Apis mellifera, the Western honey bee. Photo courtesy of James Sternburg

The Disappearance of Species

Neil H. Shubin and May R. Berenbaum
Introduction by John Katzenellenbogen
Welcome by John W. McCarter, Jr.

This presentation was given in collaboration with The Field Museum and the Chicago Humanities Festival at the Academy's 1918th Stated Meeting, held on November 10, 2007, at The Field Museum in Chicago.

John W. McCarter, Jr.

John W. McCarter, Jr. is President and Chief Executive Officer of The Field Museum. He has been a Fellow of the American Academy of Arts and Sciences since 2005.

Welcome

Distinguished members of the Academy, members of the Chicago Humanities Festival, and any others who may have wandered in from the cold, we are delighted that you are here in The Field Museum. I thought I would tell you about two milestones that are currently taking place at The Field Museum. The first is that our team that conducts biological inventories in Peru, Colombia, Bolivia, and Ecuador returns this week from their latest month in the field. This distinguished group of ornithologists, botanists, ichthyologists, environmental biologists, and anthropologists has worked throughout the Andes and the upper reaches of the Amazon to areas of marvelous biological diversity that are critically threatened by deforestation, mining, oil and gas exploration, and agricultural expansion. To date, with the cooperation of those governments, we have set aside 40,000 square miles of threatened rain forest – that is two-thirds the size of Illinois.

The second is that we are partners in a new endeavor funded by the John D. and Catherine T. MacArthur Foundation and the Alfred P. Sloan Foundation called "The Encyclopedia of Life." This idea belongs to Edward O. Wilson, the distinguished biologist from Harvard University. His plan is to create a web page for every one of the 1,800,000 species that has been identified and named thus far. The coalition consists of Harvard University, which has focused on the curriculum for higher education; the Smithsonian, which is working on a curriculum for K-12; the Marine Biological Laboratory at Woods Hole, which is doing the bioinformatics; the Missouri Botanical Garden, which is taking care of the botany; and The Field Museum, which is creating a biosynthesis center to handle the taxonomic, geographic, and paleontological issues related to "The Encyclopedia of Life." Our objective, by March 1, 2008, is to have pages for 80,000 of the 1,800,000 species up and running.

The Field Museum is a Center for the Study of the Environment and of Evolution. We opened our exhibit on evolution in March 2006, and currently we have had almost 2 million people come through to see the story of evolution over the course of the last 4 billion years of life on Earth. Earlier this year, we brought over from Brno in the Czech Republic the archival papers and materials from Gregor Mendel's laboratory; and currently, in conjunction with the American Museum of Natural History, whose provost, Michael Novacek, is here, we are hosting an exhibit on Charles Darwin.

Once again, welcome to The Field Museum. We are delighted to serve as the venue for this evening's discussion.

John Katzenellenbogen

John Katzenellenbogen is Swanlund Professor of Chemistry at the University of Illinois at Urbana-Champaign. He has been a Fellow of the American Academy of Arts and Sciences since 1992 and is Vice President of the Midwest Region of the American Academy.

Introduction

The theme of the Chicago Humanities Festival this year is the climate of change. Our program tonight on "The Disappearance of Species" addresses one aspect of that theme most appropriate for presentation here at The Field Museum, where one can learn about species past and present and the implication of their stories for species in the future. It is my pleasure to introduce our two distinguished speakers this evening, Neil Shubin and May Berenbaum.

Neil Shubin serves as Provost of Academic Affairs at The Field Museum. A paleontologist and a professor at the University of Chicago, Neil was in the news last spring with his discovery of *Tiktaalik*, an unusual fossilized creature – part fish, part amphibian – that demonstrates a key transition in evolution. Some of you may have visited the *Tiktaalik* exhibit here at the Museum. This evening, Neil will provide us with lessons from the past about the disappearance of species.

May Berenbaum, my colleague at the University of Illinois at Urbana-Champaign, is a professor of entomology. She specializes in the study of species in the here and now, particularly the relationship between insects and plants. May was most recently featured in the Public Broadcasting series *Nature*, talking about the topic that she will address this evening: another aspect of the disappearance of species – the strange phenomenon affecting bees known as "colony collapse disorder."

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Neil H. Shubin

Neil H. Shubin is Provost of Academic Affairs at The Field Museum. He is also Associate Dean of Organismal and Evolutionary Biology and the Robert R. Bensley Professor at the University of Chicago.

Presentation

I will admit to feeling a certain degree of fear when I was asked to speak about the disappearance of species, because I am a paleontologist who has spent his career focusing on the origin of species in deep time. That said, paleontology gives us a wonderful perspective – a perspective of millions, if not billions, of years. What lessons can we extract from that perspective about our world today?

Let me open with a vignette. I work in ancient rocks in the Canadian Arctic at a latitude of about 80 degrees north. I look for fossils inside rocks that are about 380 million years old. What we look for is the transition from life in water to life on land. What we find, when we are very lucky, are creatures like the *Tiktaalik*, which is a mix of amphibian and fish.

> *Paleontology gives us a wonderful perspective – a perspective of millions, if not billions, of years.*

But what I am here to talk about tonight is the enormous disconnect between present and past. When one looks inside ancient rocks, one sees an environment that is both tropical and subtropical. It is lush, teeming with life and plants. One can also view some of the earliest forests and shallow freshwater streams, as well as very warm, adapted species. The difference between present and past could not be more stark.

As paleontologists, we are used to dealing with the dynamism of our earth. One of the reasons the Canadian Arctic was so warm 380 million years ago was because Ellesmere Island was much closer to the equator than it is today. What we now know, when we look at the 4.5-billion-year history of our planet, is that everything about our earth is dynamic. Over time, the continents have rafted around. Seas have formed. Mountains have risen and eroded away. The environment has changed dramatically, from the atmosphere to the life in it.

So what lesson can I offer as a paleontologist? When I look at the ancient earth, I see that virtually every property of our earth has changed. Yet, when I look at our social systems, I see that society and well-being are based on a snapshot of time. We humans have created a system that is changing the earth, but we – our environment, our agriculture, our economy, our social structures, even our relationships to microbes – are dependent on a particular kind of earth.

Nowhere is this more apparent to me than in my beloved Arctic. Figure 1 shows the Arctic ice cap on September 16, 2003. Figure 2 shows it just a few months ago. Note the dramatic change. Nonetheless, we humans are trying to harness these changes. One of

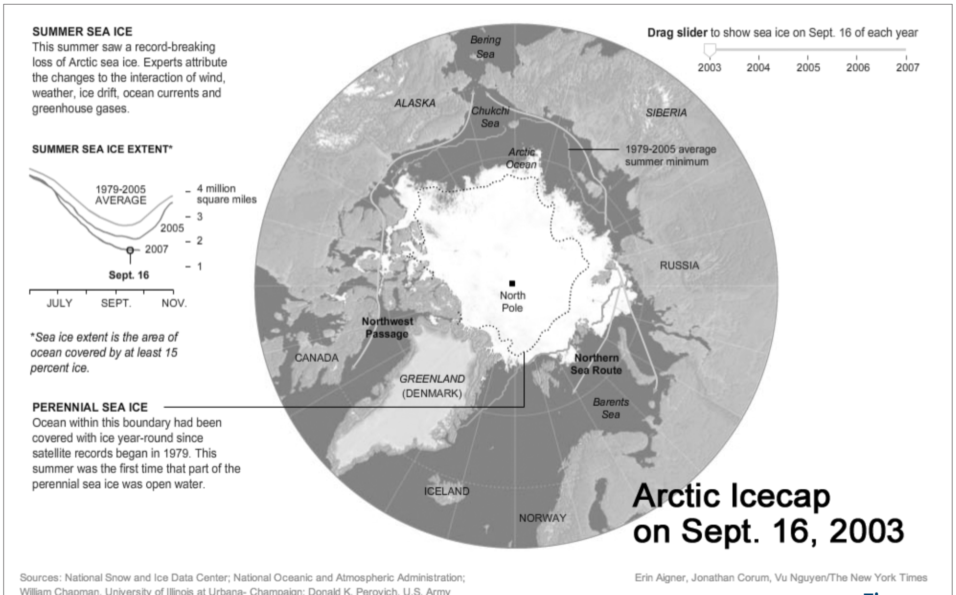

Figure 1

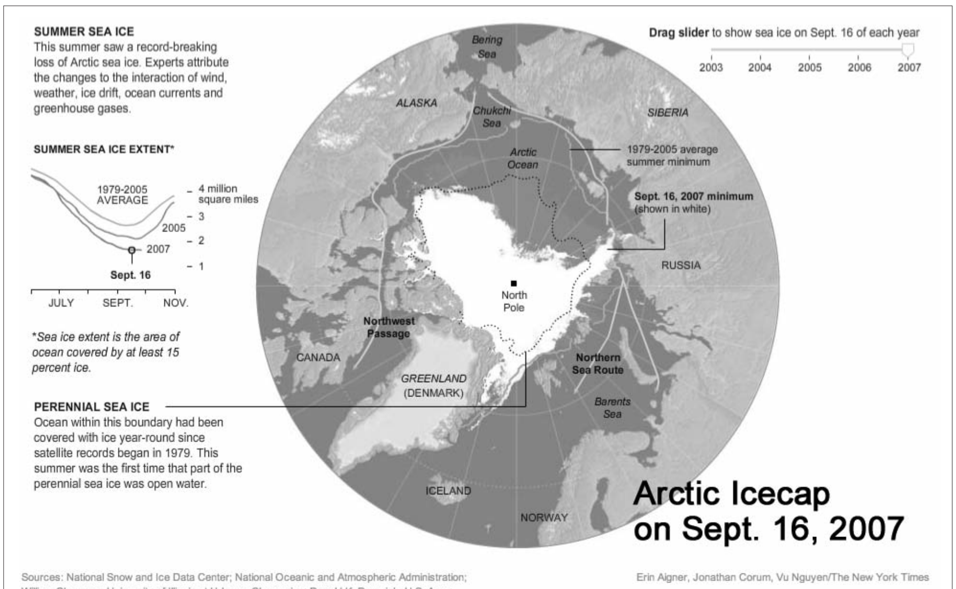

Figure 2

the best examples is the barrier islands of New Jersey. Based on a well worked-out theory about how sand is transported along beaches, we know that the barrier islands are ephemeral. They move and they change over decades, not over hundreds of years. Yet think about the coast of New Jersey and what we have done to it. Zoom into Long Beach Island, and you see house after house. These are permanent structures in a naturally ephemeral landscape. To top it off, people living in this area have insurance on their homes. So our social structures, and our economy, are based on an isolated snapshot of an inherently dynamic system.

What does this mean for species? I also work in China, where I look at rocks that are about 160 million years old, and we find beautiful fossils like a fossil of the earliest known salamander (shown in Figure 3). In many ways, they are similar to living salamanders. We also find their larvae. In Figure 4 we see a rare and beautiful salamander larva. It is a fossil, but you can see the soft tissue of its tail. You can also see its last meal, its developing appendage, and its gill structures. It is very similar to a living larva.

About 4,000 species have been around for over 160 million years, enormously successful by almost every measure of evolutionary success in terms of their ability to withstand major shocks to the environment and to speciate. To give you an example, in Figure 5 we see a curve representing geological time – the last 600 million years – versus extinction rate. When you plot extinction rate versus time, there is a normal level of extinction. Yet there are certain periods, certain pulses of change – marked here with the letters A, B, C, D, and E – of elevated extinction rate. Some of you may be familiar with the famous KT extinction, the demise of the nonavian dinosaurs. But there are others as well, including several large ones over two hundred million years ago that affected both land and sea.

Embracing change comes down to two things: managing the change that we are effecting in our world and dealing with the change itself as it is happening, so that we not only survive but thrive.

Salamanders and frogs have withstood enormous changes to our earth, including two of the largest known global cataclysms that removed several species from the planet. Yet 15 years ago, the herpetologists at the World Herpetological Congress discovered that frogs and salamanders were disappearing from their field sites. Despite having survived for over 160 million years, these creatures are now disappearing at an alarming rate (see Figure 6). Looking at the percentage of known species reveals that a number have become extinct in the wild in the last 50 years; others are critically endangered; others are vulnerable; and there is still quite a bit that we don't know.

Now, paleontologists are good at looking at the fossil record in the aggregate. That is, we take all the fossils we know about from particular environments and ask, statistically, what properties can we extract about species that survive over time and those that don't? Are the large events somehow different from the normal stuff that happens day to day?

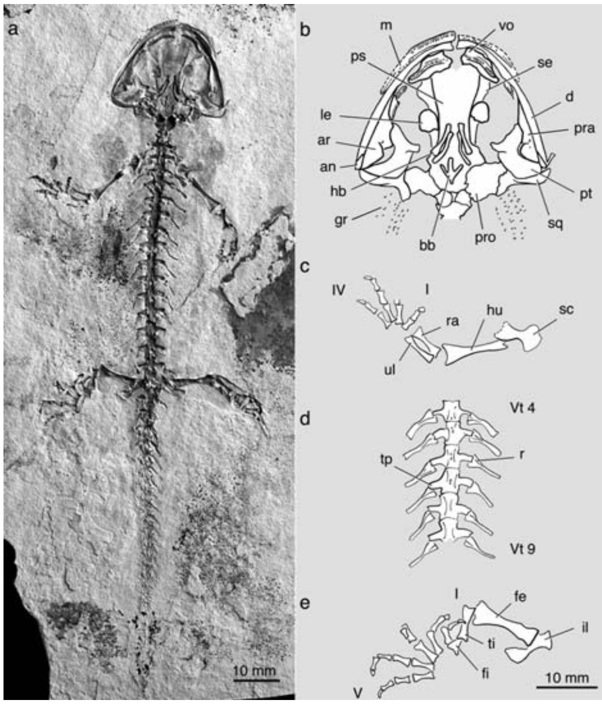

Figure 3

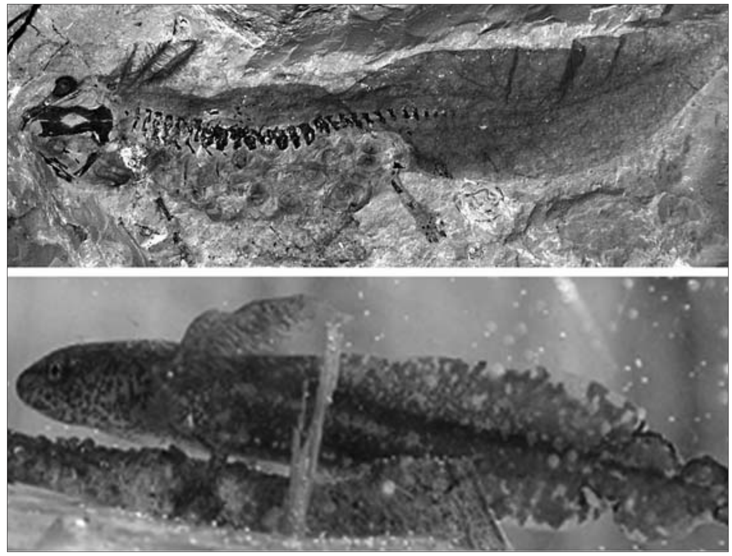

Figure 4

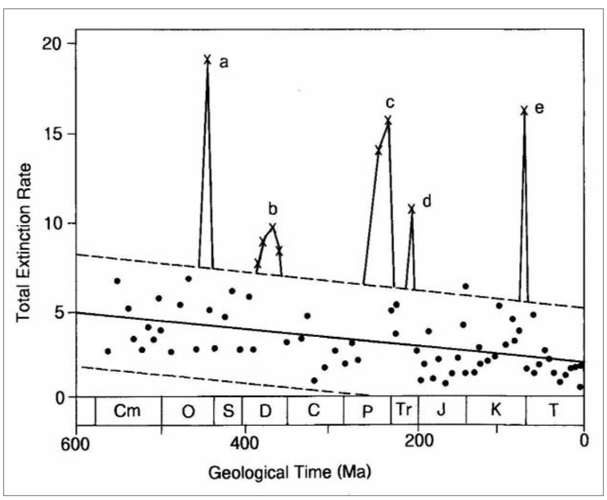

Figure 5

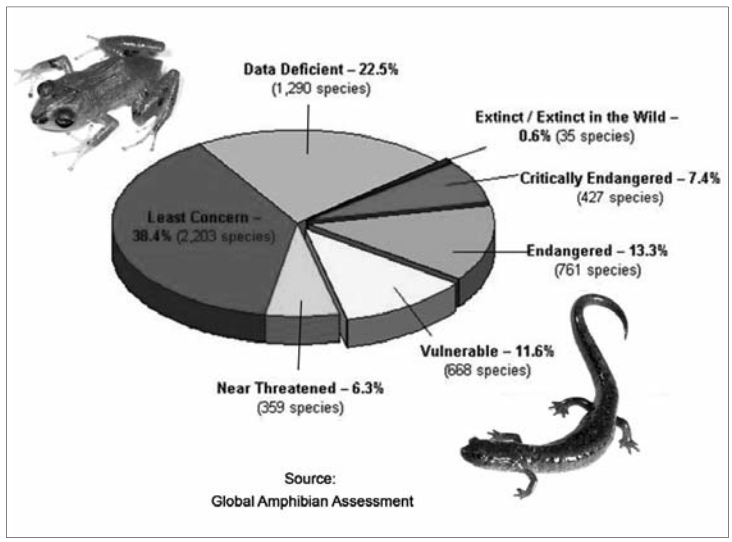

Figure 6

In a lot of these analyses, certain features have emerged that appear to confer extinction resistance. Some of them are obvious. Widespread range is one of them: species that are globally dispersed tend to survive extinctions more readily than do creatures that are endemic to a particular area. Species that have rapid dispersal abilities, particularly those that are able to increase their populations dramatically, also tend to do fairly well. Species that have the ability to colonize new or disturbed habitats are typically overrepresented among the survivors of these mass extinctions. Finally, generalists tend to do better than specialists. If we put all these characteristics together – widespread range, ability to disperse rapidly, ability to colonize new and disturbed habitats, and nonspecialization – we have basically described, for example, weeds, zebra mussels, rats, and cockroaches.

With the changes that are going on in our world today – climate change, disturbed habitats, changes in land use, species that have not been in contact before now coming into contact – what will our world look like if nature is selecting for the weediest of species? David Quammen published a wonderful essay a few years ago, "The Weeds Shall Inherit the Earth." The obvious question is, are we a weed in some way, shape, or form? Regardless of how you view us, we come back to this essential disconnect with which I opened my presentation. We humans, through our social structures – indeed, through our biological evolution – have adapted to a particular slice of time. Our economy – and even our immune system – is geared toward a particular kind of world. But that world is changing. The kinds of species we are likely to encounter are going to change dramatically over the next few years, and we as humans have to be able to deal with that.

Embracing change comes down to two things. The first is managing the change that we are effecting in our world, and the second is dealing with the change itself as it is happening, so that we not only survive but thrive.

May R. Berenbaum

May R. Berenbaum is Swanlund Professor of Entomology and Head of the Department of Entomology at the University of Illinois at Urbana-Champaign. She has been a Fellow of the American Academy of Arts and Sciences since 1996.

Presentation

Thank you for inviting me to speak on a topic that is of great interest and importance. I am here to talk about the birds and the bees, a concept so familiar that it doesn't bear an explanation. It is an exemplar of reproduction, how male sex cells and female sex cells get together to fuse and generate new offspring. Now plants, being firmly rooted to the ground, face a particular challenge in carrying out this arrangement. As a result, about three-quarters of all flowering plants depend on a third party, a go-between, to deliver the male sex cells, or pollen grains, to receptive female surfaces. That is basically the process implied by the use of the phrase "the birds and the bees," the process of animal-mediated pollination. Although today it is very familiar, it is surprisingly a fairly new idea in the history of science.

For millennia, no one really knew exactly what the birds and the bees were doing with the plants and the flowers; it wasn't until the eighteenth century that the scientific community recognized that plants have sexual organs at all. Rudolph Camerarius recognized that plants need two different floral parts, the stamen and pistol, in order to reproduce and that in all probability these parts represent the male and female reproductive organs. This observation inspired Carolus Linnaeus, the great chronicler of all life and the developer of the binomial system of naming organisms that we maintain today, to use the sexual organs of plants for the purpose of classification. This practice didn't go over well at the time. Contemporaries were shocked at the prospect of botanists inspecting the private parts of plants. Reverend Samuel Goodenough, the Bishop of Carlisle, was moved to remark, "to say that nothing could equal the gross prurience of Linnaeus's mind is perfectly needless."

The role of insects in the sex life of plants was another biological reality that was slow to be recognized. Probably the first person to suggest explicitly that insects play an important role in plant reproduction was Christian Konrad Sprengel – not exactly a household name today. In 1793, he wrote *Das entdeckte Geheimnis der Natur im Bau und in der Befruchtung der Blumen* (*The Secret of Nature Revealed in the Structure and Fertilization of Flowers*), followed by a second book on the utility of bees in the reproduction of plants. The fact that he is not a household name today reflects that his suggestion did not go over well either. His idea languished for almost half a century until Charles Darwin read his book.

We now know that at least 200,000 animals are responsible for pollinating an estimated 80 percent of all flowering plants.

Darwin, like many Victorian gentlemen of the era, was interested in, among other things, the domestication of animals and the breeding of plants, particularly orchids. He was struck by the writings of Sprengel and quickly realized that the remarkable relationship between plants and the insects that pollinate them was a terrific example of the process that he described as natural selection, especially the "coadaptation of organic beings to each other and to their physical conditions of life." He introduced this idea in his *Origins of Species*, but then expounded upon it at great length in his book *On the various contrivances by which British and foreign orchids are fertilized* – even going so far as to predict that the orchid *Angraecum sesquipedale*, with the 12-inch corolla and with no known pollinator on the island of Madagascar, had, somewhere, a pollinator with a 12-inch proboscis. And, at the turn of the century, a hawk moth was found that indeed had a 12-inch proboscis, and it was named *Xanthopan morganii* variant *praedicta* in honor of the prediction.

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We now know that at least 200,000 animals are responsible for pollinating an estimated 80 percent of all flowering plants, which amounts to almost a quarter of a million species. There are a few vertebrates, a thousand or so, in at least three classes. Many bird species are involved, bats are also involved, and there is even one known example of lizard pollination. But these numbers are dwarfed, of course, by the 200,000-plus species of insects, the real workhorses in the world of pollination. There are at least six orders, ranging from relatively inconspicuous Thysanoptera, or thrips, and Hemiptera, or true bugs; to the Lepidoptera, the butterflies and moths; the Diptera, the flies; and the Hymenoptera, the bees and wasps.

Knowing the nitty-gritty of pollination is a matter of considerable economic importance, and these relationships vary from extremely specialized to extremely generalized. The fig industry in California, which is second now to Turkey for worldwide production, did not get started until the late 1890s, because it took ten years for those trying to cultivate figs to figure out that they needed to import a tiny species of Agaonidae, the only species of wasp that could pollinate the figs. If you like Fig Newtons, you have a wasp to thank for it.

At the other extreme are the generalized pollinators, such as *Apis mellifera*, the Western honey bee. This nonnative species has an extraordinary ability to pollinate an enormous variety of plants and was imported early on by European colonists, at least in part for that purpose. Today, we rely on honey bees to pollinate over 90 crops in North America; and their contributions amount to over $14 billion, both in direct results (most of the fruits, vegetables, and nuts we consume fall into this category) as well as indirect results (bees pollinate alfalfa and clover, which are used as fodder for cattle, so the dairy and beef industries also depend on bees). And even when pollination is not an absolute necessity because some plants are self-fertile, visitation by bees can enhance yields.

Managed bees in North America are dependent on beekeepers. The number of beekeepers has been in steady decline over the last 30 years for numerous reasons. Among them, and particularly devastating, is the accidental importation of two species of parasitic mites in the mid-1980s that led to a massive loss of colonies. In the late 1990s, another interloper, the small hive beetle from Africa, was accidentally introduced and also caused more localized losses. Then, the African bees, brought into Brazil to breed a better bee with more resistance to tropical conditions, escaped from management, and they have steadily made their way north. Their more aggressive behavior is causing all kinds of problems for beekeepers.

Around the world, on virtually every continent, groups concerned with biodiversity took note of the apparent decline in a number of pollinator taxa.

While all this was going on, two ecologists, Stephen Buchmann and Gary Nabhan, noticed that honey bees were not the only pollinators having problems. In fact, most of the major groups of pollinators seemed to have species in trouble. Numbers were declining; ranges were contracting. Around the world, on virtually every continent, groups concerned with biodiversity took note of the apparent decline in a number of pollinator taxa. In 2004, the United States finally became involved, and the National Academy of Sciences approved a study to determine the status of pollinators in North America. I was asked to chair this committee, and we spent 18 months reviewing what is known about pollinators in North America.

We were charged with determining which pollinators were in decline, what the causes and consequences were, what research and monitoring were needed, and what steps could be taken to prevent or reverse those declines. We identified a clear downward trend for honey bees in the United States, but for other managed pollinators we simply did not have enough data to reach any conclusion about their present status. For wild pollinators, there was evidence of decline in some pollinators – notably several bumble bees, and some butterflies, bats, and hummingbirds – but the strength of the evidence varied.

In terms of the causes of the known declines for both managed and wild species, it was clear that introduced pathogens and parasites were one factor; habitat degradation and loss were another. Central Illinois once had forests that were quite extensive; now they are postage stamps on envelopes of corn and soybean fields.

What are the consequences of these declines? For managed pollinators, those that are kept for agricultural purposes, there has been a staggering increase in the cost of pollination services. In terms of wild pollinators, it is unclear in nonagricultural systems what the consequences of pollinator loss will be, but an important one could be an increased danger of extinction of plant species that are already endangered.

Our report was released in October 2006, which was just about the time when the agricultural community announced even more disturbing news. Bees were disappearing due to what was initially called fall dwindle disease. There have been disappearances of bees in the past, going back at least to 1880, but the pattern of this particular disappearance varied from those of the past in a significant way: there were no dead bodies. There were massive losses of the older bees, the forager bees. What remained behind in the hives was a small nucleus of very young bees as well as brood and honey and pollen stores. Even more surprising, the perennial pests of beehives, such as wax moths and hive beetles, appeared to avoid the collapsed colonies, which had not been noticed before. This pattern of collapse also varied from past collapses, particularly in terms of its extent. By February 2007, it had managed to mani-

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fest itself in over 25 states. Rental fees increased almost tenfold for almond growers who, every spring, rent half of America's 2,400,000 colonies of honey bees expressly for the pollination of almonds. There is no way to produce almonds without honey bees to pollinate the almond flowers. People even started stealing honey bee colonies – that's how valuable they were.

This decline was so alarming that in February 2007 USDA bee researchers collected samples of afflicted bees in California and Florida to determine what was causing these problems. Because Florida and California are important agricultural states, there were two congressional hearings about what became known as "colony collapse disorder." Bee disappearances even made their way into the popular conscience. In the comic strip, *Over the Hedge*, the characters are dismayed at the disappearance of bees, along with the disappearance of Sanjaya from *American Idol*.

In April, a group of about 50 scientists, bee biologists, beekeepers, representatives from federal agencies (including the U.S. Army), and other people concerned about these disappearances gathered in the USDA bee research facility in Beltsville, Maryland, to discuss the problem. We discounted a number of hypotheses that had been circulating, including and not limited to genetically modified corn pollen, cell phones, Wi-Fi, elevated carbon dioxide, elevated UVB, Osama Bin Laden, automobile grilles, solar maxima, jet chemical contrails, mutant bee cannibalism, fluctuations in the earth's magnetic field, Chernobyl, alien abduction, and bee rapture.

Instead, we focused on three more plausible possibilities. First, neonicotinoid insecticides were considered as a possible cause. These pesticides have sublethal effects on the behavior of bees, interfering with their ability to communicate, navigate, and orient, and thereby potentially preventing them from returning to the colony after exposure. A novel pathogen or parasite was another possibility. Third, we considered immune suppression related to management practices and nutritionally deficient diets. Despite the fact that it is a $14 billion industry, beekeeping has not changed significantly since the nineteenth century. There have been – with the exception of artificial insemination in the early twentieth century – no major innovations in beekeeping technology, yet increasing demand for pollination is pushing the limits of the system in an unprecedented way, with millions of bees trucked thousands of miles to deliver pollination services. We are facing this crisis situation in the apiculture industry, at least in part, because of the loss of other pollinator species. Little new technology has been developed to promote the management of alternative species.

Beekeeping has not changed significantly since the nineteenth century. There have been no major innovations in beekeeping technology, yet increasing demand for pollination is pushing the limits of the system in an unprecedented way.

In a perfect storm for bees in October, the honey bee genome was released. Approximately 11,000 genes had been sequenced, and the genome provided some insight into why bees might be so vulnerable. Compared to other insect genomes that had been sequenced at the time – including *Drosophila melanogaster*, *Anopheles gambiae* (the malaria mosquito), and the Japanese silkworm – honey bees, in particular, are exceedingly deficient in those gene families associated with resistance to infectious diseases and with the ability to detoxify xenobiotics or foreign toxins in the environment. We don't know whether this is typical of all Hymenoptera, or whether just bees are at risk.

Most recently, a group of researchers led by Ian Lipkin at Columbia University used a metagenomics approach facilitated by the sequencing of the honey bee genome. Genetic material from afflicted colonies was examined and the bee genes were effectively subtracted out: what was left was an astounding number of infectious diseases, including one new to North America – Israeli acute paralysis virus. This pathogen was not thought to be the cause of colony collapse disorder, but rather a symptom of a suppressed immune system. What we are doing at the University of Illinois, the home of the annotation component of the honey bee genome project, is comparing healthy colonies to collapsing colonies to see if there are differences in patterns of expression in those gene families that could account for these losses – notably the xenobiotic metabolizing genes, which encode enzymes that break down toxins, as well as genes that encode proteins that help bees fend off diseases.

But even if we figure out the cause of colony collapse disorder, it does not mean that bees are out of the woods or into the fields. And it certainly does not reflect on the problems that other pollinators are having. Again, habitat degradation and loss, as well as accidental importation of parasites due to globalization of trade, are still affecting pollinators. It is really astonishing that we are better able, here in the United States, to land a spacecraft on the surface of Mars than we are to land a pollen grain on a stigma in a prairie. Our knowledge of this interaction upon which most of terrestrial life depends is scandalously inadequate, and if nothing else, colony collapse disorder has brought that deficiency to the attention of the nation. We cannot afford to lose our pollinators, and we certainly cannot afford not to know who they are and where they are. So if nothing else, it is probably a good time for the country to stop and smell the roses and the other 200,000 species of plants that depend on insects as pollinators.

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