the weekly anthropocene

dispatches from the wild, weird world of humanity and its biosphere

By Sam Matey

Scientist Spotlight #3: An Exclusive Interview with Ben Novak

Ben Novak is a paleogeneticist and currently one of the only practicing "de-extinction biologists" in the world. He is the head of the Revive & Restore Foundation's pioneering Passenger Pigeon De-Extinction Project, which seeks to create birds fulfilling the ecological function of the extinct passenger pigeon (*Ectopistes migratorius*). Mr. Novak and his team are sequencing DNA from ancient passenger pigeon museum specimens (pictured) and are working to splice that DNA into the germ line of some of their closest living relatives, the band-tailed pigeon (*Patagioenas fasciata*) in order to create passenger pigeon-like organisms. Mr. Novak is currently completing his Ph.D. at Monash University in Melbourne, Australia, while continuing his pigeon gene editing work. For more on this amazing project, check out www.reviverestore.org/about-the-passenger-pigeon/ and especially reviverestore.org/passenger-pigeon-de-extinction/.

Hi Mr. Novak! There are so many things I want to talk to you about! Let's start chronologically, if you will. Can you tell our readers the story of how you became interested in de-extinction? I believe it started with a science fair project.

Yeah. I was quite interested in extinct species when I was very young. That started with dinosaurs, and eventually I learned about animals like the Tasmanian tiger, the dodo bird, and the New Zealand moa. The more recently extinct species really captivated me. When I was in the eighth grade, I decided I would do a science fair project on whether or not it would be possible to bring the dodo back to life. It was just a thought experiment, of course, but I ended up qualifying to go to the state science fair and winning my division there. In between all of that, I ended up picking up a book by the Audubon Society-I think it was *A Century of Conservation*. That was where I found the passenger pigeon. And the dodo happens to be a pigeon, so it was a pretty easy leap to go from one species to the next. It was really the

story of the passenger pigeon that captivated me, the history of flocks of billions. That kept me passionate about it for many, many years.

From there, how did you get involved with the Revive & Restore Foundation? How did your current work begin?

Well, I went to Montana State University and studied ecology and evolution. I studied a fair amount of mixed classes, everything from paleontology to ornithology to genetics, all with the idea that I wanted to work with ancient DNA-that's known as paleogenomics today-and study extinct species, and learn more about their populations. I wanted to find out what the difference is between species that do really well with humans, like the common rock pigeon, and species that go extinct due to human impacts, like the passenger pigeon. When I finished university, I was putting together records on the passenger pigeon, and I wanted to go to graduate school for that. I went to graduate school at McMaster's University, but the first year I was there, no one would give us any passenger pigeon tissues to work on. I ended up switching projects work on the mastodon. The second year I was at McMaster's, I went to Chicago to sample some mastodon bones. And while I was there, I talked to them and said that I would just love to see the bird collection, I'd love to see the passenger pigeons. And they said "Yeah, sure, no problem," and the mammal guys escorted me over to the bird section. The curator was there, and he said "Hey, you sent a request for some passenger pigeon samples, didn't you? Did you ever get those?" And I said no, no one had ever responded. And it turned out that our request fell through the cracks. The Chicago curator was a forward-thinking guy, really amenable to using the collections for genetic studies, but he was retiring at the time and passing his duties onto his successors, and they dropped the ball on that. The curator said, right there on the spot, "How about I cut you some samples right now and you can take them?"

Wow. Yeah. I picked the ones that I thought were most valuable, information-wise, from the collection. I picked three specimens that were all shot from the same flock in 1860, and there's a reason I picked those. 1860 predates the collapse of the species into extinction-it's really about when they started the decline into extinction. So the population was probably around three billion birds at that time. And it's very rare, actually, to find passenger pigeons from the same flock. These were shot in the springtime, meaning they were most likely part of a breeding flock. These were actually contemporaries, these were birds that were flying together, possibly related to each other, so they actually represent a small population.

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So I picked those, he cut those tissues, and I took those with me. And because I was just there on the spot, the loan agreement was put in my name rather than in my supervisor's name, so I had the technical permission to do with those

samples what I wanted to independent of my graduate study. I raised some money from family and friends to pay for some sequencing and process those samples in the lab, and started working with them a little bit. That was right around the time that Revive & Restore was forming. Ryan and Stewart-Ryan Phelan and Stewart Brand, the cofounders of Revive and Restore-were very much inspired to start Revive and Restore, and Stewart thought the passenger pigeon would be a great first project. They held a meeting at Harvard about the passenger pigeon. One guy who attended was Joel Greenberg, a historian every bit as nutty about the passenger pigeon as me, if not more. I had met Joel digitally-I should clarify that all of this is happening in 2012-and he just sent me a message and said "I just went to this meeting, and this Stewart Brand is talking about doing exactly what you've always wanted to do. You should get ahold of him." The main name that popped up a lot was George Church, so I emailed him, and I said "I've got some passenger pigeon DNA, and if you guys can use it, it's yours. I want to be involved in this any way I can." He forwarded my email to Ryan and Stewart, and the next day I woke up and I had emails from all of them. Ryan and Stewart wanted to talk about what I had done with the passenger pigeon DNA and what my interest were, and that phone call kicked off a lot of thinking. Ryan and Stewart were forming this organization right on the spot, and they needed somebody that was passionate and willing to dedicate their whole life to this goal. I clearly had the motivation, if not the experience, and I also had three passenger pigeon samples that were mine to do with whatever I wanted, so that was a bit of a leg up. Ryan Phelan asked what I was doing that summer, and she offered me a preliminary internship. I spent the summer at George Church's lab trying to sequence band-tailed pigeon DNA. We did sequence it, but it wasn't good enough to assemble the genome properly. We ultimately learned from a few mistakes, and it led to assembling enough data. Revive and Restore organized a meeting at National Geographic in 2012 in October, and Ryan and Stewart gave me a chance to speak in front of 30 of the world's experts in ancient DNA, ecology, genetics, and biotech. And I didn't screw up, so they were impressed, and by November I had signed a contract which basically gave me my career.

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Wow. And that's how it happened. Another piece of the story-and part of this has been published at least once before-is how I was available that summer. I was not actually doing very well mentally at emotionally at McMaster's. I had been diagnosed with obsessive-compulsive disorder, and I'd had a lot of major depressive episodes. At that age, I'd been able to take a pause from my work, get some counseling, take some medication. When I was talking to Ryan and Stewart, I

knew I needed to take some time off, but it was such a great opportunity. I attribute a part of my recovery to the fact that I had the opportunity to fully embrace something I was so passionate about. One of my goals has been to share my history with mental health, because I feel like a lot of students face those challenges and feel pressured to perform. I think a very key element to me getting better was being able to step away and really focus on myself, and I've now been compulsion-free for seven years.

That's awesome. Yeah, it was really about recognizing opportunity and deciding to seize that opportunity when it came about. That's pretty much the whole story.

This is fascinating. Could you tell our readers why it is important to bring back the passenger pigeon? I know your team has done a lot of research on their ecological impact, from seed dispersal to canopy disturbance and the impact of their famously large flocks. Can you tell me more about that?

Yeah. When we started the project, a lot of what we talk about now, with their ecological significance, that was just a hypothesis, which a lot of people had bantered about. It was hard to imagine that a flock of a billion birds didn't have a significant impact on their ecosystem. One of the big arguments, for decades, was whether that impact was positive or negative. This was all based on one piece of information that was missing from the passenger pigeon story. The argument, the real debate, was whether passenger pigeons had been in flocks of billions for a long time, in which case their impacts would be positive, because it would be a long-term element that the forests had adapted to that was constantly there. Versus the idea that their population had exploded recently, due to some impact in the environment, possibly due to human influences, in which case they'd be somewhat like a pest species, and they'd be negative. I was never really fond of the negative hypothesis, it didn't make a lot of sense. The more I researched it, it looked like everyone who came up with that idea didn't explore the whole picture. The reason I wanted to pursue genetics was because with population genetics you could reconstruct the population history. So it was really the big piece missing from the passenger pigeon story, and genetics could answer that question. So that was one of the things we set out to do, early on. We had a bunch of hypotheses in our original work as to when passenger pigeons might have gone from low numbers to abundant numbers. One hypothesis was that they exploded 500 years ago due to Europeans decimating the First Nations people. The idea was that it was competition between humans and passenger pigeons for resources that had kept passenger pigeon numbers low, and that when the First Nations people were decimated and

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removed, the passenger pigeons moved up. Another hypothesis that was published was basically the same hypothesis, but it put the timing back to 1000 years ago because that's when the First Nations people changed their agricultural tactics, which allowed passenger pigeons to boom because the competition was freed up. That one was maybe a little more plausible than the other-it's really implausible to imagine a population booming up to billions in 500 years. Actually, in 40, it would have been 40 years because the first ever record of a passenger pigeon written down is in 1532, only forty years after the arrival of Europeans. At this point, First Nations people had not been completely decimated yet.

Did that description list them as being in immense flocks?

The exact description was very short, it was a ship's captain who said "We saw an infinite number of wood pigeons today." **That would seem to support that very large flocks have been around for a while.** Exactly. From then on, in every single record the pigeons are "innumerable" or "countless," et cetera. People didn't even try to put numbers on them until the 1800s.

Our other hypotheses were built on habitat. The passenger pigeons required certain things to eat, like oak or beech trees. Beech trees didn't become really abundant until about 6000 years ago, so we decided that would be one hypothesis ***(that passenger pigeon populations first became super-numerous at that time due to the availability of beech trees)***. And then oak trees became really abundant starting around 9000 to 8000 years ago, which really followed the recession of glaciers. A typical hypothesis is always going to be the Ice Age-the ice sheets covered about half of the passenger pigeon's known range. So it's like, okay, there's half the land for them to live in, maybe there were fewer of them. Forests were less dense then. So the other one was tracking how the population maybe more gradually expanded as the ice sheets melted away. **Fascinating.**

We had basically those five hypotheses. We got the data back, and they were all wrong. That was our first big mind-boggling discovery. We tried out a bunch different of ways to calculate passenger pigeon population genetics, and even the most absurdly rapid mutation rates we used put them ***(the ultra-large flocks)*** just slightly before 20,000 years old, older than our

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oldest hypothesis, and the more reasonable ones dated them to 50,000 years. That's a long time. It turned out that the passenger pigeon genome is completely shaped by their history of abundance, to a point that you cannot calculate population history from it. **Wow.** The best we can come up with is that passenger pigeon populations became abundant sometime between 50,000 years ago and one million years ago. I think we all felt that that definitively answered the question that passenger pigeons had always been abundant. It's likely that they were playing the exact same role that people observed them in in the 1800s for tens of thousands if not hundreds of thousands of years. And that would mean that the entire ecosystem was being shaped by that dynamic for a long time. And then you investigate the ecosystem, and you find out things. Oak trees don't even germinate unless it's in a disturbed forest. American chestnut trees are the same way. White pine and spruce trees can coexist best in a disturbed area of forest, otherwise one dominates over the other. Basically, the very evolutionary biology of dominant tree species, plants, and vertebrates that live in the eastern United States are all adapted to an ecosystem that's constantly being disrupted and turned over and regenerated.

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By passenger pigeons. Yeah, that was the argument I made in the thesis, that it's passenger pigeons. The competing hypothesis was that it was fire, because a lot of coincidences in history made it seem like it was fire. I'm not the first person to think that it wasn't fire, but I think I am the first person to write that it was the pigeons. Over the last 40 years, forestry managers have tried to restore disturbance cycles. They've used fire, they've used clearing, they've used canopy thinning. The results are really varied, and it seems like fire doesn't always do the job. When you look at the history of periodic fires, it doesn't make sense, when you go from west to east, the frequency of fire goes from every once every three years ***(which is why Western American forests, like those of Yellowstone and Yosemite, have fire-dominated disturbance regimes)*** to every seventy years to every three hundred years. If fire's happening every 150 to 300 years, that's not going to be enough to influence these species' life cycles.

Whereas passenger pigeons were creating disturbances every three to ten years, in a specific area. So passenger pigeon disturbances really fit the bill for the frequency needed, and they also fit the bill for what kind of disturbance is best. Fire alone doesn't do the job, but paired with these mechanical thinning treatments, you get pretty good results. What's happening is, fire goes through and clears out the undergrowth, and that resets the competition phase. Anything that germinates after that, they're all starting with everything equal. Fire also changes the biochemistry of the soil, in a way that a lot of species of plants do really well with. And then when you clear the canopy, you disrupt the canopy, you're

allowing more sunlight in. And when you think about what passenger pigeons are doing, they're overcrowding the branches, breaking the branches, thinning the canopy, letting the sunlight in. And then they're depositing tons of guano, snuffing out and killing everything living on the forest floor, and then also changing the biochemistry of the soil. Enriching it possibly much more than fire does, because it's basically fertilizer. So, passenger pigeons alone are doing the dualistic action of a windstorm and a wildfire, a very intense fire. They've been doing that for fifty thousand years, they do the ideal disturbance. And there's no doubt that fire is part of this ecosystem, but the major factor perpetuating this was definitely the pigeon.

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So something that started as a hypothesis about why this would be a valuable project to pursue really became more of a validated theory about their ecology and has become the main driving force behind why we want to bring them back. The more we look into it, the more we realize that without these disturbance cycles, we're going to continue to lose species in the eastern United States. It's also, and this isn't really published anywhere yet, but disturbance cycles in forest that foster growth are actually pretty good for climate change. You end up getting more net carbon storage when you open up little areas of forest to allow grass and flowers to grow. They sequester more carbon than trees do underground, so you end up with an interesting cycle of carbon going in and out. It's not the kind of thing that's going to save us from climate change anytime soon, but similar to the mammoth project, the more we can do to produce functional, viable, carbon-regulating ecosystems, like grasslands and regenerating forests, the more that's going to give us long-term climate stability when we try to reverse some of the crap that we've done.

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We've also been thinking about the social factors. Birding in the United States has become a multimillion-dollar industry each year. It's hard to imagine that there won't be a great allure to a flock of, say, even a million passenger pigeons all in one spot. And since they're nomadic, they aren't just going to be hitting Cincinnati, Ohio, every year. They're going to be going into a lot of communities and areas, and for small rural communities, a flock of passenger pigeons coming through

will be a huge ecotourism draw. For the birders, and eventually for recreational hunters when the population's large enough. Hunting in the United States is also a several billion-dollar revenue stream. What's great about hunting in the United States is that a lot of that money goes straight back to wildlife conservation.

Awesome. Actually, in the United States, I think hunting revenue and taxes represents the largest funding source for nature conservation. That's money that goes straight to state and federal wildlife and game agencies. So we see a lot of different economic opportunity long-term with this. We also see it being really married well to what the Forest Service wants to do with their management. And it all stems from this initial piece of insight about their population, which is something we could have only got from gene data.

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That is such an incredible ecological web of connections, that's amazing. That passenger pigeons can help with carbon storage, and restore the diverse landscape of the forest, that's incredible. We certainly thought so.

So another question I have was, could you summarize for a general audience the techniques you're using to restore the passenger pigeon genome? On Revive and Restore's website, they list three phases for the passenger pigeon revival project. These are-correct me if I'm wrong-Genome Research, or in silico, followed by Cellular Engineering, in vitro to in vivo, and finally, of course, Restoration of the birds themselves to the wild. Could you walk me through the broad strokes of this roadmap and discuss where exactly you are now?

Yeah, sure. When we announced the project in 2013, with the TedX series, we made a splash because I provocatively said a few things. About training passenger pigeons with birds that had been dyed to look like passenger pigeons, that sort of thing. Maybe we'll do that, maybe we won't. Really, the idea was: how do we innovate a program that goes from data in a computer and tissues in a museum collection to birds thriving in the wild? And something we've been fast to point out to everybody is that the final phase, going from breeding in captivity to putting animals in the wild, that's already a very mature discipline. That's something that's done all the time. Even though it's a mature discipline, it's always in need of innovation. That's because every species is different, with a unique evolutionary history and ecology. The California condor program is a great model for that. They went extinct in the wild, they brought the last ones into

captivity, and over the course of the last few decades they've been innovating again and again how to improve going from breeding in captivity to putting birds back in the wild.

Last year was the first year in which condors in the wild produced more chicks than were produced in captivity. That's an amazing milestone. And they went through a lot of tweaking, and different versions of raising birds to get to that point. And then there's programs like the restoration of the pink pigeon on Mauritius. Which once again, went through similar stages. Their population was down to 12 or 15 birds, there's 400 of them today. They are dependent on human help, because of compromises in their ecosystem, but they're thriving in the wild again. I got to see some when I went to Mauritius, and it was amazing. We get the opportunity to look at these programs that have already forged the process and really build from that. That's what gives us a lot of confidence and structure to what we've designed in the final phase. It's the first two phases that are new science. How do you go from sequencing a genome to genetically editing an individual? That's where we need a lot of the new biotech innovation. From start to finish, the broad concept is to sequence the passenger pigeon genome from those tissue specimens that are at museums-wait a moment, I can't remember where are you based? **Maine.** Yeah, undoubtedly there were a lot of passenger pigeons in Maine. **Yeah, I saw that we were in their historical range map. That's part of the reason I got interested in your project, to see if maybe someday your passenger pigeons might end up back here as part of their expansion.** Well, Maine is one of the most forested states today, so I undoubtedly know that they'll be there. It'd be nice if maybe one of our breeding facilities was in Maine. That's actually one thing I was trying to point out to a lot of people-Maine, Vermont, New Hampshire, those states actually have forest levels today almost equivalent to those there when Europeans arrived. **Yeah!** And with climate change, Maine is technically like the new Pennsylvania for passenger pigeons. There might be more passenger pigeons in Maine that were ever there in history.

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This is actually something I was really interested in. It's fascinating that you're thinking along the same lines.

Well, the general trend in climate change is that species move north. When you look at where passenger pigeons used to primarily breed, or at least where most of the records are from it's the Great Lakes area. And a lot of the forests around the Great Lakes have been decimated and become farmland. But when you look slightly more north, into Ontario, Quebec, and Maine, that's where the forest is much more intact. That really could be the next step. A lot of

forestry managers are actually preemptively planting tree species farther north to facilitate migration, because they've noticed there's a slow march of tree distributions changing. But anyway, let's put that aside. I'll come back to that, this'll be important for your EA.

The technology, basically, we take the tissue from a specimen in a museum, we sequence the DNA, we analyze that and compare it to a band-tailed pigeon. We're still doing that, we've been doing it that for several years. It's been on and off because we haven't always had someone available to look at that data. We've got a guy down here in Australia looking at it right now. We can see the mutations in the genome really easily, but the issue is trying to figure out which of those mutations matter. This is something we try to get across to people. It's like this-do you have any cousins? You and your cousin are obviously both human beings. But you have thousands of mutations that are different from each other. Obviously those mutations don't matter in defining you as a human being, they only matter to define you as an individual. So if I were to try and turn a chimpanzee into a human being, would I really care about your cousin's unique mutations or your unique mutations? That wouldn't do anything. But over time, over millions of years, some of those mutations that are not truly defining of a species can spread through a population due to genetic drift or something like that. A lot of these mutations build up over time and they're just noise, they don't do anything at all. Every once in a while mutations pop up that affects a trait, and selection works on that. Mutations that evolution has really "picked out," that we care about, those are a much smaller number of mutations than the total mutations. Between the band-tailed pigeon and the passenger pigeon, there's been twelve million years of evolutionary divergence, and that's enough time for a lot of noise to build up. So we're trying to comb through and pick out which mutations shape the passenger pigeon species. Those will be mutations that are shared by every single passenger pigeon, because if they're not there, they're no longer a passenger pigeon. With humans, you and your cousin, me, some guy in Mongolia-we all have mutations that are all the same when you compare us to a chimpanzee. Those are what define us as humans versus a chimp. We want to take that set of mutations, and then reduce it one step further. We cannot feasibly edit millions of mutations right now. In the coming decades it will definitely be possible to synthesize whole genomes, but right now, we're really looking for the few dozen, maybe couple hundred mutations that really matter. What produces the largest impact? What is a passenger pigeon,

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when you're looking at it ecologically? It's a wood pigeon, it eats a certain amount of food and a certain range of foods, it's a certain size, it breeds a certain way, et cetera. And when you look at it that way, the living band-tailed pigeon starts to look a lot more like the passenger pigeon. Then you get to a couple key traits that make the species critically different. Passenger pigeons flocked in billions, and band-tailed pigeons, although they did form aggregations, when they breed, they spread out. And so what creates that disturbance in the forest is the fact that thousands if not tens of thousands of passenger pigeons are trying to land on the same tree, hundreds of them pooping on the same tree. Whereas band-tailed pigeons, if they come into an area, they spread way out, a couple of them in this tree, a couple in that tree. They don't socialize intensely enough to create a disturbance. And that's a behavioral thing. We're very interested in genes that are influencing that type of behavior. Then, of course, there's the fact that passenger pigeons are sexually dimorphic, while most pigeon species are not. Sexual dimorphism is seen far more often in social species than non-social species. That's because when you're in a dense social setting, and you're competing, it tends to exaggerate traits. The tail structure of the passenger pigeon is most likely related to sexual competition. We think that there's physical traits that matter, behavioral traits that matter, and then there's physiological traits that matter. If you have a flock of a billion birds, with five million offspring, they're going to consume resources exorbitantly and rabidly. Something that's noted about passenger pigeons is that they develop in about three-quarters to half the time that band-tailed pigeons develop. They essentially become ready to wean and fly within two weeks to possibly eighteen days, which is really, really rapid for their size. The earliest you can wean a rock pigeon from its parents is about 28 days, where it's close to adult size, while passenger pigeons are reaching that in 14 days. Rapid growth is definitely something that would be selected for in high abundance. If resources are being consumed really rapidly, you have to grow up really quick or else you'll starve to death. This juvenile growth is related to supporting high densities and large populations.

So those are the main traits we're trying to isolate, and once we figure that out, we'll edit those into band-tailed pigeon cell cultures, specifically primordial germ cell cultures that are reproductively competent. We take those cells after we've edited them to have those different traits, and we'll implant those into a living pigeon embryo. It will most likely be a rock pigeon rather than a band-tailed pigeon, because they're much easier to manage in captivity. They require less space, and they're more prolific, it's easier to make them breed a lot more. They'll lay eggs, and out will hatch a gene-edited band-tailed pigeon that looks and behaves like a passenger pigeon. And

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that's when we start with the captive breeding regime and releases into the wild, which is much more patterned after those other programs. We'll want to foster some individuals to use as breeding stock, some that we start acclimating to living more naturally. We'll be transplanting them into soft release, then moving them area-to-area to try to foster nomadic behavior, then releasing them into the wild. And by the time we get to releasing into the wild we'll definitely use GPS tracking systems on those birds, so we'll know where they're going, are they still flocking as a unit, and so on. Part of the reason we do this stepwise increment is to ensure that the birds succeed in the wild, and part of it is to just do due diligence as a science. If we raised them the hypersocial way in captivity, we will see the behavior. But once we release them to the wild, there's no netting keeping them there. Will they disperse? Maybe in a generation they'll quit flocking together and be more like band-tailed pigeons. So it's going to be very important in those first few years that the birds are free in the wild that they are monitored very closely so we can see: are they maintaining those traits? Or is evolution turning them back into band-tailed pigeons? There's a lot of aspects to think about, but that's essentially the start-to-finish high-level look at it.

That's so awesome! Zooming ahead in time a little bit: Revive and Restore's website for your project says that the goal is to reintroduce passenger pigeon facsimiles to the wild by the 2030s. Would you say that's likely to happen at this point? When do you think the first genetically edited passenger/band-tailed pigeon will hatch? What does the timeline of your work for the next ten to fifteen years look like right now?

I'm really hoping that sometime between 2025 and 2030 is when we actually get those birds hatching, and that in the 2030s we start with some releases. It's pretty rapid to think we can do it like that, and our date keeps pushing a little into the future. One thing with this work is that technologically, we could definitely reach those milestones. But the innovations we need require the right expertise and funding. Getting people with the right expertise and the bandwidth to take that on and getting that funded is always the challenge. Our project goes with surges of "we've got some work going" and then we have a delay of "we're waiting to get someone else involved." It's been pretty staggered so far. I think the timeline is reasonable from a technological

"I'm really hoping that sometime between 2025 and 2030 is when we actually get those birds hatching, and that in the 2030s we start with some releases… Our project goes with surges of "we've got some work going" and then we have a delay of "we're waiting to get someone else involved." It's been pretty staggered so far. I think the timeline is reasonable from a technological standpoint, but it's possibly going to be longer due to the realities of trying to get the money and people for this going."

standpoint, but it's possibly going to be longer due to the realities of trying to get the money and people for this going. The further along we go, the bigger the team has to become. When we get into captive breeding, we're going to need many facilities and lots of people. And what we're doing right now is working on genetically engineering some rock pigeons, to start testing out passenger pigeon mutations. None of these birds will ever become de-extincted passenger pigeons, but it's crucial to test. We look in the genome, we see a mutation, we think this evolved for the tail shape. Before we just put that into a band-tailed pigeon cell line and go, we want to see if we know what we're talking about. So we'll test that in a strain of pigeons we're developing now, see if it works, and build the data that way. This work, we'll see the first real milestones in the early 2020s. Depending on how complicated making a passenger pigeon becomes, it might push that timeline out a bit longer. But really, we'll be able to discover more of a realistic timeline in the next five to six years.

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I find this so fascinating that we can bring back this whole type of forest that humanity wiped out carelessly a century ago. Thanks for being a de-extinction biologist!

Well, thanks very much for your enthusiasm and support. We very much hope that we can continue with this work and follow through with the program. It really comes down to public support. If we don't have public support, we'll just die in the water. So your support, and people spreading awareness, and trying to turn that into donations, that's what matters for this work. **I can share a link for that. (Check out https://reviverestore.org/get-involved/!!!)** Yeah, that's be great. Constantly letting people know that they can donate anything, literally anything, like ten dollars, and that's what pays for everything from my salary to sequencing a DNA sampling to editing a bird. It all goes into that.

Again, Mr. Novak, thank you so much for your time. I look forward to seeing how your work progresses. Thank you!