After all, an animal is more than a simple string of As, Cs, Gs, and Ts—the letters that represent the nucleotide bases that make up DNA. Today, we don't fully understand the complexities of how we get from simply stringing those letters together in the correct order to making an organism that looks and acts like the real thing. That will involve much more than merely finding a well-preserved bone and using it to sequence a genome.

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When I imagine a successful de-extinction, I don't imagine an Asian elephant giving birth to a slightly hairier elephant under the close scrutiny of veterinarians and excited scientists. I don't imagine the spectacle of this exotic creature in a zoo enclosure, on display for the gawking eyes of children who'd prefer to see a *T. rex* or *Archaeopteryx* anyway.

What I do imagine is the perfect arctic scene, where mammoth (or mammoth-like) families graze the steppe tundra, sharing the frozen landscape with herds of caribou, horses, and reindeer—a landscape in which mammoths are free to roam, rut, and reproduce without the need for human intervention and without fear of re-extinction. This constitutes the second phase of de-extinction, which builds on the successful creation of an individual to produce and eventually release an entire population into the wild. In my mind, de-extinction cannot be successful without this second phase.

That idyllic arctic scene might be in our future. But first, science has some catching up to do with the movies. Though we have sequenced nearly the entire mammoth genome, that work is not yet complete. We are also a long way from understanding precisely which bits of that sequence are important to making a mammoth look and act like one. This makes it hard to know where to begin and nearly impossible to guess how much work might be in store for us.

Another problem is that some major differences between species or individuals, such as when a particular gene is turned on during development, are inherited epigenetically. That means that the instructions for these differences are not coded into the DNA but are determined by the environment in which the animal lives. What if that environment is a captive breeding facility? Baby mammoths, like baby elephants, ate their mother's feces to establish a microbial community capable of breaking down the food they consumed. Will it be necessary to reconstruct mammoth gut microbes? A baby mammoth will eventually need a large, open space where it can roam freely but also be safe from poaching and other dangers. This will likely require a new form of international cooperation and coordination.

My goal is not to argue that de-extinction will not and should never happen. In fact, I'm nearly certain that someone will claim to have achieved de-extinction within the next several years. I will argue, however, for a high standard by which to accept this claim. Should de-extinction be declared a success if a single mammoth gene is inserted into a developing elephant embryo and that developing elephant survives to become an adult? Purists may say no, but I would want to know how inserting that mammoth DNA changed the elephant. What if a somewhat hirsute elephant is born with a cold-temperature tolerance exceeding that of every living elephant? And what if that elephant not only looks more like a mammoth but is also capable of reproducing and sustaining a population where mammoths once lived?

While others will undoubtedly have different thresholds for declaring de-extinction a success, I argue that this—the birth of an animal that is capable, thanks to resurrected mammoth DNA, of living where a mammoth once lived and acting, within that environment, like a mammoth would have acted—is a successful de-extinction, even if the genome of this animal is decidedly more elephant-like.

De-extinction is a process that allows us to actively create a future that is better than today, not just one that is less bad than we anticipate. It is not important that we cannot bring back a creature that is 100 percent mammoth or 100 percent passenger pigeon. What matters is that—today—we can tweak an elephant cell so that it expresses a mammoth gene. In a few years, those mammoth genes may be making proteins in living elephants, and the elephants made up of those cells might, as a consequence, no longer be isolated to pockets of declining habitat in Africa and Asia. Instead, they will be free to wander the open spaces of Siberia, Alaska, and Northern Europe, restoring to these places all the benefits of a large dynamic herbivore that have been missing for around 8,000 years. Large herbivores knock down trees and trample bushes, for example, and transport seeds and nutrients over long distances. By removing snow, mammoths—or rather, cold-tolerant Asian elephants—may also expose the permafrost to the bitter cold of Siberian winters. This would lower the temperature of the soil and slow the release of greenhouse gases trapped within it.

DE-EXTINCTION IS A PROCESS THAT ALLOWS US TO CREATE A FUTURE THAT IS BETTER THAN TODAY.

De-extinction is a markedly different approach to planning for and coping with future environmental change than any other strategy that we, as a society, have devised. It will reframe our possibilities. PS

This story was adapted from Beth Shapiro's book How to Clone a Mammoth: The Science of De-extinction, *published in May.*