Plague of Absence:
Insect Declines and the Fate of Ecosystems

by

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ABSTRACT

In November of 2017, a group of researchers published a paper showing that since the 1980s, insect populations in protected areas in Germany have decreased by over 75 percent. The decline, dubbed by one reporter the "insect armageddon," was widespread, affecting sites on nature reserves across the country. It was also indiscriminate, affecting not just certain species, but overall biomass. In the following years, similar studies from Greenland, Puerto Rico, and locations in North America have also shown declines in number of insect species, abundance, and habitat. These declines have serious implications for ecosystems and for humans, some of which we can already see in effect, and some that scientists can't even predict to their full extent. This thesis will profile a research team in Costa Rica who are using caterpillar-parasitoid interactions to make estimates about insect population health, and explore the reasons for and extent of insect declines and their consequences for humans.

Thesis Supervisor: Alan Lightman
Title: Professor of the Practice of Science Writing

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Eva Frederick

On a hot winter day in the Costa Rica rainforest, Lee Dyer led a group of scientists and educators down a narrow, moss-covered concrete path. Dyer, slim and sandy-haired, scanned the dense vegetation on either side of the trail. Above, the January sun beat down with a ferocious intensity, signaling close proximity to the equator. Down here, though, the only light that made it through the canopy was the dim greenish glow of the understory. The air was laden with the earthy aroma of compost mixed with the heady scent of plants after rain. I was tagging along, a science writer from MIT.

Ahead of us, Dyer's four-year-old son Hank tangled brazenly with the undergrowth. He turned up treasure after treasure, with the unadulterated joy of someone young enough to realize that *everything* is a treasure; a speckled leaf, a fallen flower, the bright pink seed pod of a nutmeg tree that smells like pepper and sugar and something else spicy-sharp that makes your eyes water if you crush it.

We'd barely been walking for five minutes when Hank found exactly what we were looking for. "Caterpillar!" he yelled.

Dyer stepped off the path to examine the plant in his son's hands. The caterpillar was not immediately obvious. He palmed a glossy leaf at the end of the stem, and there, nestled in a sandwich of leaf and silk, was a small translucent larva.

Dyer is a tropical ecologist and chemist at the University of Nevada, Reno. Since 1991, he has been collecting caterpillars at La Selva Biological Station, six square miles of low-lying tropical rainforest in northeastern Costa Rica. He and his graduate student Danielle Salcido study "multitrophic" interactions in the tropics, which are intricate to say the least. Caterpillars eat plants; that's one trophic level. Then, wasps parasitize caterpillars by laying eggs inside of them. The wasp larvae then eat the caterpillar from the inside out. Every now and then, another kind of wasp will come along and use its whisper-twitch front legs to feel up and down the length of a caterpillar to see if it already has wasp larvae inside, in which case it will lay its eggs *inside the wasp larvae* inside the caterpillar.[i] Those are just a few of the interactions scientists have observed.

To study these relationships, Dyer and Salcido go out collecting each year with a group of volunteer researchers in rainforests in Costa Rica and Ecuador. Their trips are staffed through the nonprofit environmental organization EarthWatch, and some volunteers return every year, pile onto a wide-windowed tour bus in San Jose, and travel two hours northeast to La Selva for a week to help bring in the annual haul of caterpillars.

Since they started the project, Dyer, Salcido and the volunteers have collected tens of thousands of individual caterpillars from around 4,500 species (just over half of the estimated number of species in La Selva), and raised them to see whether or not they have been parasitized by wasps or other parasitoids. Dyer and Salcido then document the percentage of caterpillars that have been parasitized, and use this number to make estimates about the ecosystem service of biocontrol and the health of both species. For example, if fewer wasps are killing caterpillars — which is true, according to the dataset — the caterpillar populations should be growing. But in their analysis of Dyer's dataset, the researchers discovered something surprising: the number of caterpillars at La Selva is actually decreasing.

This might seem like a small issue, but according to Dyer and Salcido, it's likely a sign of something much bigger: in the dense tropical rainforests of Costa Rica, populations of wasps and caterpillars, two important groups of insects in the forest ecosystem, are falling. This result mirrors studies in Germany, England, and the United States that show drastic declines in insect numbers. Dyer told me that this decline is most likely the result of human activity: human agriculture, human deforestation, human cities, and human-caused climate change.

Dyer had seen papers come out about declining insect populations, but what really shocked him about the wasp and caterpillar declines was the massive scale. "I was really surprised at how big the decline in parasitism was — especially in the diversity of parasitoids," he said. "The magnitude of effect was something I never would have predicted at all. We're still doing the analyses, so maybe it's not as bad as it looks, but it looks pretty bad right now."

Losing "the little things that run the world"

In the 1980s, the global "biodiversity crisis" emerged, the term brought to public attention by entomologist and conservationist Edward O. Wilson[ii]. Wilson saw what others had already begun to see: for some years, the world has been losing entire species nearly as quickly as they could be discovered. Extinction is natural, but the background rate, one scientist calculated, should be about 1-5 species annually. The current rate is thousands of times that. Scientists estimate that the world loses anywhere from 10,000 to 100,000 species in a year. Losing this diversity is bad for humans. Diverse ecosystems are healthier all around; they have more total energy flowing through the system and they facilitate natural cycles in soil nutrients and water.[iii] Around 40 percent of the world's economy is based in natural biological resources. Furthermore, studies of the variety of life and how living systems work together can lead to advances in medicine and technology.

Insects are the poster-class of biodiversity. A recent analysis shows that there are around 5.5 million species of insect in the world.[iv] The vast numbers of insects include the more than 350,000 glittering, armor-shelled species of Coleoptera alone, inspiring the twentieth century scientist J.B.S. Haldane to remark that God, if He exists, must have had "an inordinate fondness for beetles."[v] But despite their seemingly infinite variety, insects are not immune to changing environmental conditions or the encroachment of humanity. Over the following decades since the scientific community became aware of the biodiversity crisis, a few studies and a wealth of anecdotal evidence have indicated that the problems faced by mammals, birds, reptiles, and amphibians were also echoed in insects.

"One of the analogies that you hear a lot is that we just don't have to clean our windshields as much as we used to," said David Wagner, an entomologist and a professor of ecology and evolutionary biology at the University of Connecticut. "Just a few decades ago, you'd pull up to gas stations all the time and clean the bugs off your windshield. Now you can go days without scraping off the bugs."

Lee Dyer and other researchers at La Selva first noticed the absence through a popular evening activity for entomologists: blacklighting. The La Selva blacklighting set-up is a blank expanse of white sheet stretched taut across a metal frame. Overhead, a tin roof protects the sheet from rain. Each night, as the sun sinks below the tangle of the surrounding forest, UV lights above the sheet blink on.

In years past, as the lights illuminated the fabric, it began to come alive with insects. After a while, the white sheet would be almost black with crawling, fluttering life, and the space around it would host a small cloud of activity much like the cones of light cast by suburban streetlights. As the sheet filled up with moths and beetles, the space around the sheet would fill up with researchers. Here, Dyer told me, a particular scientist, tired of unwanted attention from her male coworkers, used to eat insects to garner their disgust (it is unclear whether this tactic worked), and students and professors alike would fight over who got to add which species to their ever-expanding insect collections. In the early morning, when the howler monkeys deep in the woods began their guttural screams, the light would blink off again and the insects would return to the forest.

That was in the nineties. A casual observer nowadays would be lucky to see a few dozen insects. When I went out to look at the sheet one night in January of 2019, I saw fewer than that. As I ventured close to the fabric, I saw a scattering of tiny winged things clinging to the sheet and three medium-sized moths sitting primly, wings neatly folded behind them like elegant vintage coats. One larger one, as I approached it with my camera, arched its abdomen and raised its wings in a gesture of defiance. I considered myself lucky to have seen these few delicate creatures. That's how the concept of shifting baselines works. If you hadn't seen the sheet before, you'd be impressed; you'd never know — unless someone told you — that this sheet was once a churning mass of six-legged life.

The blacklighting sheet at La Selva. Photo: Eva Frederick

Despite the word-of-mouth evidence, it wasn't until recently that the drops in insect populations started to receive scientific global attention. In November of 2017, a team of researchers and citizen scientists, led by Caspar Hallmann, a graduate student at Radboud University in The Netherlands, published a study based on 27 years of insect population data collected from protected areas in Germany. The results showed declines of more than 75 percent in total insect biomass.[vi]

Hallmann's was one of the first large-scale population studies on insects that focused on sheer abundance instead of individual species. Many scientists found the paper's results alarming because the studied areas each had some level of government protection — they included conservation areas, water protection zones, or nature reserves — and therefore were likely better off than much of the German countryside.

Subsequent studies in other locations, from a Mexican desert to the densely populated forests of southern New England, garnered similar — if not quite as dramatic — results, leading one reporter to dub the phenomenon the "insect apocalypse."[vii] A recent paper published in the Journal of Biological Conservation in April 2019 showed that a staggering 40 percent of insect species are threatened with extinction over the next few decades.[viii] Moths, butterflies, wasps, bees and dung beetles will be the most severely affected, the authors predicted, while other groups, such as dragonflies, damselflies, and lacewings have already experienced substantial species losses. Of the remaining 60 percent, some are projected to decline at a slower rate or maintain their population size. Others, such as cockroaches and house flies (go figure), are likely to boom.

Insects are an invaluable part in the global economy. A 2016 study published in *Nature* estimated that the services provided by wild insect pollinators are worth between 235 and 577 billion dollars.[ix] Without these services, economically important crops such as apples, pumpkins and even strawberries could suffer, Cornell research suggests. Some insects, such as ladybugs and parasitic wasps, serve as natural pest control by eating other insects or laying eggs in their larvae. These services save U.S. farmers an estimated $4.5 billion, according to a 2006 paper in *BioScience*.[x] Insects are essential players in wild ecosystems as well. Around 80 percent of wild plants would not survive without insects to spread their pollen, and the majority of bat and bird species depend on insects for food. Our society today can't afford to lose insects, the under-appreciated but absolutely essential creatures that E.O. Wilson once called "the little things that run the world."[xi]

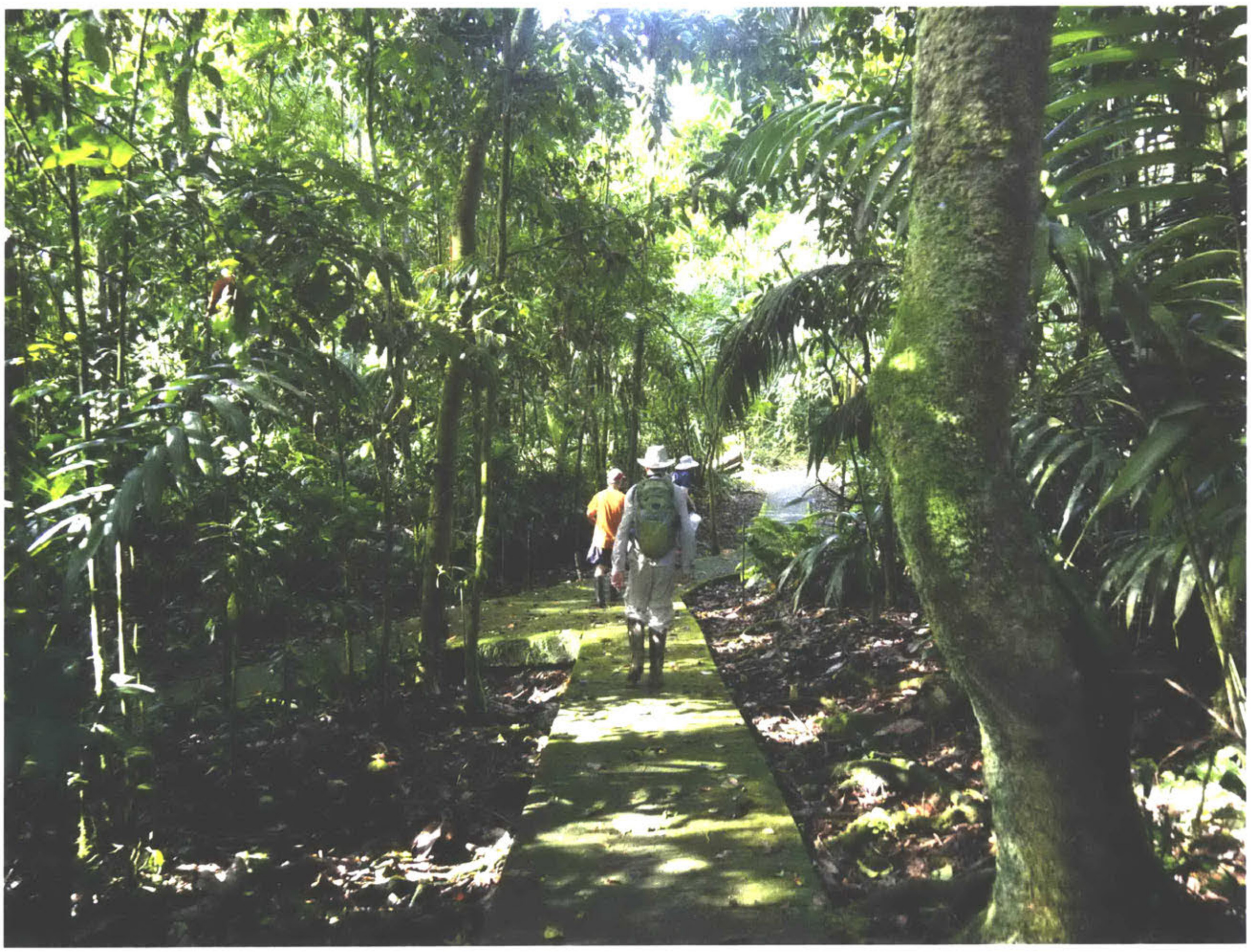
What's killing the bugs?

Halfway through a week of collecting at La Selva, Danielle Salcido sent a team out looking for caterpillars. Salcido is tall and soft-spoken, with a youthful lilt to her voice. This collecting expedition, she told us, was general. Look everywhere, collect whatever you find. Make sure you get leaves of the host plant so the caterpillars have something to eat. It was exciting and distracting to be set loose on the forest like this, a generalist in search of whatever catches the eye.

We set off down one of La Selva's shady trails and spread out into the woods on either side, our booted feet shuffling through muddy leaf litter. While I haphazardly searched the undersides of moss-encrusted leaves, Julie Elliott, an eagle-eyed caterpillar hunter from Tennessee, was determined to find a sphingid. Sphingid caterpillars are legendary at La Selva. First of all, they're enormous — some are as long as a person's middle finger. Second, they come in all sorts of fascinating varieties. One, when approached by a predator, flips upside-down to display a head that looks startlingly like that of a viper. Another has a round blue face and a red spike on its back. When mature, many types of sphingid will emerge as huge brown hawk moths with dagger-like wings swirled with the pattern of damascus steel.

Elliott was not in luck that day, though. In fact, there are some types of sphingid that hardly anyone in Dyer's group has been lucky enough to find at La Selva in several years. "The one with the baby blue head and red tail — it's been at least 10 years since I've seen that," he said. The sphingids were never that common — at least not as common as some other caterpillars lurking in La Selva. "If you're looking for a parameter, the slope of the decline doesn't seem dramatic because there weren't that many there in the first place," he said. "What's really dramatic is that I just don't see them anymore."

The slow disappearance of these caterpillars may be due to the positioning of their home forest at La Selva Biological Station. The station lies in a sort of geographic bowl, bordered by natural landforms. To the south of the station, the heavily forested mountains of Braulio Carrillo National Park jut up out of the ground like mysterious figures shrouded in ever-present mist. To the north, the Sarapiquí and Puerto Viejo rivers cut muddy paths through the earth. Much of the land surrounding the station is not forest, but croplands. From above, the green fields seem as benign as the comforting patchwork of a quilt. A closer look at the farming practices, though, shows a darker picture.



A trail through the forest at La Selva. Photo: Eva Frederick

As of May 2018, Costa Rica leads the world in pesticide use per unit of cropland — 16.2 pounds per acre, according to the Regional Institute of Studies of Toxic Substances at the National

University in Costa Rica. To put that in context, one acre is about three quarters the size of a football field. Sixteen point two pounds of paraquat dichloride, one of the most common pesticides in Costa Rica, is enough to kill several thousand people if ingested. Because of La Selva's lowland location, Salcido said it's possible that pesticide runoff from the surrounding agricultural areas could be affecting the insects in the forest.

But pesticides might not be the only factor in the declines at La Selva. Salcido is also investigating the possibility that changes in environmental conditions — specifically, more extreme weather events and flooding as a result of climate change — could be to blame. "On this Costa Rica site in particular we've seen an increase in flooding events," she said. "We're looking at the idea of more extreme precipitation, which leads to flooding events and may be affecting these populations, both herbivores and parasitoids, leading to the declines that we see."

Elsewhere in the world, other human factors may be at work. In Germany, intense agriculture and loss of habitat is likely to blame for the lack of insects in protected areas, according to Hallmann's study.

David Wagner, the UConn entomologist, said the variety of causes is one reason insect declines are hard problems to solve. "It is death by a thousand cuts," Wagner said. "It's pollution, it's invasive species, it's climate change, it's pesticides, it's pathogens being moved around by global commerce. That's what really sucks, because if it were one thing we could try to correct it."

Climate change, according to Wagner, is one of the deeper cuts for many insect species. Richard Karban, an ecologist at the University of California, Davis, was the first to notice climate-related decline in the vibrant flora of the California coast.[xii] Karban has been studying the ecology of seaside daisies for the past 35 years. Over the years, he'd go survey pretty often, counting the numbers of the vibrant lilac plants and checking on what was eating them.

One common muncher was the meadow spittlebug. The insects themselves are a nondescript brownish tan. Even their compound eyes are tan, with a horizontal line of brown across the centers which gives them the appearance of being permanently relaxed, eyes-half-closed. It is these insects' childhood homes, however, that are their namesake and distinguishing feature. When baby spittlebugs hatch from the eggs their mothers lay on plants, they exude a frothy liquid, creating a foamy home of bubbles.

If you're not searching for meadow spittlebugs, they're easy to overlook. That's why, when they began dying out, Karban was one of the few to notice. In 1982, when Karban started his research, spittlebugs were the most abundant insect he saw in coastal ecosystems. Now, he rarely sees them at all. "[The decline] is concerning for sure," Karban said. Karban's next study documented the decline, and he cited a 1986 experiment to show that the most likely culprit was climate change. Meadow spittlebugs need moist habitats to survive, and warming temperatures along the California coast, along with drought conditions, may have left the insects unable to find adequate shelter. And although for some creatures, warming temperatures mean an expanded range, this didn't seem to be the case for the spittlebugs. Their range actually decreased, Karban said.

The temperature of the environment affects some creatures, like insects, fish, amphibians and reptiles, more severely than others. These creatures are ectotherms: they cannot regulate their own body temperature, and therefore must depend on outside sources to keep them at a livable temperature.[xiii] If you've ever seen a slow and sluggish grasshopper cling unmoving to a blade of grass on a cold morning, you know this. But while cold temperatures can incapacitate insects, heat can affect them by more subtle, and often more damaging, means. A study by researchers at England's University of East Anglia showed that sudden spikes in temperature, which will become more common with the onset of climate change, had drastic effects on the fertility of male beetles.[xiv] One heat wave cut male beetles' sperm production in half. A second rendered them nearly sterile.

These unfortunate beetles aside, rising temperatures can affect insects in another way: by reducing their livable habitats. A 2018 report by the Intergovernmental Panel on Climate Change — a dystopian prediction of the results of differing degrees of warming — suggests that more insects will be affected by climate change in the coming years. If we experience a temperature increase of even 1.5 degrees, the report shows, 16 percent of insects species worldwide will lose their habitats, like Karban's spittlebugs. If we continue on our current trajectory, we can expect a more substantial warming. With a 2 degree increase, the number of displaced insect species jumps to 66 percent.

Other factors can also drive insects out of their home territory. Urbanization clears land once populated with native plants, creating concrete wastelands that aren't friendly for many species. Afforestation, the unnatural emergence of forests where there were none before, often a product of abandoned farms being reclaimed by nature as people move towards cities, can also shift habitats. And the encroachment of invasive species can directly and indirectly impact native insect populations. In a 2010 study, Wagner found that invasive plant and animal species were the number two threat to the 57 federally protected species of insect in the US after development.[xv] At worst, new species can shift community dynamics to the point that basic ecosystem properties such as soil chemistry, fire susceptibility, nutrient cycles and light availability, are irreversibly changed.

What insect declines mean for the rest of us

Our second day of collecting at La Selva was New Years Eve. Back in San Jose, before we had even left on the bus to the forest, some of the EarthWatch volunteers had made a quick trip to a gas station and picked up a couple of bottles of champagne. At 9 p.m. we gathered in Dyer's cabin to celebrate, sip champagne, and swap stories.

"Are you going to be awake at midnight?" Dyer asked me.

I said that I was, because I had an article due the next day at noon.

"Then you should go out on the bridge," he said. "It's a nice place to be for the new year."

An hour or so later, it was time for Dyer's son Hank to go to bed, so we trooped out of Dyer's family cabin and back to our own. I spent a couple of sweaty, champagne-blurred hours ironing out the article I had due the next day, then slipped into my boots and headed out into the night. The bridge, which joined the two sides of an opaque brown-green river, was make of thick wood planks, and swayed gently as I stepped onto it. During the daytime, you could stand on the bridge and watch fat orange iguanas sunning themselves in the trees, or look down and see snorkeling researchers looking for cichlid fishes, or the bright bodies of two transplanted koi fish someone had let loose in the dark water.

In the dark, the bridge felt like a different world. The trees flanking the river were insubstantial masses, the water nothing but glinting moonlight. I could hear far-away sounds of a party, punctuated every now and then by the pop of fireworks. Beneath the rest of the sounds was the faint hum of the insects in the forest. Earlier that day, at dinner, I had been talking to Ronald Parry, a white-haired and soft-spoken professor emeritus of chemistry at Rice University, who has been coming to La Selva for nearly 40 years for research trips.

"When I was here in the 80s the insect noise from the jungle was deafening," Parry had said. "Now it is almost completely quiet." Parry was right about the quiet. Even the summer hiss of cicadas in Texas is louder than the hum of insects in the Costa Rica jungle.

As I looked out into the darkness, I wondered about the declines Dyer and Salcido had observed here. Their wasp and caterpillar data, though telling of trends in two important insect groups, is only a small window into what might be a much larger shift in the rainforest ecosystem. I wondered what was different about the forest now, minus some percentage of insects, from how it had been in the 1980s. Had the ever-shifting ecosystem simply rolled with the punches, filled the missing niches with other species, and continued business as usual? I also wondered about other locations. According to existing studies, these declines are widespread, but much of the research I read on their consequences seemed only to project the future. If the data are correct, many species of insects have been declining for decades, so we should be able to see some effects already.

The welfare of insect-dependent plants and animals may be the most direct effect of insect declines. A *Science* study in England and the Netherlands, where there is arguably the most extensive data on insect population sizes, have shown parallel declines in bees and hoverflies, both wild pollinators, with plants that relied on those species for pollination.[xvi] Although there are many factors affecting plant diversity, the study strongly suggests that the insect declines are to blame.

Animals too, are dependent on the presence of a substantial biomass of insects. In a cave near San Antonio, Texas, for example, lives the largest bat colony in the world; each night, the 20 million bats consume 100 tons of insects before returning to their subterranean home in Bracken Cave. Even grizzly bears, known for their taste for macrofauna such as elk or deer, dine heavily on insects.[xvii] The bears in Yellowstone National Park can consume up to 40,000 moths per day. These creatures are important to the ecosystems they live in — bats keep down pest insect populations such as mosquitoes and bears are important apex predators — but also to our conception of place. Bats in Texas are generally celebrated as a natural attraction and and grizzlies, while terrifying, are the stuff of American legend.

The decline of many species of pollinating insects will also mean less food for humans to eat at a time when we are already struggling to feed our ever-expanding population. Over one third of all food crops are pollinated by insects.[xviii] In the early days of U.S. agriculture, farmers could generally count on local insects to pollinate their crops. Now, due to agricultural expansion, and possibly the slow declines of native pollinators, many farmers depend on migratory beekeepers who ferry around trucks stacked high with buzzing boxes of imported honey bees. The trucks stop at, say, a blooming almond farm, and loose their bees, which fly around from flower to flower (bees visit 2 million flowers to make a single pound of honey) and then return to their hive at night, pollen-coated and nectar-bloated. Over 2,000 people in the U.S. are employed in this unlikely economic niche, and with the predicted declines in native pollinators (a review study called *Pollinators in Peril* by the Center for Biological Diversity suggests that the populations of more than half of the 1,437 wild pollinators in the US that we have data for are decreasing), it will likely only grow.

But a lack of pollinators is just one part of the problem for agriculture. The other side is less intuitive. "With climate change, opportunities open up for certain species of insects, depending on what climate they're used to, to actually reproduce at greater rates," said David MacNeal, author of the book *Bugged.* Some insects, like the aforementioned beetles whose fertility rates drop after heat waves, don't do so well in warmer weather. Other insects, like crickets and some species of moths, like it hot.

One agricultural pest, the European corn borer (*Ostrinia nubialis)*, produces one generation of offspring per year in the northern corn belt and two or more in the warmer southern states. Not only does the heat increase their reproductive rates, it also raises their metabolisms, causing them to eat more. This is bad news for agriculture, since insects that thrive in heat include common pests such as the corn borer.[xix] Warming temperatures may also allow these species to expand their ranges to a whole new agricultural buffet, and declines in predatory insects such as parasitic wasps mean their numbers may further increase.

Insect declines might also affect the global economy. According to a much-cited 2006 study in *BioScience* by Cornell associate professor John Losey and Xerces Society researcher Mace Vaughn, the value of insects for recreation — yes, recreation — in the US totals $49.96 billion.[xx] That's tallying the value of insects for small-game hunting, fishing, and observing wildlife, all of which are activities that depend on healthy, functioning ecosystems. Even a slight decrease in prey insects can mean a decrease in the number of birds to observe or fish to catch in American rivers.

Another unlikely service is thanks to dung beetles. Steady, earnest, and surprisingly adept at maneuvering a ball of poop up to ten times their size, these beetles play a vital role in burying the millions of pounds of waste produced by the livestock industry. If left on the surface, dung fouls the rangeland and provides breeding ground for pest species. When beetles bury dung, they facilitate the decomposition of the dung into a natural, nitrogen-rich fertilizer. Losey and Vaughn value this service at $0.38 billion in the US alone. Dung beetles are currently declining in the Iberian Peninsula and in several regions in Europe, and a study in Nature by researchers in Spain pointed to veterinary drugs as a possible cause.[xxi] [xxii] [xxiii]

Of the 60 percent of insects that are *not* facing imminent extinction, those that thrive on disturbance, Wagner and others predict, will fare especially well. So too will species like mosquitoes and houseflies, which prosper in human-dominated environments. Because insects evolve and adapt relatively quickly to changing environmental conditions, it is fairly certain that we will be sharing our planet with them for the foreseeable future. The question, Wagner said, is which insects will survive to live alongside us? They may not be the good guys, like ladybugs, or the delicate multi-level parasitoids that Dyer and Salcido study in the tropics, but instead the hardy survivors of human disturbance. And those survivors might not be particularly friendly to human beings. For example, cockroaches aren't going anywhere, and declining insect populations are more an issue of biodiversity than of sheer numbers.

Counting insects

As research on insect declines has become a high priority for many scientists, researchers are encountering a data problem: there is not enough of it. Lee Dyer started his Costa Rica parasitism datasets in 1991 to study species interactions in the rainforest. A chemical ecologist by training, Dyer was interested in how rainforest plants respond to being eaten by hungry insects. He added another location to the dataset a few years later, in a similar lowland rainforest in Ecuador.

Dyer published several papers with the information he found in his burgeoning datasets, but it took a nation-wide disaster for him to see their full potential. In 2005, Hurricane Katrina devastated New Orleans and destroyed Dyer's house. In the aftermath, Dyer couldn't help but think of the insects. Climate scientists predicted that storms of Katrina's magnitude could hit different parts of the world with increasing frequency. Storms flood forests, blow down trees, and generally disrupt the forest equilibrium. "That was when I first started thinking about how these long-term datasets could serve as a thermometer of global change," he said.

Dyer didn't probe them immediately for insights into wasp and caterpillar populations. But after reading reports of insect declines in Germany and other locations, he thought it might be worth a shot, just to see if the data contained any obvious trends. He asked Salcido to draw up a quick graph to see if his hunch was correct. "It was the easiest graph I've ever made," Salcido said. But that graph — a delicate downward slope showing the important ecosystem service of parasitism in decline — sent their research in an entirely new direction.

The dual use of Dyer's dataset is not an uncommon occurrence in the existing literature on insect declines, primarily because there just aren't a whole lot of people out there counting insects. And even when researchers do collect population data, it's often just for one species such as monarchs (their populations are also trending downward)[xxiv], or the researchers just don't make it public.

Salcido is the first to admit that there is not nearly enough data on insect populations that is readily available. "The longer I'm in this field, the more I learned that those datasets are out there, but they're sitting on people's hard drives," Salcido said. "We need to start sharing our data and posting it to these repositories of datasets."

This shortage of relevant data is one reason it is hard to gauge exactly what is going on with insect populations around the world. Then there is the issue of the actual surveying. How *does* one count insects, anyway? Insects are an incredibly diverse group. They fly, swim, and burrow. They can grow to nearly twice the length of a newborn baby, or be too small to see with the naked eye. This variability means that to say anything of consequence about "insects" as a whole, scientists must have some pretty compelling data. And to create a reliable dataset, the methods of data collection have to be precise enough to be carried out in the same way over years and years.

The team looks at a caterpillar that has been parasitized by a fungus. Photo: Eva Frederick

Salcido and Dyer, for example, are looking at species interactions as a proxy for ecosystem health, and from that are able to make guesses about population trends. Every year, a percentage of the caterpillars they collect are eaten from the inside out by hungry wasp larvae. Through this somewhat brutal ratio, Dyer and Salcido are able to make inferences on the population sizes of both creatures. More healthy caterpillars most likely means fewer wasps. Fewer caterpillars and fewer wasps is bad news for the forest.

Beyond this sort of sampling difficulty, there is also the issue of humans' tendency to generalize occurrences in one area to trends on a larger scale. By this logic, fewer bugs in Costa Rica could be interpreted to mean fewer bugs in other similar rainforests — but this is not the case. Dyer also works on a site in Ecuador, where he and his team also collect caterpillars. They haven't been tracking caterpillars and wasps there for as long as they have in Costa Rica, but long enough, Dyer said, to detect declines if they were happening. So far, they aren't.

This variability has led some to question the narrative of widespread and catastrophic insect declines. Bob Peterson, a professor at Montana State University, said in order to tell if these declines are a general problem, we need more data. "We don't have that same weight of evidence with respect to insect losses or whatever you want to call that," he said. "We've got these handful of papers and some show losses. Some show increases. It's complicated. Extraordinary claims require extraordinary evidence. And I would argue as a professor and a researcher that we do not have the extraordinary evidence yet to show to show that these are trends that are general in nature. They definitely are alarming and concerning, but not general in nature yet."

With a group of creatures as large and diverse as insects, some might argue that nothing short of a catastrophic meteorite impact could propel us to the point where *any* population trend could be called "general in nature." Cockroaches, after all, are often predicted to be the sole survivors of a nuclear holocaust (the TV show "Mythbusters" tested this, and found that while roaches do survive longer than humans, they still die under extreme amounts of radiation). But while it may not be productive to paint insect declines with such a broad brush, the fact remains that we will likely lose forty percent of species in the next few decades. That number is too high to ignore.

Looking ahead

As the group of Costa Rica caterpillar hunters returned to the lab on the last night of my stay, I felt late-afternoon heaviness pulling on my arms and weighting my yellow-rain-booted feet. The daytime forest seemed to be winding down too, the greenish-yellow glow of the canopy now coming at a slant. A parade of leaf-cutter ants scurried by in a never-ending line, carrying pieces of glossy leaves and delicate pink flowers into their hole as dinnertime offerings to their fungus beneficiary. A huge red flower beside the trail caught a rare beam of unfiltered sunlight and lit up like a Chinese lantern.

The ambient lab — so called because its wire-panel walls kept it close to the same temperature as the shady forest understory — waited silently in a clearing frequented by a herd of brazen peccaries that were completely unbothered by human company. I pushed open the screen door, slipped out of my jungle boots and padded soft-footed across the concrete floor. The room was filled with slick metal tables, and backless stools had the green-smelling nostalgia of an evening at summer camp. Salcido was sitting at a bench inside, playing zookeeper to our already hefty collection of plastic-bagged caterpillars.

I unhooked my new caterpillar-filled bags from around the strap of my backpack and spread them on the table. Next to me, Julie unloaded about twice the amount that I caught, including several *Quadrus cerialis* caterpillars. These are pale, translucent, worm-like creatures that create little leaf-and-silk homes like they are tucking themselves into bed. After they pupate, the *Quadrus* caterpillars emerge as soft, dusky moths that fly in the hazy sunlight of dawn. They gravitate toward liminal spaces, living just where the cover of the canopy opens into the wide cerulean sky, flitting easily between shade and sunlight.

I was struck by how *Quadrus cerialis* — and all the caterpillars we found over three days in the forest — fits so beautifully into its niche. As a caterpillar it eats mostly plants in the Piper family, which have finely tuned defenses against insect herbivores. Some species host ant colonies within their hollow stems. Others defend themselves with cocktails of chemicals. Somehow, these caterpillars are able to survive by eating *only* these plants. The interaction of these caterpillars with the plants, and wasps with the caterpillars is another example of intertwined species revealed by years of painstaking research, and a reminder of the many other interactions scientists have no idea of.

Ralph Waldo Emerson, in his essay "Nature," writes about how "a leaf, a drop, a crystal, a moment of time" — or the smallest insect — "is related to the whole, and partakes of the perfection of the whole. Each particle is a microcosm, and faithfully renders the likeness of the world."[xxv] I can see what Emerson means here in Costa Rica. Lee Dyer likens these tangled co-dependencies to novels, brilliant stories full of colorful characters and plots. Their gradual declines, he compares to a slow-burning blaze. "When we lose these interactions, we aren't only burning down libraries of books," Dyer said. "We are burning books that have never been read before."

Completely putting out the fire, Dyer said, is not possible. "I'm afraid that there is nothing we can do to stabilize some of these species," Dyer said. The changes that are affecting insects and their interactions might be reversible on a timescale of 1,000 years, he went on, but we are still going to lose many of them in the meantime. As David Wagner said, insect populations are suffering from death by a thousand cuts. Even if we could slow the pace of urbanization, more dangers arise to take its place. Pesticide use is one of the more preventable causes. Humans can and do take precautions prevent the spread of invasive species, but their slow encroachment seems inevitable as the distributions of plants and animals shift. But then there is the seemingly insurmountable obstacle of climate change. Earth's warming temperatures will guarantee changes in insect distribution, and even if we are able to limit emissions to the 2 degrees mandated by the Paris agreement, a substantial percentage of insects will still lose their habitat.

Still, despite the bleak outlook, Dyer pushes on with his insect research. Some of his more fatalistic colleagues are quick to compare Dyer's intense interest in studying these insects and their interactions to rearranging deck furniture on the Titanic. But Dyer considers his work to be more about preserving history. "I'm interested in reading those books that we are burning, so that at least somebody in the future will have those stories," he said.

When we finally left the ambient lab that night, it was nearly dark. The light bulbs above the blank white blacklighting sheet had already blinked on, drawing a scattering of moths from the surrounding trees. Deep in the forest, some caterpillars lay tucked in their leaf-beds. Others clung club-footed to the undersides of leaves. A few of their bodies — those soft sacs of protein and fat — writhed with wasp larvae. I thought about the future of their populations.

For now, as Dyer said, insect populations in many parts of the world will most likely continue to decline. But instead of pouring resources to save every creature, we should step back and consider our role in the situation and the most productive use of our resources. Some effort, of course, should go toward preserving habitat and trying to save species that are still ecologically valuable. But some of those resources should go to the people — passionate entomologists like David Wagner, ecologists like Lee Dyer and Danielle Salcido, and thousands of others who care about the colorful variety of organisms that populate this planet — who have dedicated their lives to telling the stories of the tiny creatures that hold our world together.

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