HOW TO CLONE A MAMMOTH

BETH SHAPIRO

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THE SCIENCE OF DE-EXTINCTION

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For my children, James and Henry, who will inherit whatever mess we make.

PROLOGUE

The first use of the word "de-extinction" was, as far as I can tell, in science fiction. In his 1979 book *The Source of Magic*,[1] Piers Anthony describes a magician who suddenly finds himself in the presence of cats, which, until that moment, he had believed to be an extinct species. Anthony writes, "[The magician] just stood there and stared at this abrupt de-extinction, unable to formulate a durable opinion." I imagine that this is precisely how many of us might react to our first encounter with a living version of something we thought was extinct.

The idea that de-extinction might actually be possible—that science might advance eventually to the point where extinction is no longer forever—is both exhilarating and terrifying. How would de-extinction change the way we live? Would de-extinction provide new opportunities for economic growth and galvanize global conservation efforts? Or would it lull us into a false sense of security and ultimately increase the rate of species extinction?

The year 2013 saw "de-extinction" become its own new branch of science, at least according to the *Times*.[2] Despite this lofty status, there is as yet no consensus as to what the goal of de-extinction science is. At first, it seems obvious. De-extinction aims to resurrect, via cloning, identical copies of extinct species. For species that have been extinct for a long time, however—the passenger pigeon, the dodo, the mammoth—cloning is not a viable option. In the case of these species, de-extinction will have to mean something else. Most likely, it will mean that specific traits and behaviors of the extinct species will be genetically engineered into living species. The living species would then gain the adaptations necessary to thrive where the extinct species once did. Will society, however, respond favorably to de-extinction if the goal is not to bring back an actual mammoth, dodo, or passenger pigeon?

Piers Anthony's novel was eerily prescient with regard to our reaction to de-extinction. Immediately after his magician accepted that de-extinction was possible and, presumably, in the midst of forming an opinion about it, Anthony's magician had another thought. Anthony writes, "If [the magician] killed these animals, would he be re-extincting* the species?"

* A warning to grammarians: In this sentence, Anthony's magician provides what is perhaps the earliest example of that awkward moment when, while discussing some aspect of de-extinction, it suddenly becomes clear that there is no satisfying way to complete a thought without offending people like you. How should one designate a species that has been brought back to life? While "de-extinction" seems perfectly logical with reference to a process, to refer to the end-result of that process as "de-extinct" seems inappropriate. "De-extincted," while more logical, is painful to write down, much less to say out loud. I prefer "unextinct" to "de-extinct," as "unextinct" seems to describe the state of being, rather than the process of getting there. One might say, for example, "The mammoth is unextinct." Of course, "The mammoth is no longer extinct" is certainly sufficient.

What, then, is the present participle? I shudder when I say that George Church's lab is de-extincting the mammoth. My reaction to the phrase, however, has nothing to do with the science. At the first formal scientific discussion of de-extinction, some of us suggested using "resurrection" and its various conjugates, as in, "We are resurrecting extinct species." While "resurrect" makes perfect grammatical sense, however, its religious connotations seemed misleading. Certainly, "De-extincting," is terrible, as is "re-extincting." Yet, here we are. While it takes longer to say it, perhaps we should stick with something that is simple to understand and entirely inoffensive—at least grammatically: We are developing the science necessary to bring extinct species back to life.

Many of the people with whom I interact believe that de-extinction is inevitable. I'll admit, however, that this is a biased sample of the population, and that most people are likely to care about de-extinction only insofar as it might affect them personally. Some people of course love the idea of de-extinction. They may be swayed and enthused by the idea that resurrected species might improve wild habitats. Or they may just want the opportunity to see and touch a mammoth. Other people, including very sensible and intelligent people, hate the idea of de-extinction, citing both the high cost of resurrecting extinct species and the myriad risks of reintroducing organisms into the wild whose environmental impacts are—because they are extinct—necessarily unknown. Those people who fear de-extinction the most, like Anthony's magician, take solace in its reversibility. This worries me. It is undoubtedly true that history repeats itself and that, if need be, we could *re*-eradicate any species we brought back. However, our goal as scientists working in this field is not to create monsters or to induce ecological catastrophe but to restore interactions between species and preserve biodiversity. If we do arrive at a time when science makes it possible to resurrect the past, it might take years or decades to see the results of this work. I certainly hope we do not simply turn around at the first signs of imperfection and destroy what we worked so hard to accomplish.

Certainly, if we are to make room for extinct species—or for hybrids of extinct and living species—in the real world, we as a society will have to alter our attitudes, our actions, and even our laws. Science is paving the way to resurrect the past. The road, however, will be long, not necessarily direct, and certainly not smooth.

With this book, I aim to provide a road map for de-extinction, beginning with how we might make the decision about what species or trait to resurrect, traveling through the circuitous and often confusing path from DNA sequence to living organism, and ending with a discussion about how to manage populations of engineered individuals once they are released into the wild. My goal is to explain de-extinction in a way that separates science from science fiction. Some steps in the de-extinction process, such as finding well-preserved remains of extinct species, will be relatively simple to complete. Others, however, such as cloning extinct species, may never be feasible. My perspective, as a scientist who is actively involved in de-extinction research, is that of an enthusiastic realist. I believe that de-extinction is in many cases scientifically and ethically unjustified. However, I also believe that de-extinction technology has great potential to become an important tool for conserving species and habitats that are threatened in the present day. If that seems paradoxical, read on.

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CHAPTER 1

REVERSING EXTINCTION

A few years ago, a colleague of mine practically bit my head off for getting the end date of the Cretaceous period wrong by *a little bit*. I was presenting an informal seminar about my research to graduate students at my university, which at the time was Penn State. My seminar was about mammoths—in particular, about when, where, and why mammoths went extinct, or at least what we've learned about the mammoth extinction by extracting bits of mammoth DNA from frozen mammoth bones. Before talking about this very recent extinction, I opened with a discussion of older and more famous extinctions. My offending slide cited the date for the end of the Cretaceous period and beginning of the Paleogene, also known as the K-Pg boundary and best known as the time of the extinction of the dinosaurs, at "around 65 million years ago." That date, I was told, was inexcusably imprecise. The K-Pg boundary occurred 65.5 ± 0.3 million years ago (at least that was the scientific consensus of the time), and I was *not* to be forgiven those 200,000 to 800,000 years.

While I appreciate that my fellow academics would have preferred meticulous attention to detail, I did not bring up the dinosaurs to discuss the precise timing of their demise. My goal was simply to make the point that while we think we now know why the dinosaurs went extinct so many millions of years ago, we still argue about what caused extinctions that took place within the last ten thousand years. Did the mammoths and other ice age animals go extinct because Earth's climate was suddenly too warm to support them? Or did our ancestors hunt them to death? The question remains open, perhaps because we are not particularly comfortable with the answer.

The last dinosaurs went extinct after a massive asteroid struck just off the coast of Mexico's Yucatan Peninsula. Similar cataclysmic events—major explosive volcanic eruptions or impacts of large asteroids or comets—are thought to have caused the other four mass extinctions in Earth's history. Each time, dense clouds of dust and other debris were suddenly ejected into the atmosphere, blocking out the sunlight. Without sunlight, the plants suffered and many species died. As the plant communities collapsed, so did the animals that ate the plants, and then the animals that ate the animals that ate the plants, and so on up the food chain until somewhere between 50 percent and 90 percent of all species that were alive at the time of the catastrophic event became extinct.

The mammoth extinction is different. We know of no single catastrophic event that happened within the last 10,000 years that might have caused mammoths to go extinct. Recent genetic research shows that mammoth populations probably started to decline sometime during or just after the peak of the last ice age some 20,000 years ago, as the rich arctic grasslands—often called the steppe tundra—on which they relied for food were gradually replaced by modern arctic vegetation. Mammoths were extinct in continental North America and Asia by around 8,000 years ago but survived for another few thousand years in two isolated locations in the Bering Strait: the Pribilof Islands off the western coast of Alaska, where mammoths survived until around 5,000 years ago, and Wrangel Island off the northeastern coast of Siberia, where they survived until around 3,700 years ago.

We know from the fossil record that mammoths, steppe bison, and wild horses dominated the Arctic landscape for a long time before the peak of the last ice age. In fact, they were the most abundant large mammals in the North American Arctic for most of the last 100,000 years. This was a very cold period of Earth's history and included two ice ages—one that peaked at around

80,000 years ago and another that peaked around 20,000 years ago—separated by a long cold interval. It was only after the peak of the most recent ice age that the climate really began to warm up, transitioning into the present warm interval (the Holocene epoch) by around 12,000 years ago. Because mammoths, steppe bison, and wild horses disappeared only *after* the Holocene had begun, it is reasonable to conclude that these species may simply have been adapted to living in a cold climate. When the world warmed up, the cold-adapted went extinct.

While this explanation is attractively simple, it has some problems. Most importantly, while we know from the fossil record that woolly mammoths lived in North America throughout at least the last 200,000 years, that period does not include only very cold intervals. In fact, around 125,000 years ago, Earth was as warm as or warmer than it is today. This was the peak of what we call the last interglacial period, which lasted from around 130,000 years ago until the beginning of the ice age around 80,000 years ago. Remains of mammoths, steppe bison, and wild horses are found in the fossil record of the last interglacial, indicating that they were able to survive despite the warmer climate. Their bones were, however, much less abundant during the interglacial than they were during the later, cold interval. According to the fossil record from the interglacial, a different community of animals dominated the warm Arctic from that which dominated when it was cold. The community of the interglacial period included giant sloths, camels, mastodons, and giant beavers: animals that were adapted to life in a warm climate.

If we look further back in time in the fossil record, a pattern begins to emerge. The Pleistocene epoch lasted from around 2.5 million years ago until around 12,000 years ago, when the Holocene epoch began. During the Pleistocene, our planet experienced at least twenty major shifts between cold, glacial intervals (ice ages) and warmer interglacial intervals. Average temperatures swung a whopping 5°–7°C with each climatic shift. Glaciers advanced or retreated, causing plants and animals to scramble (figuratively) to find suitable habitat. When the climate was cold, cold-adapted species were widespread. When it was warm, these cold-adapted species survived in isolated patches of refugial habitat, often at the edges of their former ranges. During the warm periods, warm-adapted species were widespread, and these warm-adapted species became restricted to warm refugia when it was cold. Range shifts were common during the Pleistocene, but extinctions were rare. And then, around 12,000 years ago, the climate swung from cold to warm, just as it had many times before. This time, however, cold-adapted fauna did not simply become less abundant. This time, many of them went extinct.

What was different about this most recent climate shift? The answer is not entirely clear. However, one potential explanation stands out: By the beginning of the Holocene, a new species had appeared on nearly every continent. This new species had a remarkably big brain and a capacity to transform its habitat to suit its needs, rather than seek habitats to which it was best adapted. This species was also alarmingly destructive. Wherever it went, its arrival seemed to coincide with the extinction of other, mostly large-bodied species. This species was, of course, humans.

Was it our fault that mammoths and other ice age animals went extinct? Interestingly, there is strong evidence that climate, and not humans, may have triggered the declines toward extinction. Humans and mammoths lived together in the arctic regions of Europe and Asia for many thousands of years during the last of the Pleistocene ice ages. The archaeological record shows that humans did hunt mammoths during this time, but since mammoths survived until much later, this hunting pressure was clearly not sufficient to drive mammoths to extinction. In North America, there is even clearer evidence that climate is to blame for diminishing mammoth populations. Humans did not arrive in North America until well after the populations of mammoths, steppe bison, and wild horses had already begun to decline toward extinction. Given this evidence, it is tempting to conclude that these extinctions were not our fault. After all, if we were not there, we could not have done it.

It is important, however, to understand the difference between declining populations and disappearing populations. Estimates of population size based on the fossil record or from genetic data can pinpoint when species began to decline from their ice age peaks but not when they actually went extinct. If we focus on disappearance rather than on decline, it is difficult to say with confidence that humans did not play a pivotal role in these extinctions. Populations of cold-adapted animals declined during every warm interval, not just during the most recent warm interval. In the past, however, these populations survived by finding and hiding out in refugial habitats, biding their time until the next cold period got under way. They probably did exactly that when the present warm interval began. This behavior, however, may have made them more vulnerable to extinction once humans were in the picture.

Ultimately, mammoths, steppe bison, and wild horses probably went extinct because of a combination of climate change, human hunting, and the disappearance of the steppe tundra. Rapid warming after the last ice age led to a decline in crucial habitat. Fewer herbivores trampling and consuming the vegetation meant that nutrients recycled more slowly, reducing the productivity of the ecosystem. To make matters worse, a new and intelligent predator appeared that was capable of zeroing in on any remaining ice-age habitat as ideal hunting grounds. Growing human populations and increasingly sophisticated human technologies further isolated these refugial populations from each other and from the resources they needed to survive. For some species, refugial populations may have held on well past the beginning of the Holocene. For example, our DNA work has shown that steppe bison survived in isolated patches in the far northern Rocky Mountains until as recently as one thousand years ago. As we learn more about the timing and pattern of these and other recent extinctions, there is little doubt that the role of humans will become increasingly clear.

THE SIXTH EXTINCTION

More than 3,700 years after the last mammoth died on Wrangel Island, we are witnessing an alarming number of contemporary extinctions, and the rate of extinction appears to be increasing. Some scientists have gone so far as to refer to the Holocene extinctions as the Sixth Extinction, suggesting that the crisis in the present day has the potential to be as destructive to Earth's biodiversity as the other five mass extinctions in our planet's history.

The word alone—extinction—frightens and intimidates us. But why should it? Extinction is part of life. It is the natural consequence of speciation and evolution. Species arise and then compete with each other for space and resources. Those that win survive. Those that lose go extinct. More than 99 percent of species that have ever lived are now extinct. Indeed, our own species' dominance is possible only because the extinction of the dinosaurs made space for mammals to diversify, and eventually we outcompeted the Neandertals.

I think people are scared of extinction for three reasons. First, we fear missed opportunities. A species that is lost is gone forever. What if that species harbored a cure for some terrible disease or was critically important in keeping our oceans clean? Once that species is gone, so is that opportunity. Second, we fear change. Extinction changes the world around us in ways that we both can and cannot anticipate. Every generation thinks of our version of the world as the authentic version of the world. Extinction makes it harder for us to recognize and feel grounded in the world we know. Third, we fear failure. We enjoy living in a rich and diverse world and feel an obligation, as the most powerful species that has ever lived on this planet, to protect this diversity from our own destructive tendencies. Yet we chop down forests and destroy habitats. We hunt and poach species even when we know they are perilously close to extinction. We build cities, highways, and dams and block migration routes between populations. We pollute the oceans, rivers, land, and air. We move around as fast as we can on airplanes, trains, and boats and introduce foreign species into previously undisturbed habitats. We fail to live up to our obligation to protect or even coexist with the other species with which we share this planet. And when we stop to think about it, it makes us feel terrible.