; by 1985, three hundred and forty-six parts per million; and, by 2005, three hundred and seventy-eight parts per million. If current trends continue, it will reach five hundred parts per million (nearly double pre-industrial levels) by the middle of this century, and could reach as much as seven hundred and fifty parts per million (nearly triple pre-industrial levels) by 2100. The equilibrium warming associated with doubled CO₂ is estimated to be between three and a half and seven degrees, and with tripled CO₂ between six and eleven degrees. A global temperature rise of just three degrees would render the earth hotter than it has been at any point in the past two million years.

This vast geophysical experiment is a biological one as well. Darwin never imagined that the effects of climate change could be observed in a human lifetime, yet, almost anywhere you go in the world today, it is possible to observe changes comparable to the northern expansion of the comma. A recent study of common frogs living near Ithaca, New York, for example, found that four out of six species were calling, which is to say mating, at least ten days earlier than at the start of the nineteenth-century, while at the Arnold Arboretum, in Boston, the peak blooming date for spring-flowering shrubs has advanced, on average, by eight days. In Costa Rica, birds like the keel-billed toucan (*Ramphastos sulfuratus*), once confined to the lowlands and foothills, have started to nest on mountain slopes; in the Alps, plants like purple saxifrage (*Saxifraga oppositifolia*) and Austrian draba (*Draba fladnizensis*) have been creeping up toward the summits; and in the Sierra Nevada mountains of California the average Edith's checkerspot butterfly (*Euphydryas editha*) is now found at an elevation three hundred feet higher than it was a hundred years ago. To what extent life on earth will be transformed by the warming expected in the coming years is, at

this point, still a matter of speculation. Clearly, though, the process has begun.

The Bradshaw-Holzapfel lab occupies a corner on the third floor of Pacific Hall, a peculiarly unlovely building on the campus of the University of Oregon, in Eugene. At one end of the lab is a large room stacked with glassware, and at the other end is a trio of offices. In between are several workrooms that look, from the outside, like walk-in refrigerators. Taped to the door of one of them is a handwritten sign: "Warning—If you enter this room mosquitoes will suck your blood out through your eyes!"



William Bradshaw and Christina Holzapfel, who run the lab and share one of the offices, are evolutionary geneticists. They met as graduate students at the University of Michigan, and have been married for thirty-four years. Bradshaw is a tall man with thinning gray hair and a gravelly voice. His desk is covered in a mess of papers, books, and journals, and when visitors come to the lab he likes to show them his collection of curiosities, which includes a desiccated octopus. Holzapfel is short, with blond hair and bright-blue eyes. Her desk is perfectly neat.

Bradshaw and Holzapfel have shared an interest in mosquitoes for as long as they've been interested in each other. In the early years of their lab, which they set up in 1971, they raised several different species, some of which, in order to reproduce, required what is delicately referred to as a "blood meal." This, in turn, demanded a live animal able to provide such a meal. For a time, this requirement was met by rats anesthetized with phenobarbital, but, as rules about experimenting with animals grew more stringent, Bradshaw and Holzapfel found themselves forced to decide whether it was more humane to keep anesthetizing the same rat over and over or to use a new rat and let the old one wake up to find itself covered with bites. Eventually, they decided to stick to a single species, *Wyeomyia smithii*, which needs no blood in order to reproduce. At any given moment, the

Bradshaw-Holzapfel lab houses upward of a hundred thousand *Wyeomyia smithii* in various stages of development.

Wyeomyia smithii is a small and rather ineffectual bug. ("Wimpy" is how Bradshaw characterizes it.) Its eggs are practically indistinguishable from specks of dust; its larvae appear as minuscule white wrigglers. As an adult, it is about a quarter of an inch long and in flight looks like a tiny black blur. Only when you examine a *Wyeomyia smithii* very closely, under a magnifying glass, can you see that its abdomen is actually silver and that its two hind legs are bent gracefully above its head, like a trapeze artist's.

Wyeomyia smithii completes virtually its entire life cycle—from egg to larva to pupa to adult—inside a single plant, *Sarracenia purpurea*, or, as it is more commonly known, the purple pitcher plant. The purple pitcher plant, which grows in swamps and peat bogs from Florida to northern Canada, has frilly, cornucopia-shaped leaves that sprout directly out of the ground and then fill with water. In the spring, female *Wyeomyia smithii* lay their eggs one at a time, carefully depositing them in different pitcher plants. When ants and flies and, occasionally, small frogs drown in the leaves of the pitcher plant, their remains provide nutrients not only for the plant—*Sarracenia purpurea* is carnivorous—but also for developing mosquito larvae. (*Sarracenia purpurea* does not digest its own food; it leaves this task to bacteria, which don't attack the mosquitoes.) Once the young mature into adults, they repeat the whole process, and, if conditions are right, the cycle can be completed four or five times in a single summer. Come fall, the adult mosquitoes die off, but the larvae live on through the winter in a state of suspended animation known as diapause—the insect version of hibernation.

The exact timing of diapause is critical to the survival of *Wyeomyia smithii* and also to Bradshaw and Holzapfel's research. When the larvae perceive that day length has dropped below a certain threshold, they stop growing and molting; when they perceive that it has lengthened sufficiently, they take up where they left off.

This light threshold, which is known as the critical photoperiod, varies from bog to bog. At the southern end of the

mosquitoes' range, near the Gulf of Mexico, conditions remain favorable for breeding well into fall. A typical *Wyeomyia smithii* from Florida or Alabama will, consequently, not go dormant until day length has shrunk to about twelve hours, which at that latitude corresponds to early November. At the far northern edge of the range, meanwhile, winter arrives much earlier, and an average mosquito from Manitoba will go into dormancy in late July, as soon as day length drops below sixteen and a half hours. Interpreting light cues is a genetically controlled and highly heritable trait: *Wyeomyia smithii* are programmed to respond to day length the same way their parents did, even if they find themselves living under very different conditions. (One of the walk-in-freezer-like rooms in the Bradshaw-Holzapel lab contains locker-size storage units, each equipped with a timer and a fluorescent bulb, where mosquito larvae can be raised under any imaginable schedule of light and dark.) In the mid-nineteen-seventies, Bradshaw and Holzapel demonstrated that *Wyeomyia smithii* living at different elevations also obey different light cues—high-altitude mosquitoes behave as if they were born farther north—a discovery that today might seem relatively unremarkable but at the time was sufficiently noteworthy to make the cover of *Nature*.

About five years ago, Bradshaw and Holzapel began to wonder about how *Wyeomyia smithii* might be affected by global warming. They knew that the species had expanded northward after the end of the last glaciation, and that, at some point in the intervening millennia, the critical photoperiods of northern and southern populations had diverged. If the climatic conditions for *Wyeomyia smithii* were changing once again, then perhaps this would show up in the timing of diapause. The first thing the couple did was go back to look at their old records, to see if the data contained any information that they hadn't noticed before.

"There it was," Holzapel told me. "Just hitting you right in the eye."

When an animal changes its routine by, say, laying its eggs earlier or going into hibernation later, there are a number of possible explanations. One is that the change reflects an innate

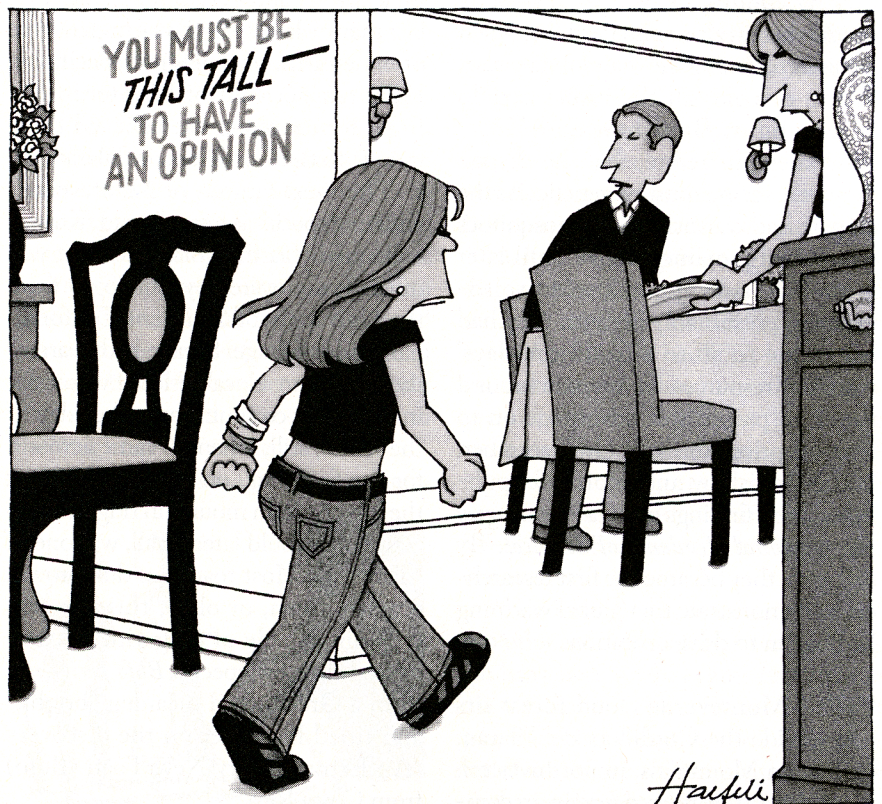
flexibility; as conditions vary, the animal is able to adjust its behavior in response. Biologists call such flexibility "phenotypic plasticity," and it is key to the survival of most species. Another possibility is that the shift represents something deeper and more permanent—an actual rearrangement of the organism's genetic structure.

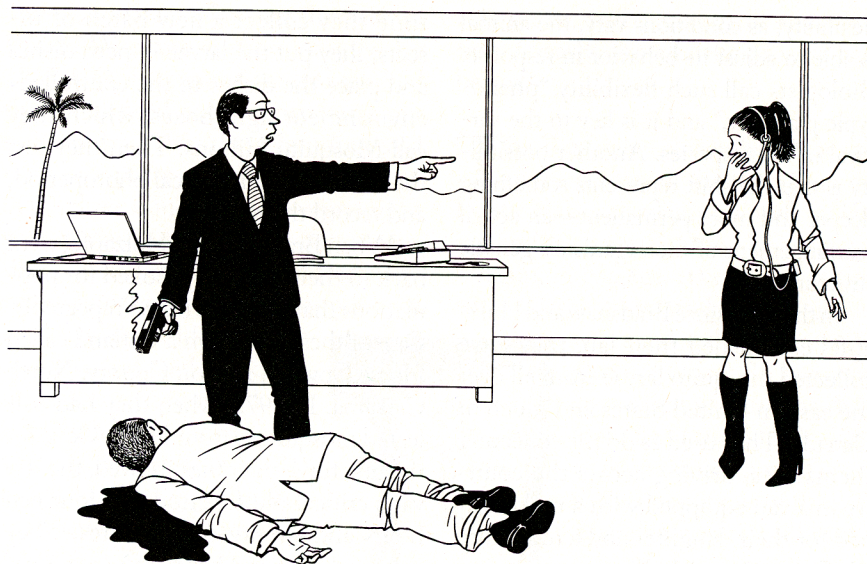
In the years since Bradshaw and Holzapel established their lab, they have collected mosquito larvae from all over the eastern United States and much of Canada. They used to do the collecting themselves, driving across the country in a van equipped with a makeshift bed for their daughter and a miniature lab for sorting, labelling, and storing the thousands of specimens they would gather. Nowadays, they more often send out their graduate students, who, instead of driving, are likely to fly. (Getting through airport security with a backpack full of mosquito larvae is a process that, the students have learned, can take half a day.)

Every subpopulation exhibits a range of light responses; Bradshaw and Holzapel define critical photoperiod as the point at which fifty per cent of the mosquitoes in a sample have switched from active development to diapause. Each

time they collect a new batch of insects, they put the larvae in petri dishes and place the dishes in the controlled-environment light boxes, which they call Mosquito Hiltons. Then they test the larvae for their critical photoperiod, and record the results.

When Bradshaw and Holzapel went back to their files, they looked for populations that they had tested repeatedly. One of these was from a wetland called Horse Cove, in Macon County, North Carolina. In 1972, when they had collected mosquitoes from Horse Cove for the first time, their files showed, the larvae's critical photoperiod was fourteen hours and twenty-one minutes. They collected a second batch of mosquitoes from the same spot in 1996. By that point, the insects' critical photoperiod had dropped to thirteen hours and fifty-three minutes. All told, Bradshaw and Holzapel found comparative data in their files on ten different subpopulations—two in Florida, three in North Carolina, two in New Jersey, and one each in Alabama, Maine, and Ontario. In every case, the critical photoperiod had declined over time. Their data also showed that the farther north you went the stronger the effect; a regression analysis revealed that the critical photo-





GREGORY

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period of mosquitoes living at fifty degrees north latitude had declined by more than thirty-five minutes, corresponding to a delay in diapause of nine days.

In a different mosquito, this shift could be an instance of the kind of plasticity that allows organisms to cope with varying conditions. But in *Wyeomyia smithii* there is almost no flexibility when it comes to timing the onset of diapause. Warm or cold, all the insect can do is read light. Bradshaw and Holzapfel knew, therefore, that the change they were seeing must be genetic. As the climate had warmed, those mosquitoes which had remained active until later in the fall had enjoyed a selective advantage, presumably because they had been able to store a few more days' worth of resources for the winter, and they had passed this advantage on to their offspring, and so on. In December, 2001, Bradshaw and Holzapfel published their findings in the *Proceedings of the National Academy of Sciences*. By doing so, they became the first researchers to demonstrate that global warming had begun to drive evolution.

The Monteverde cloud forest sits astride the Cordillera de Tilarán, or Tilarán Mountains, in northwestern Costa Rica. The rugged terrain, in com-

bination with the trade winds that blow off the Caribbean, makes the region unusually diverse; in an area of less than two hundred and fifty square miles, there are seven different "life zones," each with its own distinctive type of vegetation. The cloud forest is surrounded on all sides by land, yet, ecologically speaking, it is an island and, like many islands, displays a high degree of endemism, or biological specificity. Fully ten per cent of Monteverdean flora, for example, are believed to be unique to the Cordillera de Tilarán.

The most famous of Monteverde's endemic species is a small toad. Known colloquially as the golden toad, it was officially discovered by a biologist from the University of Southern California named Jay Savage. Savage had heard of the toad from a local resident who lived in a Quaker community at the edge of the forest; still, when he came across it for the first time, on May 14, 1964, at the top of a high mountain ridge, his reaction, he would later recall, was one of "disbelief." Most toads are dull brown, grayish green, or olive; this one was a flaming shade of tangerine. Savage named the new species *Bufo perigrinus*, from a Greek word meaning "bright," and titled his paper on the discovery "An Extraordinary New Toad (*Bufo*) from Costa Rica."

Since the golden toad spent its life underground, emerging only in order to reproduce, most of what was subsequently learned about it had to do with sex. The toad turned out to be an "explosive breeder." Instead of staking out and defending territory, males simply rushed the first available female and fought for the chance to mount her. ("Amplexus" is the term of art for an amphibian embrace.) Generally, males outnumbered females, in some years by as much as ten to one, a situation that often led bachelors to attack amplexant pairs and form what Savage once described as "writhing masses of toad balls." The eggs of the golden toad, black-and-tan spheres, were deposited in small pools—puddles, really—often no more than an inch deep. Tadpoles emerged in a matter of days, but required another month for metamorphosis. During this period, they were highly dependent on the weather: too much rain and they would be washed down the steep hillsides, too little and their puddles would dry up. Golden toads were never found more than a few miles from the site where Savage originally spotted them, always at the top of a mountain ridge, and always at an altitude of between forty-nine hundred and fifty-six hundred feet.

In the spring of 1987, an American biologist who had come to the cloud forest specifically to study the amphibians there counted fifteen hundred golden toads in temporary breeding pools. That spring was unusually warm and dry, and most of the pools evaporated before the tadpoles in them had had time to mature. The following year, only one male was seen at what previously had been the major breeding site. Seven males and two females were seen at a second site a few miles away. The year after that, a search of all spots where the toad had earlier been sighted yielded a solitary male. No golden toad has been seen since, and it is widely assumed that after living its colorful, if secretive, existence for hundreds of thousands of years *Bufo perigrinus* is now extinct.

In April, 1999, J. Alan Pounds, who heads the Golden Toad Laboratory for Conservation, in the Monteverde Preserve, published a paper in *Nature* on the golden toad's demise. In it, he linked the toad's extinction, as well as the de-

cline of several other amphibian species, to a shift in rainfall patterns. In recent years, there has been a significant increase in the number of days with no measurable precipitation in Monteverde, a change that, in turn, is consonant with an increase in the elevation of the cloud cover. In a separate article in the same issue of *Nature*, a group of scientists from the United States and Japan reported on their efforts to model the future of cloud forests. They predicted that as global CO₂ levels continued to rise, the height of the cloud cover in Monteverde and other tropical cloud forests would continue to climb. This, they speculated, would force additional high-altitude species "out of existence."

Climate change—even violent climate change—is itself, of course, part of the natural order. In the past two million years, great ice sheets have advanced over the Northern Hemisphere and retreated again at least twenty times. In addition, there have also been dozens of abrupt climate shifts, like the Younger Dryas, which occurred some twelve thousand eight hundred years ago. (The event is named after a small Arctic plant—*Dryas octopetala*—that suddenly reappeared in Scandinavia.) At that point, the earth, which had been warming rapidly, cooled back down into ice-age conditions. It remained frigid for twelve centuries and then warmed, even more abruptly; in Greenland, ice-core records show, average annual temperatures climbed by nearly twenty degrees in a single decade.

Thompson Webb III is a paleoecologist who teaches at Brown University. He studies pollen grains and fern spores, in an effort to reconstruct the plant life of previous eras. In the mid-seventies, Webb began to assemble a database of pollen records from lakes all across North America. (When a grain of pollen falls on the ground, it usually oxidizes and disappears; if it is blown onto a body of water, however, it can sink to the bottom and be preserved in the sediment for millennia.) The project took nearly twenty years to complete, and, when it was finally done, it showed how, as the climate of the continent had changed, life had rearranged itself.

A few months ago, I went to visit

Webb in Providence. He has an office in the university's geochemistry building, and also a lab, where, on this particular day, one of his research assistants was examining charcoal particles from an ancient forest fire. Webb took some slides from a cabinet and slipped one under the lens of a microscope. Most pollen grains are between twenty and seventy microns in diameter; to be identified, they must be magnified four hundred times. Peering through the eyepiece, I saw a tiny sphere, pocked like a golf ball. Webb told me that what I was looking at was a grain of birch pollen. He replaced the slide, and a second tiny golf ball swam into focus. It was beech pollen, Webb explained, and could be distinguished by a set of three minute grooves. "You see, they're really very different," he said of the two grains.

After a while, we went down the hall to Webb's office. On his computer he called up a program named Pollen Viewer 3.2, and a map of North America circa 19000 B.C. appeared on the screen. Around that time, the ice sheets of the last glaciation reached their maximum extent; the map showed the Laurentide ice sheet covering all of Canada as well as most of New England and the upper Midwest. Because so much water was tied up in the ice, sea levels were some three hundred feet lower than they are now. On the map, Florida appeared as a stubby protuberance, nearly twice as wide as it is today. Webb clicked on "Play." Time began to move forward in thousand-year increments. The ice sheet shrank. A huge lake, known as Lake Agassiz, formed in central Canada, and, a few thousand years later, drained. The Great Lakes emerged, and then widened. Around eight thousand years ago, open water finally appeared in Hudson Bay. The bay began to contract as the land around it rebounded from the weight of the ice sheet.

Webb clicked on a pull-down menu



that listed the Latin names of dozens of trees and shrubs. He chose *Pinus* (pine) and again hit "Play." Dark-green splotches began to move around the continent. Twenty-one thousand years ago, the program showed, pine forests covered the entire Eastern Seaboard south of the ice sheet. Ten thousand years later, pines were concentrated around the Great Lakes, and today pine predominates in the southeastern United States and in western Canada. Webb clicked on *Quercus* (oak), and a similar process began, only *Quercus* moved in a very different pattern from *Pinus*. More clicks for *Fagus* (beech), *Betula* (birch), and *Picea* (spruce). As the earth warmed and the continent emerged from the ice age, each of the tree species migrated, but no two moved in exactly the same way.

"The trick you've got to remember is that climate is multivariate," Webb explained. "The plant species are having to respond both to temperature changes and to moisture changes and to changes in seasonality. It makes a big difference if you have a drier winter versus a drier summer, because some species are more attuned to spring and others to fall. Any current community has a certain mixture, and, if you start changing the climate, you're changing the temperature, but you're also changing moisture or the timing of the moisture or the amount of snow and, bingo, species are not going to move together. They can't."

Webb pointed out that the warming predicted for the next century is on the same scale as the temperature difference between the last glaciation and today. "You know that's going to give us a very different landscape," he said. I asked what he thought this landscape would look like. He said he didn't know—his central finding, from more than thirty years of research, is that, as the climate changes, species often move in surprising ways. In the short term, which is to say in the remainder of his own life, Webb said that he expected mostly to see disruption.

"We have this strange sense of the evolutionary hierarchy, that the microorganisms, because they came first, are the most primitive," he told me. "And yet you could argue that this will just give a lot of advantage to the microorganisms of the world, because of their ability to

evolve more quickly. To the extent the climate is putting organisms as well as ecosystems under stress, it's opening the opportunities for invasive species on the one hand and disease on the other. I guess I start thinking: Think death."

Any species that is around today, including our own, has already survived catastrophic climate change. The fact that a species has survived such a change, or even many such changes, is no guarantee, however, that it will survive the next one. Consider, for example, the outsized megafauna—seven-hundred-and-fifty-pound sabre-toothed cats, elephantine sloths, and fifteen-foot-tall mastodons—that once dominated the North American landscape. These megafauna lived through several glacial cycles, but then something changed, and they nearly all died out at the same time, at the beginning of the Holocene.

Over the past two million years, even as the temperature of the earth has swung wildly, it has always remained within certain limits: the planet has often been colder than today, but rarely warmer, and then only slightly. If the earth continues to warm at the current rate, then by the end of this century temperatures will push beyond the "envelope" of natural climate variability.

Meanwhile, thanks to us, the world today is a very different—and in many ways diminished—place. International trade has introduced exotic pests and competitors; ozone depletion has in-

creased exposure to ultraviolet radiation; and many species have already been very nearly wiped out, or wiped out altogether, by overhunting and overharvesting. Perhaps most significantly, human activity, in the form of farms and cities and subdivisions and mines and logging operations and parking lots, has steadily reduced the amount of available habitat. G. Russell Coope is a visiting professor in the geography department at the University of London and one of the world's leading authorities on ancient beetles. He has shown that, under the pressure of climate change, insects have migrated tremendous distances; for example, *Tachinus caelatus*, a small, dullish-brown beetle common in England during the cold periods of the Pleistocene, today can be found only some five thousand miles away, in the mountains west of Ulan Bator, in Mongolia. But Coope questions whether such long-distance migrations are practical in a fragmented landscape like today's. Many organisms now live in the functional equivalent of "oceanic islands or remote mountain tops," he has written. "Certainly, our knowledge of their past response may be of little value in predicting any future reactions to climate change, since we have imposed totally new restrictions on their mobility; we have inconveniently moved the goal posts and set up a ball game with totally new rules."

A few years ago, nineteen biologists from around the world set out to give, in their words, a "first pass" estimate of the

extinction risk posed by global warming. They assembled data on eleven hundred species of plants and animals from sample regions covering roughly a fifth of the earth's surface. Then they established the species' current ranges, based on climate variables such as temperature and rainfall. Finally, they calculated how much of the species' "climate envelope" would be left under different warming scenarios. The results of this effort were published in *Nature* in 2004. Using a mid-range projection of temperature rise, the biologists concluded that, if the species in the sample regions could be assumed to be highly mobile, then fully fifteen per cent of them would be "committed to extinction" by the middle of this century, and, if they proved to be basically stationary, an extraordinary thirty-seven per cent of them would be.

The mountain ringlet (*Erebia epiphron*) is a dun-colored butterfly with orange-and-black spots that curl along the edges of its rounded wings. It overwinters as a larva, and as an adult has an extremely brief life span—perhaps as short as one or two days. A montane, or mountain, species, it is found only at elevations above a thousand feet in the Scottish Highlands and, farther south, in Britain's Lake District, only above fifteen hundred feet.

Together with a colleague from the University of York, Chris Thomas has for the past few years been monitoring the mountain ringlet, along with three other species of butterfly—the Scotch Argus (*Erebia aethiops*), the large heath (*Coenonympha tullia*), and the northern brown Argus (*Aricia artaxerxes*)—whose ranges are similarly confined to northern England and Scotland. In the summer of 2004, researchers for the project visited more than four hundred sites where these "specialist" species had been sighted in the past, and last summer they repeated the process. Documenting a species' contraction is more difficult than documenting its expansion—is it really gone, or did someone just miss it?—but preliminary evidence suggests that the butterflies are already disappearing from lower-elevation and more southerly sites. When I went to visit Thomas, he was getting ready to take his family to Scotland on vacation and was planning to recheck



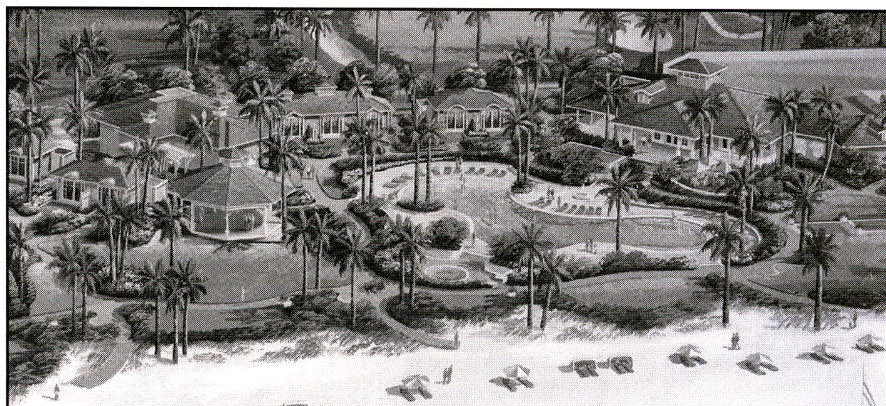
"You're really starting to bug me."

some of the sites. "It's a bit of a busman's holiday," he confessed.

As we were wandering around his yard in search of commas, I asked Thomas, who was the lead author on the extinction study, how he felt about the changes he was seeing. He told me that he found the opportunities for study presented by climate change to be exciting.

"Ecology for a very long time has been trying to explain why species have the distribution that they do, why a species can survive here and not over there, why some species have small distributions and others have broad ones," he said. "And the problem that we have always had is that distributions have been rather static. We couldn't actually see the process of range boundaries changing taking place, or see what was driving those changes. Once everything starts moving, we can begin to understand: is it a climatic determinant or is it mainly other things, like interactions with other species? And, of course, if you think of the history of the last million years, we now have the opportunity to try and understand how things might have responded in the past. It's extremely interesting—the prospect of everything changing its distribution, and new mixtures of species from around the world starting to form and produce new biological communities. Extremely interesting from a purely academic point of view.

"On the other hand, given our conclusions about possible extinctions, it is, to me personally, a serious concern," he went on. "If we are in the situation where a quarter of the terrestrial species might be at risk of extinction from climate change—people often use the phrase of being like canaries—if we've changed our biological system to such an extent, then we do have to get worried about whether the services that are provided by natural ecosystems are going to continue. Ultimately, all of the crops we grow are biological species; all the diseases we have are biological species; all the disease vectors are biological species. If there is this overwhelming evidence that species are changing their distributions, we're going to have to expect exactly the same for crops and pests and diseases. Part of it simply is we've got one planet, and we are heading it in a direction in which, quite fundamentally, we don't know what the consequences are going to be." ♦



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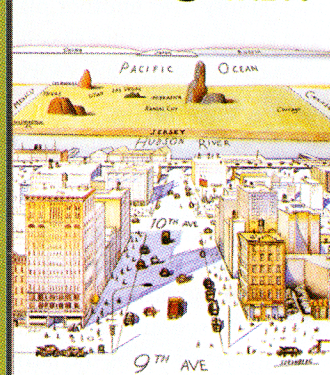


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