BIOLOGY

Could Genetic Engineering Save the Galápagos?

In the Galápagos, invasive species are driving native animals to extinction. Some conservationists are asking whether genetic manipulation is the solution

By Stephen S. Hall on November 1, 2017

Marine iguanas of the Galápagos are vulnerable to feral cats and other invasive predators. *Credit: Tui de Roy*

On September 25, 1835, during the HMS *Beagle*'s sojourn to the Galápagos archipelago, Charles Darwin first set foot on what was then known as Charles Island. He found a colony of 200 to 300 inhabitants, nearly all political exiles sent there by Ecuador, aka the "Republic of the Equator," after a failed coup attempt. The lowlands did not much impress Darwin, with their "leafless thickets," but after trudging four miles inland and upward to a small, impoverished settlement in the highlands, he found "a green and thriving vegetation," cultivated with bananas and sweet potatoes, along with a group of islanders who, "although complaining of poverty, obtain, without much trouble, the means of subsistence." That was mainly because of the tens of thousands of giant tortoises that once

prowled these islands. “In the woods,” Darwin noted, almost as an afterthought, “there are many wild pigs and goats.”

On the morning of August 25, 2017, Karl Campbell bounded off a twin-engine motorboat and onto the dock of that same humble island. Now known as Floreana, the island has 144 residents, half as many as in Darwin’s time, and Campbell seemed to know them all. Dressed down in a baseball cap, blue jeans and gray T-shirt that read “Island Conservation,” he ambled up to Claudio Cruz, at the wheel of a local bus (a converted truck with benches in the back), and exchanged some banter. He waved hello to Juanita and Joselito, who manned the Ecuadorian government’s biosecurity checkpoint on the dock. He shouted out another “*Hola*” to the postmaster, popped his head into the community center to greet Myra and Holger, a farmer, and paused to catch up with Carmen, the woman who monitors the public bathrooms near the landing. His path up Floreana’s one paved road was interrupted by salutations, chitchat, short jokes and the one-cheek kisses that are the custom in Ecuador.

Campbell, a 42-year-old Australian who has lived in the Galápagos Islands for 20 years, is a gregarious and outgoing fellow, with a tendency to begin conversations with “All good, mate?” But the cheery demeanor and bonhomie he displayed that morning is an essential part of a massive scientific undertaking. Campbell has a Ph.D. in vertebrate pest management from the University of Queensland in Australia, and in 2006 he began working as an animal removal specialist for Island Conservation, an organization based in Santa Cruz, Calif., that is devoted to preserving biodiversity and preventing extinctions by removing invasive species from islands throughout the world. Campbell has been working on eradications in the Galápagos since 1997, including a 2006 campaign to remove all the feral goats and donkeys from Floreana. A decade later he’s a project manager with Island Conservation, and the most ambitious project on its agenda is once again on Floreana: to eradicate every single rat and mouse on the island.

There are hundreds of thousands of islands in the world. “You can’t work on all of them,” Campbell says. Conservationists, according to Campbell, “are currently able to do 10 to 20 islands a year to rid them of mice. So which are the ones you should be working on most urgently? We basically draw up a list of places where we should be working to prevent extinctions.” Topping that list, he says, is Floreana.

“Floreana has one of the highest endemicity rates in the Galápagos, the highest rate of extinctions due to the invasive species here and the highest rate—by far—of critically endangered species, which makes it one of the highest-priority targets not just in the Galápagos but in the world,” Campbell says, in a spiel that has the polish and urgency of countless recitations to funders, journalists and probably every one of Floreana’s residents.

Floreana is at the limit of feasible projects using current eradication tools. The island is large (17,253 hectares, or about 46,600 acres), and it is inhabited, which complicates the task enormously. It means having to explain the logistics and consequences of the entire project—not least of which is a plan to dump 400 tons of rodent poison all over the island. That is why, since 2012, Campbell and his colleagues, such as Carolina Torres and Gloria Salvador, have been visiting Floreana almost once a month, enduring the bumpy two-hour boat ride from the main island of Santa Cruz to meet with residents, describe their proposed project, and figure out the massively complicated steps needed to protect adults,

children, livestock, water and endangered species from the effects of the poison.

Such eradications require almost military-scale logistics and precision, which is why Campbell has been desperately seeking an alternative to the blunt-force tools of current techniques. One of the most appealing, to his mind, is a controversial new form of genetic manipulation known as gene drive. Compared with the frustrations he endures every day on the Floreana project, he likens the technology to a magic wand out of *Harry Potter*.

The basic strategy of using gene drive in the conservation setting would be to tinker with the DNA of mice, using either the new gene-editing tool CRISPR or other tools of genetic manipulation, in such a way as to tilt the odds of sex inheritance; one example would be to produce offspring that would be exclusively male, eventually producing a daughterless population of mice. The elimination of females, of course, would create a reproductive dead end for that invasive species. Gene drive is far from a practical technology at this point, but Island Conservation has been working with molecular biologists in the U.S. and Australia to create these genetically modified mice, and Campbell has made no secret of his enthusiasm for the approach at recent scientific meetings.

And that, in turn, may be why the National Academies of Sciences, Engineering, and Medicine, in a 2016 analysis on the potential benefits and risks of gene drive, included the example of daughterless mice among a series of potential scenarios where the technology might be applied. As the report noted, “Perspectives on the place of human beings in ecosystems and their larger relationship to nature—and their impact on and manipulation of ecosystems—have an important role in the emerging debate about gene drives.” That debate, in a sense, has already begun on Floreana, where residents have been weighing the benefits and risks of a massive, albeit nongenetic manipulation of their precious ecosystem for the past five years.

Brown rats (*1*) are a primary target of a massive invasive-species eradication effort planned for the island of Floreana, where donkeys (*2*), cattle (*3*) and many other nonnative species have been introduced over the centuries. On neighboring Isabela Island, feral goats denuded the landscape of a giant Galápagos tortoise stronghold (*4*). Credit: Krystyna Szulecka *Alamy* (*1* and *3*); Wolfgang Kaehler *Getty Images* (*2*); Tui de Roy (*4*)

Campbell is the first to acknowledge that the Galápagos will not be the first or best place to test gene drive in the field. But it may be the best place to think about the implications, good and bad, of gene drive in the context of species preservation. If, as a global community, we value the preservation and protection of biodiversity in the Galápagos (a value ratified by its selection as among the first World Heritage sites by the United Nations agency UNESCO), we also have to come to terms with the complexities and paradoxes of invasive species eradication, which legitimizes the local elimination of certain animals for the benefit of other species—not least humans. As Campbell likes to point out, "No one comes to the Galápagos to see rats and goats and cats."

I. "RED IN TOOTH AND CLAW"

If the Galápagos Islands have become synonymous in the public imagination with ecological harmony and thrillingly pristine biodiversity, the reality is somewhat different. Yes, the massive tortoises are stunning, but where thousands of them once bulldozed the highlands of Floreana, there are now about two dozen—all imported from other islands because the local species went extinct. Yes, the fearless finches are charming and beautiful, but the Floreana mockingbird disappeared from the island around 1880, one of 13 species that have gone locally extinct. Yes, the sea turtles languorously swimming off La Lobería Beach are magnificent, but their eggs have been relentlessly poached by indifferent predators. All those iconic Galápagos species have been ruthlessly threatened by invasive species.

There is a darkness to the Galápagos paradise, and it has been there a long time, perhaps since Tomás de Berlanga, then the bishop of Panama, went off course and discovered the islands in 1535. The first true invasive mammals on the islands were the pirates who frequented them in the 17th century, followed by sailors from whaling ships in the 18th century. These mariners brought in tow a malign ark of mammalian deplor-ables they introduced to islands that had been largely unperturbed for millions of years. If you want to be provocatively precise about it, the very first documented resident invasive species on Floreana was an Irish sailor named Patrick Watkins, marooned around 1805. He reportedly grew vegetables, which he bartered to visiting ships in exchange for rum (he was the model for a story by Herman Melville).

Three years before Darwin's arrival, a zoo's worth of invasive species had become entrenched on Floreana. It is no accident that in the scientific literature, the earliest date for many invasive species is 1832. That's when General José de Villamil, the first governor of the Galápagos Islands, arrived on Floreana to organize the penal colony. As Cruz—farmer, amateur historian, sometime bus driver and the largest landowner on Floreana—puts it, "He brought everything—goats, donkeys, cows, mules, horses, dogs, pigs, rats, everything." Similar animal importations occurred on other islands in the Galápagos during the 19th century, with devastating consequences on the local flora and fauna. Villamil brought the mules and donkeys to haul tortoises down from the highlands. At the time of his visit, Darwin reported that a previous ship visiting Floreana had loaded up on 200 tortoises in a single day (other ships reportedly collected as many as 700 apiece, according to Darwin).

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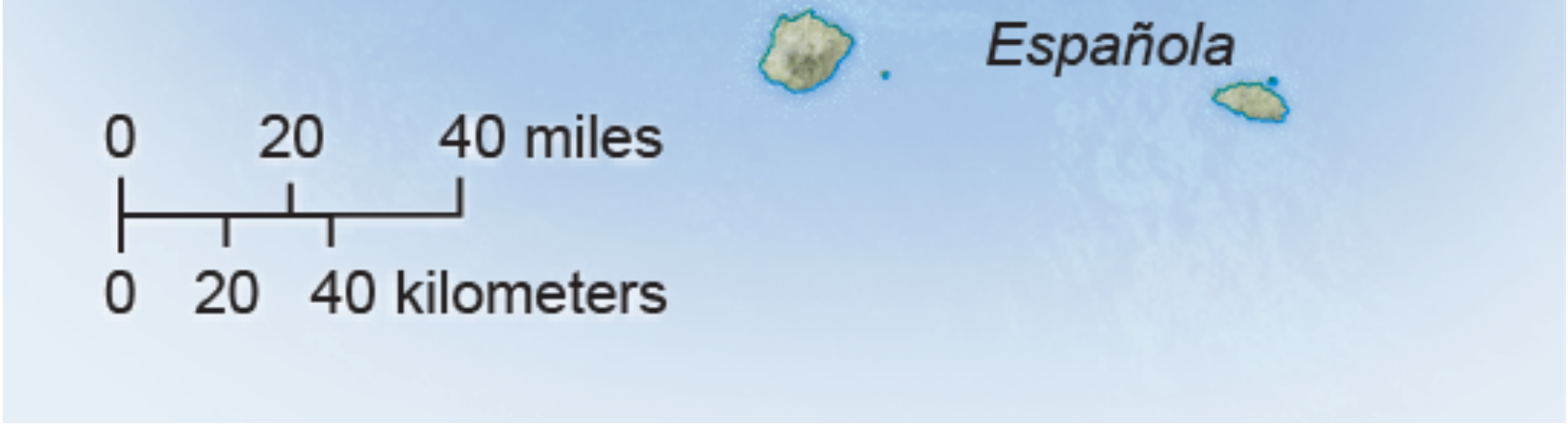
Invasive mammals have wrought havoc on the ecosystem, in direct and indirect ways. Donkeys destroy tortoise eggs when they roll on the ground to cleanse themselves. Feral cats devour seabird chicks and snack on baby lava lizards, as do mice. Feral goats, in buzz cut fashion, chew through the native vegetation, removing the food that sustained the tortoise population for centuries and clearing the way for invasive plants such as guava, which has spread throughout the highlands. The Galápagos racer, once a common snake? Gone. More than 750 alien plant species and almost 500 alien insects have taken root in the Galápagos. As much as the islands have been a global classroom on evolution, they are also a reminder that nature is not static and that conservation sometimes alters nature to preserve it.

Unnatural Selection

Island Conservation, a California-based organization, is helping Ecuadorian authorities plan the eradication of every rat and mouse on Floreana, a large, inhabited island in the Galápagos archipelago.



Credit: Mapping Specialists

It has been the same story throughout the archipelago, though with some very odd chapters. In a 2012 compendium of “alien vertebrates” on the Galápagos, R. Brand Phillips, David A. Wiedenfeld and Howard L. Snell, all then affiliated with the Charles Darwin Research Station in Puerto Ayora on Santa Cruz, catalogued a rogue’s gallery of 44 uninvited guest species, nearly half of them establishing feral populations. They ranged from obvious interlopers (goats, pigs, cattle, black rats) to an unwelcome menagerie of exotic animals. The Nile tilapia, a freshwater fish, turned up on the island of San Cristóbal in 2006; tree frogs have been spotted on two islands. Over the years nonnative visitors have included the mourning gecko, domestic ducks, cattle egrets, parakeets, peafowls and grackles. Three monkeys, of uncertain species, turned up on Floreana in the 1930s, and in 1937 one local entrepreneur tried to establish an ocelot colony on the island of Santiago. Ocelots!

Humans don’t get a waiver from these waves of invasion, and their impact is increasing, too. In 1984 only 6,000 people total lived on five of the 129 islands and islets; more than 30,000 do today. And tourists? Three decades ago there were 20,000 a year; in 2016 there were 218,000. Just as more people began to come to the Galápagos to marvel at the local biodiversity, that biodiversity became increasingly threatened by the invasive species.

The Galápagos National Park Service, which controls 97 percent of the land in the archipelago, first attempted to eradicate goats on Pinta Island in 1971—an undermanned campaign that proved the adage in the eradication business that “a 99 percent success is a 100 percent failure.” Only 10 goats remained on the island after the eradication program, recalls Victor Carrion, a former national park service official who participated in many eradication efforts. Within 10 years the number had climbed back up to 2,000. “The problem,” Carrion says with a shrug, “was the final stage.”

The Galápagos National Park Service began to develop more effective eradication plans in the late 1990s. Around this time, Campbell, then 22 years old and trying to decide what to do with his life, turned up in the archipelago. He had no particular affinity for the Galápagos—except, perhaps, that as a teenager back in Brisbane, he kept hundreds of pet birds in aviaries he built himself. In August 1997 he served as a volunteer on a goat-eradication project on the island of Isabela. Within a decade he would play a leading role in some of the most ambitious—and controversial—island eradication projects in the world.

II. THE DEVIL WE KNOW

Eradication is an ugly, euphemistic business. In 2004 the national park service and the Charles Darwin Foundation initiated a more systematic campaign to eradicate goats from

the northern, uninhabited part of Isabela, the largest island in the archipelago. Two helicopters were used for aerial hunting; two or three hunters in each helicopter shot goats from the air, using semiautomatic 12-gauge shotguns and semiautomatic .223-caliber AR15 rifles. After the first aerial sweep, ground hunters with specialized dogs went into heavily vegetated parts of the island to flush out goats that had survived the initial onslaught. In the final phase, beginning in March 2005, the eradication team deployed some 700 “Mata Hari goats” and “Judas goats.”

Campbell’s Ph.D. project was the development of the Mata Hari goat—a variation on the Judas goat, which was developed in the 1980s. Judas goats are outfitted with radiotelemetric collars. The animals are very gregarious, so hunters use goats wearing a wire, if you will, to find other goats. Mata Hari goats take the gambit one step further—they are female goats outfitted with hormonal implants that induce a permanent state of estrus, so that they seek and attract male goats. Mata Hari goats, needless to say, were not cooked up in the evolutionary hot pot of the Galápagos. Indeed, Campbell trained local hunters to perform field surgery on female goats—tying their fallopian tubes, terminating any pregnancies and inserting hormonal packs so that they were in constant heat, after which they were outfitted with radiotelemetry transmitters on collars so they could be traced. Once released, the Judas and Mata Hari goats tracked down the last holdouts. When all was said and done, Project Isabela killed 62,818 goats, at a cost of about $4.1 million. To hear Carrion tell it, the main complaint of the locals was that they didn’t get any of the meat. “They said, ‘We’re hungry, and we need the food!’” he recalls. Even 100 percent success, in this case, wasn’t enough—on at least nine occasions, according to Carrion, disgruntled locals deliberately reintroduced eradicated species, in part to protest local fishing regulations.

Black rats (*1*), which came to the Galápagos on ships as early as the 17th century, devour eggs laid by native reptiles and birds. To fight back, biologists have resorted to baiting the nesting areas of the Galápagos storm petrel (*2*) and other species with rat poison. Credit: Tui de Roy (*1*); Pete Oxford *Getty Images* (*2*)

But the magnitude of the eradication campaigns in the Galápagos is staggering: 79,579 goats “removed” from Santiago, 41,683 from Pinta, 7,726 in San Cristóbal—in all, 201,285 goats have been “removed” from 13 islands (and you know it’s a grisly business when euphemisms such as “removed” are used instead of “killed”). It’s a pretty good bet that the tourists who flock to the Galápagos to swim with the sea turtles and follow the graceful arc of its storied birds are unaware that the islands have been turned into killing fields over the past two decades to preserve their famous biodiversity.

Even a modest rodent-eradication campaign illustrates just how tricky the traditional approaches can be. In 2012 the Galápagos National Park Service and collaborators began applying the rodent poison brodifacoum on the small, uninhabited island of Pinzón to eliminate rats, which had ravaged the eggs and hatchlings of giant tortoises for decades. The eradication was successful, and substantial numbers of tortoise hatchlings were reported on the island for the first time in a century. But the poison made its way into lava lizards, which in turn were eaten by endangered Galápagos hawks, resulting in at least 22 deaths because of brodifacoum poisoning (even though many of the hawks had been protected by “captive holding” for two weeks). In one instance, researchers found extremely high levels of rat poison in an owl carcass more than two years after the baiting.

And that brings us to the most ambitious island eradication in the Galápagos and perhaps anywhere in the world, an endeavor that everyone on Floreana refers to simply as the "*Proyecto*"—the Project.

III. THE DEVIL IS IN THE DETAILS

There is one store in Floreana and one main road. As elsewhere in the Galápagos, the houses are simple cinder block constructions with corrugated metal roofs. If you go to one of the few restaurants in the island's single town, you better tell them ahead of time that you are coming: otherwise, they won't have enough food for you. The residents of Floreana are quiet-spoken, generous, subtly good-humored and deeply principled. Several years ago, when an entrepreneur from another island stiffed local workers out of their pay, no one on the island would serve him food, no one would rent him a room to sleep in and no

one would speak to him. The entrepreneur's project collapsed. The island's quirky politics and fierce independence make such an endeavor socially daunting. As Campbell says, "It gets complicated real fast."

A recurring mantra in the recent National Academies report on gene drive—and, indeed, in almost every official white paper about genetic engineering in the past four decades—is the need for "public engagement." But that bloodless phrase does not begin to capture the passion and complexity of real projects in real circumstances. If eradications in general are hard, eradications on inhabited islands are *really* hard. That became clear to Campbell several years ago, during a small meeting with members of the Floreana community to discuss the *Proyecto*. One resident, adamantly opposed to the idea of having to remove livestock from the island, looked straight at Campbell and said, in unprintable language, "If you do this, I'm going to kill you." Campbell recalls the moment as "very conflictive."

The intensity of emotion does not seem entirely inappropriate, given the magnitude of the disruption. Since 2012 authorities in the Galápagos, with Island Conservation, have been formulating what they consider to be the most complex eradication plan of an inhabited island to date. It's not just the contentious adults on Floreana who make it complicated. It's children, pets and livestock, in addition to endangered birds and lava lizards.

Floreana giant tortoises were once thought extinct, but recent genetic research identified related species living on nearby Isabela. Biologists are breeding the tortoises and reintroducing them to Floreana. Credit: Tui de Roy

Consider the staggering environmental risks of a “traditional,” nongenetic eradication. To eliminate every rat and mouse from Floreana, the project calls for helicopters to drop some 360 million one-gram (0.035-ounce) pellets of brodifacoum—in Campbell’s words, “Basically, systematically paint the whole island”—not just once but two times in the lowlands and three in the highlands, over a period of two months. To minimize potential health and environmental risks, the plan calls for extreme precautions. Water resources must be protected. Children may have to be removed from the island for up to six weeks. Pets will either need to be removed or restricted to domiciles or cages. Large agricultural livestock, such as cattle, pigs and horses, will have to be restricted in corrals (after the farmers of Floreana made clear that sending animals off the island for six months was not an acceptable option). Chickens will have to be housed in new covered coops built specifically for the project. Giant Galápagos tortoises in the Asilo de la Paz refuge will have to be temporarily restricted. Endangered birds will be trapped and held in specially built aviaries during the aerial baiting. In places off-limits to aerial baiting, such as buildings, homes or other structures, the eradication team will deploy traps and bait stations (the

location of each bait station, in each home, has to be specified, and Carolina Torres, the lawyer for Island Conservation, is now drawing up a written agreement for each and every household). “A single pregnant female, or a single area missed, is a failure,” Campbell says. “You need to get into every building, in every house, in every crawl space, in every closet, under every fridge to get every mouse.”

The people from Island Conservation have taken the idea of “public engagement” to a new level. On a recent trip, Torres brought chocolates for Ericka Wittmer, a matriarch of one of the island’s oldest families, and paid house calls to several island farmers to explain a legal issue involving contracts with the tenants who worked on parcels of their land. The organization recently provided paint for local homeowners to beautify their cinder block houses. When one resident expressed interest in starting a restaurant, Campbell and Torres encouraged her and promised to be customers. The organization has enlisted architects to design new chicken coops for the island’s farmers; each unit will cost about $22,000. Campbell has learned the hard way that one-on-one relationship building is the best way to involve people in the decision-making process on such a delicate project. “If you do a town hall type of thing, they’ll absolutely butcher you,” he says. “Two or three people dominate the conversation, you don’t know what other people think, and then afterwards, you have to spend a lot time dealing with the misinformation.”

Despite initial reservations, Campbell says, most residents on Floreana support the eradication plan. In the highlands, Holger Vera, the farmer, stands amid a grove of orange trees, pineapple plants and other crops, lamenting the rapaciousness of the local rodents. They eat fledgling corn plants, he says; they devour pineapples; they eat the tubers of yucca. “Now they are even eating the sugarcane,” he complains. “They are eating everything. But if we get rid of them, we can grow everything.” Vera was initially skeptical about the *Proyecto*, Torres says, but he now sounds enthusiastic. Even if he has to board his seven dogs? “Yes, yes,” he replies. Similarly, Cruz—who owns 80 cows, 130 pigs, more than 200 chickens, 10 horses and two dogs—agrees with the plan and the way it has been discussed with residents of Floreana. “We feel we are on the same page in terms of what’s going on,” he says.

“Essentially we have verbal agreements” from nearly all the residents, Campbell says. The plan still awaits final approval from Galápagos authorities. He believes the project could have been launched this year if funding had been secured in a timely fashion. (Costs are expected to be $20 million overall, but funding hiccups have now delayed it until at least

2020; Campbell estimates that each year of delay costs $1 million.) Despite funding uncertainty, the reality of the *Proyecto* recently sunk in when seven orange, 20-foot shipping containers arrived in Floreana in mid-July. They are intended to store uncontaminated livestock feed, or silage, for use during the rodent eradication; some farmers have already begun to store animal feed in the containers.

Pulling off a project this complicated is like managing a bureaucratic ecosystem—balancing the regulatory piece, the public engagement piece, the logistical piece, the funding piece, the poison mitigation piece. That's why Campbell thinks the Floreana project is "maxing out" the capability of traditional eradication tools. And that is why, not infrequently, he will say, "If we engaged the gene-drive technology, the conversations would be simpler, and the answers would be much more pragmatic."

IV. THE DEVIL WE DON'T KNOW

Campbell first became intrigued by the possibilities of gene drive in 2011, when he sat in on a conference call between biologists at North Carolina State University and officials of the U.S. Fish and Wildlife Service to discuss a possible genetic approach to control a runaway mouse problem on Southeast Farallon Island, about 20 miles west of the California coast, near San Francisco. John Godwin, a North Carolina State neurobiologist who studies animal behavior, had learned of the Farallon issue while skimming the Internet in 2011. He happened to be at a university with an established infrastructure dedicated to experimenting with—and considering the ethical implications of—genetic manipulation. Two of his colleagues, Fred Gould and David Threadgill, were already discussing the possibility of tinkering with the mouse genome in an attempt to create mice incapable of producing female offspring. Two other colleagues, Jennifer Kuzma and Jason Delborne, became deeply involved in how to engage the larger world of stakeholders—government regulatory agencies, animal management officials, bioethicists and, of course, the general public—in considering the prospect of releasing genetically altered animals into the wild. Kuzma and Gould serve as co-directors of the Genetic Engineering and Society Center at North Carolina State.

To make a long story short, Island Conservation joined forces in 2016 with other international groups to launch the GBIRd—Genetic Biocontrol of Invasive Rodents—program. GBIRd scientists are "cautiously investigating" genetic tools to preserve island

ecosystems. The advent of the gene-editing tool CRISPR boosted efforts to develop an alternative approach to eradication. Those efforts gained traction in July, when the Defense Advanced Research Projects Agency gave the North Carolina State group $3.2 million to pursue gene drives for mouse eradication on islands.

The basic idea of gene drive seems counterintuitive to anyone raised on the notion of Gregor Mendel's pea plants and the random inheritance of genes from parents. You usually have a 50–50 chance of inheriting a gene from one parent or the other. In rare instances, however, certain genes are favored, or "selfish"—they are inherited at much higher rates than random sorting would suggest. One such gene (technically, a region of the genome) exists in mice on chromosome 17; it is called the T-complex, and it is inherited at a rate of 95 percent. It might theoretically serve as a smuggler's bible, allowing a second gene to be quickly introduced in a population.

In an eradication scenario, researchers could theoretically attach a second piggybacking gene to the T-complex and essentially drive that second trait into the majority of offspring. One such mouse gene, known as *SRY*, determines male gender, so stitching it to a selfish gene would create more and more males (and fewer and fewer females) in each generation, until a mouse population would be daughterless. One of the basic requirements of gene drive is that the time between generations in the target animal is short; mice certainly qualify because their time between birth and reproductive maturity is 10 weeks. If the mice in the lab can be manipulated to pass along a desired gene, such as one to produce a single gender, and if those mice are reproductively successful in the wild, that gene could be rapidly driven into a population.

That's a lot of "ifs," but Threadgill, now at Texas A&M University, has been pursuing precisely that strategy in mice. This so-called daughterless breed could eliminate a native mouse population without environmental poison, without offshore animal relocations, without all the logistical nightmares entailed by the Floreana project. Paul Thomas, a biologist at the University of Adelaide in Australia, has been exploring the use of CRISPR to inactivate genes related to female fertility in mice, an approach that could be adopted to produce a population of entirely infertile females. In addition, Godwin, the neurobiologist, is testing whether an engineered mouse will pass sexual muster with wild mice (he is currently working with a batch transplanted from Southeast Farallon).

Floreana lava lizards are easy prey for the feral cats that stalk the island. Credit: Tui de Roy

Species eradication is by no means the only application of gene drive. Target Malaria is an attempt to engineer mosquitoes so that they are incapable of transmitting malaria; the group, with funding from the Bill & Melinda Gates Foundation, has already begun community outreach efforts in Africa in anticipation of a field test. Kevin Esvelt, a biologist at the Massachusetts Institute of Technology, is pursuing a project to engineer white-footed mice on Nantucket to make them immune to the bacteria that cause Lyme disease. In the gene drive game, the rule of thumb is that islands are the best place for a field test; smaller islands are better than larger ones, and uninhabited islands are better than inhabited ones. Campbell suspects the first field test of gene drive will involve mosquitoes and adds that the U.S., Australia or New Zealand would probably be the most appropriate venue because their regulatory infrastructures are sophisticated enough to assess new hot-button genetic technologies.

Eradications are controversial, genetic modification even more so. “There is no safe way to experiment with these technologies in the wild,” says Dana Perls, senior food and technology campaigner at Friends of the Earth. Jane Goodall, Fritjof Capra and other conservationists called for a moratorium on the research in an open letter published last September. Firing a shot across the bow of Island Conservation, the signatories said they were “alarmed that some conservation organizations have accepted funding for and are promoting the release of engineered gene-drive organisms into the wild.”

The great fear is “unintended consequences”—that something unexpected and bad will happen. There is no question that gene drive, as the National Academies put it, “may have harmful effects for other species or ecosystems,” and that alone warrants cautious and prudent development. But in previous public debates over genetic technologies, such as the battle over recombinant DNA in the 1970s, it was often difficult to separate legitimate concerns from exaggerated fears.

Back in the real world, during an excursion into the highlands of Floreana, Campbell and Torres led me to a freshwater spring—not far from the cave where the island’s first settler, the drunkard Watkins, allegedly slept off his hangovers. As part of the project, the entire area surrounding the spring, which is already fenced off, will be covered with a tent, and special filters will be placed on the pipes to make sure no rodent bait gets into the system—even though brodifacoum is not water-soluble. Part of public engagement, Campbell said, is dealing with perceptions as well as legitimate fears. “You’re working with people’s perception of toxicants,” he explained. “It’s challenging to change people’s perceptions of this, because they don’t.” One more reason, Campbell continued, that the genetic approach was more appealing. Then suddenly he changed the subject.

“Here we are,” he said quickly, pointing to a rustle of vegetation inside the chain-link fence. “You see it? A rat!”

A pair of shiny, dark eyes briefly appeared amid the leaves. Campbell identified it as *Rattus rattus*—the black rat, which is known to eat the eggs and hatchlings of Galápagos petrels and giant tortoises. Like rats everywhere, it disappeared quickly—a sentinel of an inevitably larger population and a larger covert threat to what Campbell calls “species on the brink.”

V. “THE STRANGER’S CRAFT OR POWER”

Every stroll in the Galápagos is a nature walk, and each living creature tells a conservation story—some with happy endings, some not. During our last day on Floreana, a number of these stories began when Campbell’s keen eye alighted on the animals that make this landscape so beloved—and beleaguered.

During breakfast, a cactus finch stalked our table. Its strong black and yellow beak had

evolved to be larger and stronger, Campbell explained, to crack the unusually large and hard seeds of the local *Opuntia* cactus on Floreana; the cactus, in turn, is evolving even larger and tougher seeds to thwart this poaching—a reminder that evolution is not a textbook concept but an ongoing process. Moments later Campbell spotted a mouse darting behind a hunk of lava. As we finished our meal, another invasive species made an appearance—the sleek, black, smooth-billed ani (pronounced "Annie"). An example of old-school unintended consequences, farmers introduced the bird to the Galápagos in the 1960s in the belief that it could control ticks that afflicted cattle; it did not live up to its billing, so to speak, but it has exploded in numbers as an invasive species.

Later, on a walk to La Lobería Beach, Campbell pointed out fresh tracks of feral cats in the sand; they devour juvenile marine iguanas and lava lizards. ("The small ones have zero chance of getting away," he said.) Near the head of the beach, he indicated the gnawed-off limb of one of the *Opuntia* cacti. When rodents chew down the cacti, he explained, the plants fail to flower or bear fruit—eliminating a crucial source of sustenance for tortoises and mockingbirds, especially in the dry season, and depriving finches of nesting sites. And we paused to admire several magnificent sea turtles temporarily trapped in a lagoon during low tide. Their eggs and hatchlings, too, provide tasty meals for rats and cats.

It was Darwin's 20th-century bulldog, Richard Dawkins, who revived poet Alfred, Lord Tennyson's phrase "Nature, red in tooth and claw" to describe the noir side of natural selection—nature's game is not always pretty, and the postcard-perfect ecology of a place like the Galápagos often conceals a darker, more unsentimental interaction of predator and prey—an interaction whose delicate balance humans have repeatedly perturbed, whether by introducing invasive species or by attempting to atone for those ill-conceived introductions with literally toxic remedies. And now, on the horizon, we may have to decide whether to use futuristic techniques of genetic modification to restore the islands to an earlier, more pristine state.

For what it is worth, a small sampling of opinion on Floreana did not betray much local concern about the potential applications of gene drive, although it is not clear how well understood these technologies (and their potential risks) are. Vera shrugged off any worries and said he would have no problem with a genetic solution to the rodent problem. Ingrid Wittmer, another descendant of one of the earliest families on Floreana, shook her head no when asked, instead expressing concern about the fate of the short-eared owl once its main food source, mice, was eliminated during the *Proyecto*. Cruz, whose father

emigrated to the island in 1939, when the population numbered 11, offered a farmer's perspective to the idea of daughterless mice: "It's like artificial insemination in cattle," he said. "If you want females, you use the semen for females. It's the same thing."

"For me, these are issues we've created, and to sit back and do nothing, there's going to be grave consequences," Campbell said. "We know where things are heading. To actually *not* do something is … is just irresponsible. If you have the tool, and you don't use it, *you're* culpable."

We don't have the tool yet. But if the craft of molecular biology eventually captures the power of gene drive, and it is used to manage invasive species in the Galápagos or any island, it is worth remembering that almost every ecological catastrophe visited on the planet's living laboratory of evolution has come at the hands of humans. The goats, the donkeys, the rats, the cats, the pigs, the mules, the mice and, yes, even those short-lived ocelots arrived with human help, on human boats, through human agency.

In a wry observation that resonates nearly two centuries later, Darwin remarked in his journal that while birds in England had developed a well-earned distrust of humans, the birds in the Galápagos "have not learned [such] a salutary dread." He went on to offer what might serve as cautionary words about 21st-century science and gene drives in particular. "We may infer from these facts," Darwin wrote, referring to the lack of fear in birds, "what havoc the introduction of any new beast of prey must cause in a country, before the instincts of the indigenous inhabitants have become adapted to the stranger's craft or power."

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MORE TO EXPLORE

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