NUCLEAR FALLOUT

The Swallows of Fukushima

We know surprisingly little about what low-dose radiation does to organisms and ecosystems. Four years after the disaster in Fukushima, scientists are beginning to get some answers

By Steven Featherstone

Photographs by Steven Featherstone

BARN SWALLOWS in the zone around Japan's Fukushima Daiichi nuclear power plant are good subjects for studying the effects of radioactive contamination on living things.

DESERTED business district in the town of Okuma (*opposite page*).

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UNTIL A REACTOR AT THE CHERNOBYL NUCLEAR POWER PLANT EXPLODED ON APRIL 26, 1986, spreading the equivalent of 400 Hiroshima bombs of fallout across the entire Northern Hemisphere, scientists knew next to nothing about the effects of radiation on vegetation and wild animals. The catastrophe created a living laboratory, particularly in the 1,100 square miles around the site, known as the exclusion zone.

In 1994 Ronald Chesser and Robert Baker, both professors of biology at Texas Tech University, were among the first American scientists allowed full access to the zone. "It was a screaming place—really radioactive," Baker recalls. "We caught a bunch of voles, and they looked as healthy as weeds. We became fascinated with that." When Baker and Chesser sequenced the voles' DNA, they did not find abnormal mutation rates. They also noticed wolves, lynx and other once rare species roaming around the zone as if it were an atomic wildlife refuge. The Chernobyl Forum, founded in 2003 by a group of United Nations agencies, issued a report on the disaster's 20th anniversary that confirmed this view, stating that "environmental conditions have had a positive impact on the biota" in the zone, transforming it into "a unique sanctuary for biodiversity."

Five years after Baker and Chesser combed the zone for voles, Timothy A. Mousseau visited Chernobyl to count birds and found contradicting evidence. Mousseau, a professor of biology at the University of South Carolina, and his collaborator Anders Pape Møller, now research director at the Laboratory of Ecology, Systematics and Evolution at Paris-Sud University, looked in particular at *Hirundo rustica,* the common barn swallow. They found far fewer barn swallows in the zone, and those that remained suffered from reduced life spans, diminished fertility (in males), smaller brains, tumors, partial albinism—a genetic mutation—and a higher incidence of cataracts. In more than 60 papers published over the past 13 years, Mousseau and Møller have shown that exposure to low-level radiation has had a negative impact on the zone's entire biosphere, from microbes to mammals, from bugs to birds.

Mousseau and Møller have their critics, including Baker, who argued in a 2006 *American Scientist* article co-authored with Chesser that the zone "has effectively become a preserve" and that Mousseau and Møller's "incredible conclusions were supported only by circumstantial evidence." But their research and the outcome of the debate about the effects of low-grade radiation have the potential to inform everything from how we respond to nuclear disasters to nuclear energy policy in general.

Almost everything we know about the health effects of ionizing radiation comes from an ongoing study of atomic bomb survivors known as the Life Span Study, or LSS. Safety standards for radiation exposures are based on the LSS. Yet the LSS leaves big questions about the effects of low-dose radiation exposure—exactly the conditions that exist in Chernobyl—unanswered. Most scientists agree that there is no such thing as a "safe" dose of radiation, no matter how small. And the small doses are the ones we understand the least. The LSS does not tell us much about doses below 100 millisieverts (mSv), and it tells us nothing about radioactive ecosystems. For instance, how much radiation does it take to cause genetic mutations, and are these mutations heritable? What are the mechanisms and genetic biomarkers for radiation-induced diseases such as cancer?

The triple meltdown at the Fukushima Daiichi nuclear power plant in March 2011 created another living lab where Mousseau and Møller could study low doses of radiation, replicating their Chernobyl research and allowing them "much higher confidence that the impacts we're seeing are related to radiation and not some other factor," Mousseau says. Fukushima's 310-square-mile exclusion zone is smaller than Chernobyl's but identical in other ways. Both zones contain abandoned farmland, forests and urban areas where radiation levels vary by orders of magnitude over short distances. And they would almost certainly gain access to Fukushima more quickly than scientists could get into Soviet-run Chernobyl. In short, Fukushima presented an opportunity to settle a debate.

Within months of Fukushima, Mousseau and Møller were counting birds in the contaminated mountain forests west of the smoldering nuclear plant, but they could not get into the zone itself to see what was happening to the barn swallows. Finally, in June 2013, Mousseau was among the first scientists allowed full access to Fukushima's exclusion zone.

Sensitivity to radiation varies greatly in living things and among individuals of the same species, which is one reason it is important not to extrapolate from butterflies to barn swallows or from voles to humans. Butterflies are particularly radiosensitive, Mousseau says. In August 2012 the online journal Scientific Reports published a paper examining the effects of Fukushima's fallout on the pale grass blue butterfly. (*Scientific American* and Scientific Reports are Nature Publishing Group affiliates.) Joji Otaki, a biology professor at the University of the Ryukyus in Okinawa, revealed that butterflies collected near Fukushima two months after the disaster had malformed wings, legs and eyes. Mousseau and Møller's surveys of insects in Chernobyl and Fukushima show drop-offs in butterflies as a group. But Otaki's paper adds an important new wrinkle. When he bred mutant Fukushima butterflies with healthy lab specimens, the rate of genetic abnormalities increased with each new generation. Otaki is the first scientist to rigorously demonstrate the accumulation of genetic mutations over multiple generations of a creature living in Fukushima.

Mousseau believes that this phenomenon, the accumulation of genetic mutations, is a hidden undercurrent eroding the health of radioactive ecosystems, occasionally revealing itself in the offspring of mutant butterflies or barn swallows with partial albinism. Even Baker agrees with Mousseau on Otaki's conclusions: "Clearly, there's something going on with the butterflies that's radiation-induced. Multigenerational exposure does result in an altered genome."

Before he booked his flight to Tokyo, Mousseau tried to locate a Japanese supplier of lead bricks that he needed for a new set of experiments. He could not find enough in Japan, however, so he flew to Tokyo with 600 pounds of lead bricks crammed into eight suitcases. I met him and his postdoctoral fellow, an Italian named Andrea Bonisoli Alquati, at the airport and helped them load the bricks into the back of a rental car. Then we drove to our hotel in Minamisoma, north of the Fukushima power plant.

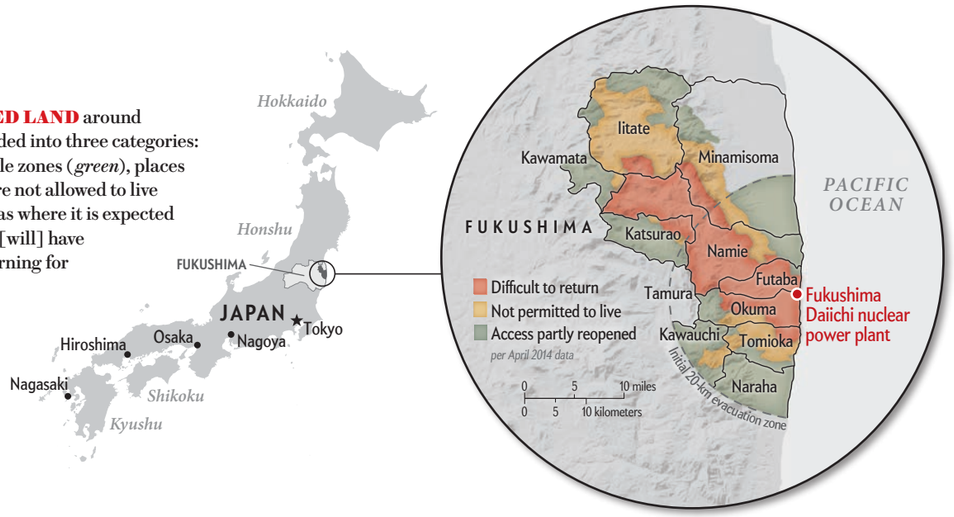
The car rattled over earthquake-heaved roads as we passed through one deserted town after the next, meandering north toward the nuclear plant. Mousseau scanned shuttered storefronts and empty houses for barn swallow nests as he drove. Barn swallows are ideal scientific subjects because they are philopatric, meaning the birds tend to return to breed in the same locations over a lifetime. Much is already known about them under normal conditions, and they share similar genetic, developmental and physiological characteristics with other warm-blooded vertebrates. The barn swallow is the proverbial canary in the coal mine, except the coal mine in question is radioactive. Mousseau counted about a dozen old nest "scars," crescent-shaped blots of mud plastered under eaves, but not one new nest.

"They were showing such negative effects the first year," he said. "I figured it'd be very difficult to find them this year."

A few miles west of the nuclear plant, we hit the border of the exclusion zone: a barricade manned by two surprised police officers, who waved their arms and shouted "U-turn!" at us through their face masks. Mousseau's permits were not yet valid, so he turned around.

"I just can't believe there aren't any active barn swallow nests," he said on the way back to the detour point. He glanced up at a lone wagtail perched on a telephone wire. "I don't see any butterflies flying. Don't see any dragonflies flying. It's really a dead zone."

Fukushima offers a vanishingly rare glimpse of an ecosystem's early response to radioactive contamination. Little is known about generations of Chernobyl's voles and barn swallows, not to mention other critters. Anecdotal reports point to massive die-offs of plants and animals, but no details exist about their recovery. Did some species evolve a heightened ability to repair DNA damaged by radiation? Studying Fukushima's ecosystem, right now, is critical to developing predictive models that could explain how adaptations to low-level radiation exposure, as well as the accumulation of genetic damage, progress over time.



CONTAMINATED LAND around Fukushima is divided into three categories: relatively accessible zones (*green*), places where residents are not allowed to live (*yellow*), and "areas where it is expected that the residents [will] have difficulties in returning for a long time."

SOURCE: SAFECAST http://blog.safecast.org

Map by XNR Productions

IN BRIEF

In the nearly three decades since the Chernobyl nuclear disaster, a consensus has emerged that the flora and fauna of the contaminated region have fared surprisingly well despite long-term exposure to background radiation.

Yet this consensus is based on very limited data. Our understanding of the effects of low-dose radiation on living things remains incomplete.

The meltdown at Japan's Fukushima Daiichi reactor four years ago provided another chance to study these effects. The first results suggest that fallout from Fukushima has harmed the biota in ways we are just beginning to see.

POLICE OFFICER inspects permits and passports for entry into the Fukushima restricted zone (*1*). Bicycles lie abandoned on a damaged street in Futaba (*2*). Women in Futaba wait while family members inspect what remains of their seafood shop (*3*). A tsunami-damaged diner in the restricted zone (*4*).

Mousseau regretted that he could not get access to the zone immediately after the accident. "We'd have much more rigorous data on how many swallows were there, how many disappeared," he said after we arrived at the hotel. "Are the ones that are coming back the resistant genotypes, or are they just lucky in some way?"

The next day, with Mousseau's permits validated, a line of officers waved our car through the barricades and into the exclusion zone. Then Mousseau drove straight to the gates of the Fukushima Daiichi power plant. He planned to work his way along the coastal plain, from ground zero to the abandoned towns of Futaba, Okuma and Namie, counting every barn swallow, plotting the location of every nest and capturing as many of the birds as possible. "Every data point we get here is absolutely invaluable," he said to Bonisoli Alquati.

A mile from the nuclear plant Bonisoli Alquati spotted a barn swallow perched on a wire near a house. A nest made with fresh mud sat on a ledge inside the garage. Radiation levels peaked at 330 microsieverts per hour, more than 3,000 times above normal background radiation and the highest level Mousseau has ever recorded in the field.

"In 10 hours, you'll get your annual dose," said Bonisoli Alquati, referring to the amount of background radiation the average person in the U.S. receives in an entire year. He and Wataru Kitamura, a faculty member in the environmental studies department at Tokyo City University, strung up mist nets, which resembled oversized volleyball nets made of nylon mesh, over the garage's entrance. Then they waited—and waited—for the swallow to fly into them. Mousseau did not want to waste time trying to catch one bird, even if it was living next to a hotspot. So they packed up the mist nets and drove into Futaba.

Futaba is a ghost town, off-limits to all except former residents, who are allowed to return for only a few hours every month to check on homes and businesses. A sign over the town's commercial center reads, "Nuclear Power: Bright Future of Energy." Radiation levels on the main street were no worse than many contaminated areas outside the zone. But contamination is only one of Futaba's problems. The magnitude 9.0 earthquake left few structures unscathed. Many buildings tilted on their foundations. Some had completely collapsed. We rolled down the street, crunching over ceramic roof tiles and broken glass. Rats and ravens poked around piles of trash and food rotting on store shelves. Peering through binoculars, Kitamura counted six swallows circling near a smashed sporting goods shop.

"Set up the nets and poles!" he shouted.

Kitamura and Bonisoli Alquati crouched outside the store, a mist net bunched loosely between them. Swallows swooped and chattered overhead. Suddenly, a pair darted into the shop. The men leaped to their feet, stretching the net over the entrance and trapping the birds inside. Bird by bird, it took two hours to catch and sample all six swallows. Before releasing the birds, Mousseau fitted them with tiny thermoluminescent dosimeters (TLDs) to track their radiation dose. Down by the Futaba train station, where radiation levels were 10 times higher, they captured two more swallows.

Later that night the team ate dinner together in Minamisoma. Everybody was exhausted. I asked Kitamura what it was like to see the zone firsthand. "I feel a kind of sadness," he said, "because nothing has happened after the accident." Troubled by what he saw in Futaba, he had no interest in going back.

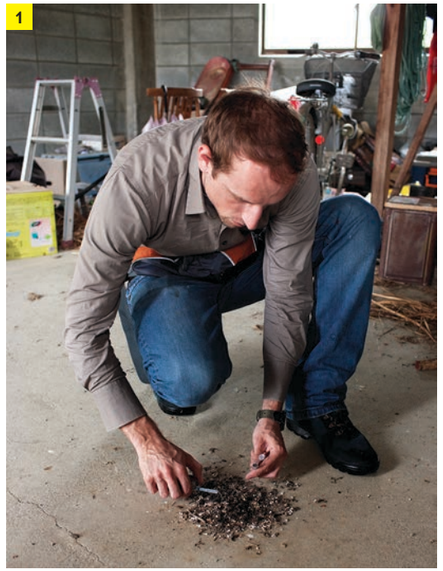
The Japanese government initially vowed to clean up 11 of the most severely contaminated municipalities in Fukushima Prefecture by March 2014. Their goal was to reduce annual dose rates to 1 mSv, the limit for the general public, according to the recommendations of the International Commission on Radiological Protection. But the bulk of the cleanup effort has so far been focused on stabilizing the damaged reactors at the nuclear plant, which continue to leak radiation into the Pacific. Japanese authorities no longer have a specific time frame for decontamination. Instead they have set 1 mSv per year as a long-term goal and are now encouraging some of the 83,000 evacuees to return to places with annual dose rates of up to 20 mSv, equivalent to the commission's dose limit for nuclear workers. The ruling party in Japan recently issued a report acknowledging that many contaminated areas will not be habitable for at least a generation.

This goalpost moving underscores the gap between our knowledge of the effects of low-dose radiation and public policy governing—among other things—nuclear cleanup protocols. Although scientists have not determined a "safe" dose of radiation, Japanese administrators need a target number to craft decontamination and resettlement policies, so they rely on advisory bodies such as the International Commission on Radiological Protection and imperfect studies such as the LSS.

"You have to ultimately set some arbitrary limits," says David Brenner, director of the Center for Radiological Research at Columbia University. "Arbitrary because we don't know what the risks are. More arbitrary because it's probably not a yes/no, safe/not safe thing anyway." Brenner's research shows evidence for increased rates of cancer associated with annual doses as low as 5 mSv. Below this arbitrary threshold, there is no firm evidence for or against direct health risks in humans, although Mousseau and Møller have observed negative effects in plant and animal populations. Of the Fukushima residents exposed to radiation in the four months after the disaster, 97 percent received a dose of less than 5 mSv. "Once you get down to these sorts of doses, you have to rely on best understandings of mechanisms," Brenner says, "and that's pretty limited."

In a residential neighborhood on the outskirts of Namie, Bonisoli Alquati spotted a barn swallow nest wedged in a narrow alley between two houses. It was the first active nest he had seen after a disappointing day of cruising the deserted districts around Futaba and Namie, counting dozens of empty nests and scars. Counting nests before the rain washes them all away is crucial to establishing a baseline for what swallow populations were before the accident, but Mousseau also needed samples from live birds for his lab work. The nest in the alley contained three chicks, the first he found in the zone, and three undeveloped eggs. "This is an important nest," Mousseau said. A recorded voice crackled over the public address system, echoing eerily across the misty hills and fallow rice paddies: the zone would close in one hour.

Bonisoli Alquati sat in the front seat of the car. He scooped a chick out of a plastic container and measured it with various



BIOLOGIST Andrea Bonisoli Alquati scrapes samples of swallow droppings from a garage floor near Futaba (*1*). Bonisoli Alquati takes a blood sample from a swallow to be examined for evidence of genetic damage and oxidative stress (*2*). Timothy A. Mousseau holds a swallow captured in Okuma (*3*). Mousseau releases a barn swallow in Futaba (*4*).

tools. Puffing on the downy underside of the chick's wing, he exposed a patch of skin and lanced it with a needle. Some of the blood went into a capillary tube; some got smeared on a glass slide. Then he cinched the chick in a canvas sack and lowered it into the "oven," a stack of lead bricks strapped together with duct tape. The bricks formed a shielded chamber, allowing Mousseau to measure the whole-body burden of individual birds without background radiation muddying the result.

"Our objective is to be able to look at individual birds from one year to the next and to determine whether the probability of survival is related to the dose they receive," he said. "If we really want to get at mechanisms of genetic variation and radiosensitivity and how they impact individuals, then it's necessary to do this finer-scale dosimetry."

But radiation levels in this spot were too hot for accurate measurements. Mousseau moved the car down the street and reset the gamma spectrometer. After a few minutes, it displayed a distinct signal for cesium 137 contamination, the main isotope in Fukushima's fallout. The chick, perhaps a week old, was radioactive.

Police stopped Mousseau's car every day to scrutinize his permits. The only thing I understood during these tense exchanges was *tsubame,* the Japanese word for "barn swallow." The utterance of *tsubame* was usually followed by puzzled smiles. Barn swallows are omens of good fortune in Japan. Many people nail little wooden platforms over the doors of their houses to attract the birds. In the zone, the platforms, like the houses, were all empty.

Each day after the zone closed, Mousseau and Bonisoli Alquati worked well into the night, capturing barn swallows in clean areas north of Fukushima to establish a control group. Clean is a relative term. Background radiation in Minamisoma, which was evacuated during the disaster, is still twice that of normal. Still, after we spent all day in the zone, Minamisoma's tidy neighborhoods, identical to those of Namie, Futaba and Okuma, felt like a parallel universe. It was strange to find barn swallow nests overflowing with fat, peeping chicks. Curious neighbors often came out to watch Mousseau and Bonisoli Alquati net the birds. Invariably, they offered us tea and cakes and politely asked about radiation.

"Last year one of the striking things going from house to house was that people were asking us, 'Is it safe or not? Should we live here?'" Bonisoli Alquati recalled. "That's for the politicians to say. I tell them we're there for the birds."

On Mousseau's last day in Japan, he spotted an active barn swallow nest on a gritty side street in Kashima. It was plastered to a light fixture in the portico of an empty home. Mousseau received permission from a neighbor to net the birds. A member of the local river society, he said he was glad somebody was investigating the radioactive contamination because the government was not. "Always secret, the government," he said, complaining about fallout washing into the river. Koi fish caught there registered 240,000 becquerels of cesium per kilogram, he said. People do not eat these fish, which is fortunate, because the radiation limit for fish consumption in Japan is 100 becquerels per kilogram.

Other neighborhood residents asked Mousseau to survey the street with his dosimeter. He obliged, scribbling figures—all well above normal background radiation levels—on a scrap of paper, which the man from the river society accepted with a solemn nod. As we packed the nets in preparation to leave, an old woman held out a package of mandarin oranges. She said something to me that translated as "safe to eat."

"I'm sorry," I said. "I can't help you."

The old woman proffered the oranges again, and I realized that she was not asking a question; she was trying to reassure me that her gift was not contaminated by Fukushima.

"Safe," she said, smiling. "From Nagasaki."

Forty percent of us will one day be diagnosed with some form of cancer. If there is a signal hidden in the noise of this sobering statistic, one that might point to low-dose radiation-induced cancers, it is too faint for epidemiologists to hear. The big questions about low-dose radiation will eventually be answered by researchers studying "radiation-induced chromosome damage, or radiation-induced gene expression, or genomic instability," Brenner says. This is the direction Mousseau and Møller are beginning to take with their research on barn swallows.

"Unfortunately, tumors don't tell us if they were caused by radiation or something else," Mousseau says. If he had enough funding, Mousseau would sequence the DNA of every swallow that he fitted with a TLD in the field. By comparing the results with individual dose estimates, he might be able to locate genetic biomarkers for radiation-induced diseases.

Last November, Mousseau made his 12th trip to Fukushima, 18 months after I accompanied him to the zone. Mousseau and Møller have published three papers demonstrating steep declines in Fukushima's bird populations. Mousseau says that the latest census data, which they are preparing to publish in the *Journal of Ornithology,* provide "pretty striking" evidence for continued declines, "with no evidence of a threshold effect." But for some reason, radiation appears to be killing off birds in Fukushima at twice the rate it is in Chernobyl. "Perhaps there is a lack of resistance, or there is an increased radiosensitivity in Fukushima's native populations," Mousseau says. "Perhaps Chernobyl birds have evolved resistance to some degree, or the ones that are susceptible have been weeded out over the past 26 years. We don't really know the answer to that, but we're hoping to get to it." The answer might be found in the blood of the barn swallows that Mousseau and Bonisoli Alquati collected on our trip. A preliminary analysis of those samples does not reveal any evidence for a significant increase in genetic damage, although it is still too early to tell. Mousseau needs many more samples from barn swallows in the most contaminated areas, where populations are crashing.

Although Mousseau and Møller's initial findings afford a compelling glimpse of a troubled ecosystem in Fukushima, the 2014 report by the U.N. Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) echoes its earlier assessment of the Chernobyl disaster, declaring that radiation effects on "nonhuman biota" in highly contaminated areas are "unclear" and are "insignificant" in less contaminated ones.

"We're doing basic science, not toxicology, but UNSCEAR hasn't gone to the trouble of either asking us about our work or finding someone to interpret our findings," Mousseau says. "They set the standard for human health, and they're ignoring a large portion of potentially relevant information."

He says the evidence being ignored is substantial. "In my years of experience at Chernobyl and now Fukushima, we've found signals of the effects of increased mutation rates in almost every species and every network of ecological processing that we've looked at," Mousseau says. "It's all there, just waiting to be observed, described and published."

Baker has no plans to conduct research in Fukushima, but he recently sequenced DNA from a different genus of vole from Chernobyl. The new data appear to support Mousseau's and Otaki's conclusions that elevated mutation rates are linked to radiation exposure. The consequences of multigenerational exposure, whether or not it diminishes an animal's fitness or reproductive capabilities or causes birth defects or cancers in future generations, are still unclear. "We need to keep doing the genomic research," Baker says, "because that's where the real story is." SA

MORE TO EXPLORE

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