by Winifred Bird and Jane Braxton Little

RADIANT WILDLANDS

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Late in the spring of 2011, the pale grass blue butterflies seemed no different. Flitting about the meadows of Fukushima Prefecture, their satin wings shimmered as they moved among the notched leaves of wood sorrel and feathery pampas grass. When Joji Otaki began looking closely at the delicate insects the size of a silver dollar, however, he was struck by abnormal patterns in the dark dots on their wings. Then he noticed dents in their eyes and strangely shaped wings and legs.

It was two months after the March 11, 2011 tsunami led to the meltdown of three reactors at Japan's Daiichi Nuclear Power Plant. The cesium, plutonium, and other radioactive emissions had forced the evacuation of more than 100,000 residents caught in the cloud of contamination from one of the worst environmental disasters in the history. Otaki, a professor at the University of the Ryukyus in Okinawa, was in the Abukuma Mountains west of the disaster site collecting butterflies to study their response to the accident. The explosion at the power plant had rained radioactive particles onto fields and forests the butterflies share with warblers and flycatchers, deer and bear in the rugged region north of Tokyo.

As Otaki and his research partners studied the Fukushima butterflies, the aberrations they found took them by surprise. Abnormalities in the first generation were within normal boundaries. But when Otaki bred these butterflies in his laboratory, mutations in the offspring increased to 18 percent. That suggested inherited genetic damage. Field samples collected in September 2011, representing the fourth or fifth generation of butterflies since the disaster, had even higher abnormality rates. The changes may not all have been caused by radiation; Otaki had previously found evidence that temperature can affect wing markings. But the deformities his team found in antennae, legs, and other body parts are truly unusual, says Hokkaido University entomologist Shin-ichi Akimoto, who is studying the impact of Fukushima fallout on aphids. The abnormalities are troubling not only because insects are commonly assumed to be more resistant to radiation than humans, but because they suggest the Fukushima nuclear disaster may be changing individual species, even entire forests.

"There is no question that ecosystems as a whole are suffering," Otaki says. "There has been a sudden, large change."

How large and how long term are questions scientists are trying to answer as they study the effects of nuclear contamination on Fukushima's forests. This is not the first landscape to provide such a grim opportunity. The worst nuclear accident in history occurred on April 26, 1986 when the Number 4 reactor at the VI Lenin Chernobyl Nuclear Power Plant exploded. More than two decades of research in the disaster-created outdoor laboratory have failed to resolve many questions about radiation's effects on wildlife.

Now, as scientists move about these evacuated, largely forested regions thousands of miles apart, some like Otaki are finding evidence that even low levels of radiation can cause genetic damage that is passed down to new generations. It's a controversial conclusion with an even more hotly disputed interpretation: As plants and animals continue to live in these irradiated environments, forests themselves may be evolving into different ecosystems.

The prospect of a permanently altered ecosystem is even more disturbing because of the decades — perhaps centuries — these nuclear forests will remain dangerous. Still beautiful in spite of the contamination, they stare us in the face with the uncomfortable truth that when our human adventures in high technology go awry and crash through the natural world, we are utterly unable to control the consequences. Nuclear forests may be the ultimate Anthropocene environment.

Both the Chernobyl and Fukushima power plants were located in small cities surrounded by farms and woodlands. When the disasters struck, radioactive fallout hit trees, shrubs, and grasses. In Chernobyl as much as 70 percent of the radionuclides fell on forests. Over time rain and snow washed plutonium, radiocesium, and other radioactive particles onto the forest floor. Plants and fungi soon began taking up these particles and passing them on to the leaves, berries, and pollen that insects and other animals eat. Traveling the very same biological pathways that normally bring sustaining nutrients to forest life, the radionuclides permeated entire ecosystems.

In Fukushima, many plants and animals are already highly contaminated, according to government and independent tests. One wild boar captured in December 2012 had 11,000 becquerels of radiocesium per kilogram of flesh — more than 100 times the level permitted for human consumption. Last spring, researchers found herons nesting in an area where radioactive cesium in the soil measured more than 24,000 becquerels per kilogram. "We humans can do a lot to avoid exposure. Animals can't. They don't know it's dangerous," says Kiyomi Yokota, a naturalist who had devoted his life to exploring the forests of Fukushima.

THE FORESTS NEAR FUKUSHIMA AND CHERNOBYL LIKELY HAVE BEEN CHANGED FOREVER.

Even 27 years after Chernobyl's No. 4 reactor explosion, much of the 1,000-square-mile "Zone of Alienation" around the power plant is considered far too hot to allow residents to return. As much as 96 percent of the radionuclides that did not blow sky high and spew across the Soviet Union and northern Europe are still right there — in the fungi, needles, branches, roots, and soil of the forests that now cover almost three-fourths of the evacuated area. Instead of releasing the radiation into the atmosphere and water systems, the Chernobyl forests are holding it, a landscape-scale model of phytoremediation. It may be decades more before it is safe for human habitation.

Ukrainian officials have enshrined this "barrier function" of the contaminated forest in law, mandating that these lands be managed to contain the radionuclides. Japan, meanwhile, is leaning toward very different policies that would attempt to remove some of the contaminants from forests by cutting down trees, scraping up forest litter, and burying or burning the debris. The enormity of that task, however, means that Fukushima's forests will likely end up holding fallout for many years.

The upshot for plants and wildlife is prolonged exposure to nuclear contaminants, with impacts that begin in the microscopic world of individual cells. As radionuclides decay, they emit energy. That energy can damage any part of a cell. If it damages DNA, the result can be cancer. If the damaged DNA is in sperm or egg cells, the changes can be passed to offspring and cause inherited deformities or illnesses. More radiation means a higher chance that these changes will occur. Scientists agree that high levels of radiation can cause fatal damage to living organisms, including humans. The debate surrounding Chernobyl, and now Fukushima, is over the effects of extended exposure to low levels of radiation.

Some scientists have disputed the causal link between the mutations Otaki found in pale grass blue butterflies and the radiation they were exposed to, but the results do not surprise Timothy Mousseau, a research biologist at University of South Carolina. A decade of field work in Chernobyl, and more

FOREVER
IS A LONG TIME

Even when nuclear power plants perform as designed, they present a problem: What to do with the radioactive wastes? Some types of spent fuel will be dangerous for 240,000 years, others for more than 2 million years. Taking responsibility for these contaminants stretches the proverbial seven generations of sustainability to 11,000 human generations — an inconceivable time span.

So far the nuclear industry has not come up with a safe solution. Engineers have considered a range of possibilities that verge on science fiction at one extreme and reckless abandon at the other. The industry has considered sending radioactive waste into outer space — an option it considers attractive because it removes it from our environment. The risks, however, are potentially catastrophic: If the vessel carrying the waste has an accident, it could spread radioactive material into the atmosphere. Then there's the Antarctica solution — placing radioactive wastes on ice sheets where their own heat would bury them. But international treaties ban such activity and the notion of violating the planet's last pristine continent has put a damper on the scheme.

There have been discussions about burying nuclear waste in the sea floor. One option involves encasing spent fuel in concrete and dropping it in torpedoes designed to penetrate it into the ocean bed. Even more audacious is the proposal to deposit radioactive waste in a subduction zone, where plate tectonics would slowly carry it downward into Earth's mantle. Violating international oceanic agreements is just one of the reasons these approaches are not being seriously considered. Another is the fear of leaks and the resultant widespread contamination.

The current focus is on burying radioactive wastes underground. Finland is in the process of constructing the first of these deep geological repositories — a 1,710-foot-deep facility called *Onkalo*, which means "hiding place" in Finnish. Engineered to last 100,000 years, the facility is supposed to be large enough to accept boron steel canisters of spent fuel for up to 100 years, when the cavity will be backfilled and sealed. Canister burial will begin in 2020.

The United States has also been pursuing deep burial. In 2002 Congress designated Nevada's Yucca Mountain as a repository for spent fuel and other radioactive wastes. By then planners had already constructed a five-mile long tunnel and a series of cathedral-like chambers to experiment with various storage designs. The Obama administration quashed the controversial project in 2010, leaving the country without a long-term storage site. The 65,000 tons of spent nuclear fuel from the 104 nuclear power plants in the US are currently stored onsite — 80 percent in water-filled pools, which are considered less safe than the steel casks that store the remaining 20 percent.

In addition to the technical challenges, nuclear power presents a political dilemma. No nation has lasted for 1,000 years, much less the 240,000 years plutonium will remain dangerous. Who will oversee radioactive waste when the governments of the 31 countries now producing it have crumbled? And how will these toxic repositories be identified when current languages are obsolete and the metal warning signs have rusted away?

The nuclear power industry faces an uncertain future unless it can successfully address waste management, says Allison Macfarlane, chair of the US Nuclear Regulatory Commission. The post-Fukushima world demands redefining a successful nuclear power program to include not only the safe production of electricity but also the secure and sustainable lifecycle of nuclear power — from uranium mining to the disposal of spent fuel. If this cannot be achieved, Macfarlane says, "then the public in many countries will reject nuclear as an energy choice."

— JANE BRAXTON LITTLE

recently in Fukushima, have convinced him that protracted exposure to radiation can have severe genetic consequences for organisms living in these contaminated environments.

On an early October afternoon, Mousseau crouched on a crumbling sidewalk in the middle of the ghost city of Pripyat patiently extracting a marsh tit from a mist net, one tiny toe at a time. Above the scientist and his quarry, the cracked and peeling walls of apartment buildings rose to 10 stories, their deserted balconies sporting poplar saplings instead of deck chairs. The long-abandoned city was built by the Soviets to house the families of workers at the Chernobyl Nuclear Power Plant.

Marsh tits are fairly tolerant of radiation, but other birds are not, Mousseau says. Since he and his colleagues began studying 14 different species of birds found in Chernobyl, they have documented reduced numbers and decreased longevity, smaller brains in some birds, and as many as 40 percent of male birds without sperm. They have also found that barn swallows living in areas surrounding Chernobyl have genetic damage that appears to be increasing with subsequent generations. Mutation rates in young swallows are between two to 10 times higher than their parents, according to one study. Chronic exposure to radioactive contaminants 27 years after the accident continues to cause tumors and mutations in breeding swallows, Mousseau says. He has found no evidence that species are evolving in ways that protect them from radiation.

Ominous as these results are, Mousseau does not predict an eventual science fiction world of three-eyed rabbits and headless horses. Instead, he believes irradiated forests will simply become less vibrant versions of their former selves. "The net effect will be fewer offspring and smaller populations until some species just disappear," he says.

Like Otaki, Mousseau was initially surprised by his findings. He assumed that natural selection would weed out abnormal individuals as time passed. "The irony is that because the radiation levels are low and nonlethal, organisms survive long enough to reproduce and thus transmit the mutations from one generation to the next," Mousseau says.

Other scientists have documented genetic changes in the cells of Scots pines, the dominant Chernobyl forest tree. Higher levels of exposure stunted growth and led to oddly bushy trees. Vasyl Yoschenko, head of radioecological monitoring at the Ukraine Institute of Agricultural Radiology, says that could benefit more radiation-tolerant species with significant forest-wide impacts: "If the Scots pine disappears, this will be a different ecosystem," he says. Even one generation of weakened Scots pines would have cascading consequences. When pines produce less pollen, bees, butterflies, and other pollinators suffer. Reduced pollination affects fruit trees, which in turn affects birds. Few studies have tracked these chain reactions. "It's not something you see quickly, and for that reason the research is difficult," Otaki says. Mousseau is more direct about the potential impacts: "It's very likely that these Chernobyl and Fukushima areas will be permanently affected unless we come up with some magical way to remove and eliminate the radioactive material."

Many scientists reject these conclusions. Numerous laboratory and field studies around Chernobyl have failed to document elevated rates of mutations or reduced survival rates among animals in higher radiation zones. As proof, some researchers tout the abundance of mammals — moose, roe deer, otters, and wild boar proliferating in the evacuation zone despite the radiation. Removing humans from the landscape is an ecological benefit of the accident, says Robert Baker, a biology professor at Texas Tech University.

Baker's research, first published in 1996, found no tumors in any of 400 bank voles from the Chernobyl region he studied, despite radiation exposure of many generations during all stages of their life cycles. In a 2009 project with several colleagues, Baker found voles in radioactive sites genetically similar to those elsewhere in Ukraine. He says the results suggest that genetic changes in radioactive regions of Ukraine are probably a function of natural geographic variation.

Although Baker and Mousseau disagree about the effect of radiation on forest species, both have called for more research. The largest body of evidence on inherited mutations comes from multigenerational studies of Hiroshima and Nagasaki atomic bomb survivors. It is inconclusive: A higher incidence of inherited deformities and disease has been neither confirmed nor definitively disproven in the children of survivors. Field research in Chernobyl, which got a late start due to Soviet politics, remains much less systematic than the atom bomb studies. And so far only a handful of biologists have launched field studies in Fukushima. Otaki believes the reason for that is partly political. "People are trying to forget what happened," he says. As a result, funding for research like his is hard to come by. Baker hopes that will change. "Perhaps the accident in Japan will serve to highlight again the undeniable fact that our scientific grasp of radiation risk to the environment is surprisingly limited," he says.

Pale grass blue butterflies still flutter in the Fukushima countryside, unaware they may be flirting with danger. Barn swallows dart around the forests of Chernobyl oblivious of the contamination they are carrying. For the hundreds of thousands of people forced to leave their homes in Japan, Ukraine, Belarus, and Russia, the radiation cycling from soil to treetop is an unnerving omnipresence. The forests they knew and depended upon now threaten instead of soothe, hiding unknowns where they once nurtured a community.

Kiyomi Yokota, the Fukushima naturalist, rarely takes his daughters to play in the woods as he did before the accident. The stress of making sure his three-year-old never touches the dirt or licks her fingers is simply too exhausting. "Just like that, everything changed," he says. Amid the stress is a sadness fueled by the knowledge that the changes are human caused, that they are irrevocable, and that they will last long after those responsible for the nuclear accidents at Chernobyl and Fukushima have passed away. ■

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