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Proving Grounds: Ecological Fieldwork in the Pacific and the Materialization of Ecosystems

Abstract

This article investigates the emergence of ecosystems as objects of study and concern. It contends that the history of ecosystem science cannot be separated from the history of nuclear colonialism and environmental devastation in the Pacific Proving Grounds. From the close of World War II until 1970, the US Atomic Energy Commission was the main sponsor of ecological research in the United States and its territories. During this period, the United States detonated 105 nuclear weapons in the Pacific Proving Grounds. The Cold War science that destroyed nature simultaneously made it available for study. Building on recent work at the intersection of environmental history and history of science, this article emphasizes the role of nonhumans, including nuclear weapons and marine organisms, in the creation of scientific knowledge.

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ENVIRONMENT AS ECOSYSTEM

Today it is difficult to imagine the environment without imagining an ecosystem. Ecosystems appear in textbooks and car advertisements; they are metaphors for economies, historical processes, and the human body; they justify more than one hundred sections of US federal environmental law; and environmental organizations aim to implement "ecosystem-based management" to confront phenomena ranging from overfishing to the global refugee crisis. But where we might look outside and see "the interacting system made up of all the living and nonliving objects in a specified volume of space," as one recent textbook defines ecosystem, a denizen of seventeenth-century England might have seen something different—a "great chain of being," for example, the top link of which was God, followed by angels, humans, animals, plants, and minerals.[1] As late as 1972, ecologist Orie Loucks, after reviewing the recent DDT hearings in Wisconsin, wondered whether scientists would ever be able to convince juries that ecosystems existed.[2] How is it, then, that people came to see environments as ecosystems?

Historians of science have grappled with this question for decades. Early histories of ecosystem science focused on ideational change: they tracked the development of the ecosystem concept in published scientific literature, and they credited individuals, among them Arthur Tansley and Howard T. Odum, with inventing or discovering ecosystems.[3] Subsequent histories challenged this "internalist" approach by focusing instead on the political and social forces that influenced ecological knowledge. Specifically, they analyzed how funding sources shaped ecology's intellectual content, arguing that postwar ecologists abandoned their naturalist roots for cybernetic theory in order to transform ecology from a "soft science" into a "hard science" and thereby increase ecologists' influence with government officials.[4]

In a third and distinct approach, this article considers the role of material change in the emergence of ecosystems. Analyzing ecological fieldwork conducted at the Pacific Proving Grounds between 1946 and 1970, I contend that ecosystems cannot be understood apart from the history of Cold War nuclear violence. Here I build on the work of scholars who have shown that, in the words of Elizabeth DeLoughrey, "American environmentalism and militarism are paradoxically and mutually imbricated."[5] My approach also engages recent scholarship at the intersection of environmental history and history of science concerning the roles of place and of nonhumans in scientific practice.[6] Scholars working at this intersection have explored how field sciences opened up new spaces (like the deep ocean) for exploration and exploitation; how field scientists distinguished themselves from laboratory scientists; and how space and place shape scientific practice.[7] Meanwhile, work under the banners of actor-network theory, posthumanism, multispecies ethnography, and new materialism strives to expand the range of actors involved in history-making, a project that has been central to the discipline of environmental history since its inception.[8]

This is a history of ecosystem science concerned with nuclear violence in the Marshall Islands, where the United States detonated 105 nuclear weapons.[9] After World War II, the US federal government invested heavily in the sciences, establishing the Atomic Energy Commission (AEC) and the Office of Naval Research in 1946 and the National Science Foundation in 1950. These and other programs dramatically reconfigured the relationships among federal, academic, and corporate spheres.[10] They also provided scientists with new materials. Between 1946 and 1955, for example, the AEC produced and distributed approximately 64,000 shipments of radioisotopes to American scientists.[11] As Angela Creager has detailed, laboratory-produced radioisotopes played an important role in the history of ecology; ecologists used them to visualize how elements like phosphorus moved through both the living and the nonliving components of lakes and fields.[12]

Ecologists also took advantage of events in which radioisotopes were released into the environment, whether accidentally (at AEC production sites like Oak Ridge and Savannah River) or quite intentionally, at weapons test sites. It is the latter case that this article considers.[13] Between 1945 and 1963, the AEC—the main funder of ecological research in the United States from World War II until the NSF eclipsed it in the 1970s—funded ecologists to conduct fieldwork at the Pacific Proving Grounds and occasionally the Nevada Test Site.[14] It was only with the signing of the Partial Test Ban Treaty that ecologists lost access to aboveground detonations and, as I explore briefly in the conclusion, turned instead to simulations of World War III.

The episodes I examine include "bioaccumulation" studies conducted by University of Washington ecologists at the Pacific Proving Grounds (1946–48) and the use of fallout to visualize ecological symbiosis by Eugene and Tom Odum during their famous 1954 visit to Enewetak Atoll. Considered together, these episodes demonstrate how ecosystems emerged from interactions among specific constellations of places, species, technologies, people, and institutions. Counterintuitive though it may seem, ecosystems are not the preexisting casualties of environmental degradation, but came into being simultaneously with the large-scale destruction of environments. Violence made ecosystems manifest. And yet, as part of the work of naturalizing ecosystems, ecologists repeatedly deemphasized their fieldwork and its attendant contingencies.

RADIATION REVEALED

On August 18, 1943, Lauren Donaldson, a fisheries biologist at the University of Washington, received an urgent telegram from the

Office of Scientific Research and Development (OSRD) requesting his presence in Washington, D.C., to discuss a sensitive matter. It gave no further explanation. Unbeknownst to Donaldson, it was actually the Manhattan Engineering District (MED) contacting him.[15] The federal government had recently acquired land in eastern Washington State on which to produce plutonium. Designs for "Hanford Works" called for pumps to channel 30,000 gallons of water per minute through each of three reactors. This water would come from the Columbia River, and it would be returned to the river warm and radioactive. Eager to ensure that this effluent would not damage the Columbia River's valuable fisheries, the MED requested that Donaldson study the physiological impacts of radiation on fish.[16] In D.C., the supposed OSRD officials asked Donaldson to lead a grant and to rename his laboratory the "Applied Fisheries Laboratory" (AFL). The title concealed the project's true objective: to study whether reactor effluent killed salmon. Donaldson agreed to lead the grant, and that fall the AFL began exposing salmon eggs and fingerlings to X-rays in their Seattle laboratory.[17]

In 1946 the AFL received the first of what would be many opportunities to study radiation outside of the walls of the laboratory. In the weeks after the United States bombed Hiroshima and Nagasaki, the US Senate and Joint Chiefs of Staff entertained proposals to test atomic weapons against naval warships, a set of plans they codenamed "Operation Crossroads." Crossroads was a theater in which the United States flaunted its atomic arsenal, but its stated purpose was simpler: it would test whether atomic weaponry made the navy obsolete.[18] Widespread radiation poisoning in Japan had made officials wary about conducting weapons tests in the United States (although they would, beginning in 1951), and the Joint Chiefs of Staff decided that Crossroads would be conducted "overseas." From a short list of Pacific islands that included the Caroline Islands and the Galapagos Islands, they selected Bikini Atoll, a coral "C" surrounding a deep central lagoon, 2,500 miles southwest of Honolulu. To justify the forced resettlement of 167 Bikini Islanders, the navy argued that Bikini was unsuitable for permanent inhabitation because it produced little food.[19] Nevertheless, American lobbyists soon voiced their concern that weapons testing might damage valuable Pacific fisheries. Although the US Fish and Wildlife Service testified that the fisheries resources at Bikini were "negligible," the MED hastily convened a conference to discuss biological monitoring at the test site.[20] There it was decided that Lauren Donaldson would lead the "Bikini Radiobiological Survey."[21]

Donaldson and fellow AFL members reached Bikini eighteen days before the first scheduled detonation, along with approximately 42,000 other people, 250 naval vessels, and 150 aircraft, as well as 200 pigs, 204 goats, 60 guinea pigs, 5,000 rats, and 200 mice that were slated to be bombed. Donaldson led a team tasked with determining the impact of the detonations on resident marine fauna. (Other biologists in the operation would inspect the pigs, goats, guinea pigs, rats, and mice.) Their first assignment was to collect "control material" to compare with any organisms collected after Test *Able*. Over an area of almost 250 square miles, they hurriedly gathered as many specimens as they could. They killed smaller fish by poisoning tide pools with derris root and caught larger fish by hook and line. By hand they picked algae, coral, clams, and sea cucumbers from reefs at low tide. As of two days before *Able*, the AFL had collected 1,926 "control" specimens.[22]

On July 1, 1946, at approximately 9 a.m. Bikini time, the B-29 aircraft *Dave's Dream* dropped an atomic bomb on a battleship stationed in Bikini lagoon. As it turned out, *Able* was an anticlimax; the bomb burst approximately 1,500 feet west of its target. By 2:30 p.m. the next day, the lagoon was declared safe for reentry, and Donaldson and his crew were unable to find any dead or injured fish. Unlike *Able*, however, Test *Baker* was spectacular. On July 25, the Joint Task Force detonated an atomic bomb 90 feet below the surface of Bikini lagoon. Within seconds, a hollow column containing some 10 million tons of water rose to a height of more than a mile (figure 1). In his notes Donaldson wrote, "The one July 1 was awe-inspiring and in many ways beautiful, but the one today just frightened the very daylights out of one."[23]

After *Baker*, Donaldson's crew had no problem finding dead fish. They visited collection points from one of the *USS Haven*'s whaleboats, and when beach landings were necessary, they used rubber rafts. Naval support vessels used Geiger counters to estimate radioactivity in

Figure 1. Test *Baker* as seen from Bikini Atoll, July 25, 1946. Credit: University of Washington Libraries, Special Collections, DON0032.

the water, and Donaldson used these records to decide where to collect. From July 25 to August 13, AFL members collected a variety of organisms, recording the date and place of each capture. To determine whether the specimens were radioactive, they placed small fish whole into Geiger counters, first reducing larger fish to ash in laboratory ovens. By the end of the summer, the AFL had processed 1,021 specimens in the field and had sent thousands more ahead of them to Seattle for analysis.[24]

The MED did not anticipate a return trip to Bikini because most scientists expected the expansive Pacific Ocean to quickly dilute and disperse any fission products from *Able* and *Baker*. A few months later, the Joint Chiefs of Staff announced the "Bikini Scientific Resurvey" as the concluding phase of Operation Crossroads. Naval officials hoped to inspect the target vessels a year after they were sunk in *Baker*, and the newly formed AEC asked physicists, geologists, and biologists to participate.[25] Unlike Crossroads, the Resurvey would bring only seven hundred people to Bikini including some twenty biologists.

Like other Resurvey scientists, Donaldson did not expect to find residual radioactivity at Bikini. Over six weeks, Donaldson's team collected 5,883 specimens from the lagoon, dividing the 250-square-mile expanse into 55 sampling stations. Their field notes speak to the difficulty of gathering representatives of hundreds of species, each with its own behaviors, across a vast area. By eye, the specimens appeared normal: "the usual patterns of life seemed unaltered, and there were no specimens of freaks or cancers or evidence of mutations in Bikini's living system," one AFL associate reflected. Meanwhile, Resurvey physicists recorded high levels of radioactivity in a layer of mud at the lagoon bottom. The radioactivity seemed to be confined to a five-foot-deep layer, however, and on July 25 the navy information office reported, "Sun-tanned sailors and scientists observed the anniversary of the world's first underwater atomic bomb explosion today by going swimming in the clear blue-green 84 degree warm waters of Bikini lagoon."[26]

This might have been the end of the story, if not for the actions of hydroids, a life stage of the hydrozoans, a class of small aquatic predators related to jellyfish that attach themselves to rocks and other substrates. While at anchor, sailors on the Resurvey's transport vessel, the USS *Chilton*, used large wooden crates to support smaller picket boats that were floated in the water. Over the month of July, hydroids and other fouling organisms grew on the crates, and when they were pulled up, an AFL member decided on a whim to run a Geiger counter over them. To everyone's astonishment, the radioactivity of the hydroids was about a thousand times that of the lagoon water.[27] The AFL team speculated that perhaps radioisotopes were still circulating in the lagoon and that the hydroids, somehow, were concentrating them.[28]

Figure 2. University of Washington scientists wading in reef around Namu Island to net poisoned fish, 1947. Credit: University of Washington Libraries, Special Collections, DON0365.

The AFL's ability to consider this phenomenon further was itself contingent on unfolding geopolitical events. When the AFL returned to Seattle that summer, they were uncertain that they would ever visit Bikini again. Donaldson wrote to AEC officials, arguing that their fieldwork could help determine when the Bikini Islanders could return home. As it happened, Donaldson would return but with no pretense of aiding the dispossessed.[29] On July 22, 1947, the AEC announced that it would be establishing a permanent proving grounds "for routine experiments and tests of atomic weapons" at the newly established Trust Territory of the Pacific Islands, encompassing two thousand islands spread over 3 million square miles.[30] Then, in April and May 1948, the United States detonated three atomic weapons at Enewetak Atoll, 190 miles west of Bikini. That July, the AFL took twelve people to Bikini and Enewetak (figure 2). At Bikini the AFL attempted to repeat the hydroid incident by anchoring twelve pieces of scrap lumber in the lagoon. Once again, hydroids attached themselves to the wood, and once again they were highly radioactive. That summer the AFL also recorded radioactivity in coral samples collected upwind of the target area. With these findings, AFL ecologists began to speculate that perhaps species, not water currents, were responsible for transporting radioisotopes. Water current patterns made it unlikely that the radioactive silt from the lagoon bottom had reached the coral.

Until this point, the AFL had quantified radioactivity through the use of Geiger counters. At this juncture, they began experimenting with radioautography, another method of measuring radioactivity. In 1943 AEC-funded physiologists at Berkeley and Chicago had concluded that radioactive iodine, like stable iodine, concentrated in the thyroids of rats, and that, like stable calcium, Ca-45 concentrated in bones.[31] To produce a radioautograph, a researcher would take a slice of an organ and place it on a photographic plate. Emissions from a radioactive sample would produce a brighter or darker image, depending on how much radiation reacted with the plate's substrate.[32] Through regular meetings with AEC officials and through bibliographies of classified

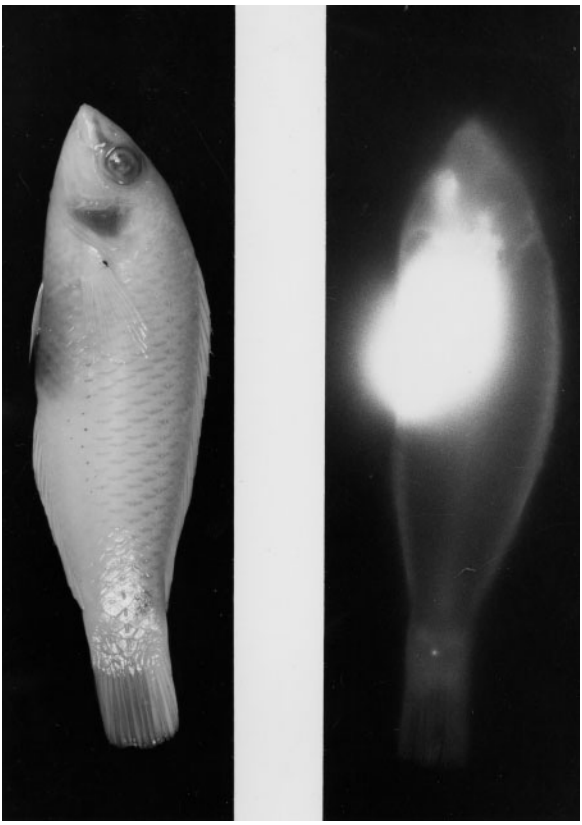

Figure 3. Radioautograph of wrasse collected from Test *Baker*. Scientists involved in the Bikini Scientific Resurvey believed the expansive Pacific Ocean would quickly dilute and disperse radioactive products from *Baker*. Radioautographs like this one showed otherwise. Credit: University of Washington Libraries, Special Collections, UW35914.

documents, Donaldson would have been aware of these laboratory experiments. When AFL members began to place fish organs and small whole fish on photographic plates, they were astonished at what they saw. In dazzling white, the film revealed the previously invisible phenomenon of internal tissue contamination (figure 3).

In a high-security talk delivered at the University of California, Los Angeles (UCLA), in 1948, Donaldson announced that the AFL team had found evidence of "selective absorption" and "concentration" of radioactive materials by all kinds of living forms, from algae to crabs to fish.[33] Rather than being distributed evenly across an organism's body, radioactivity seemed to be concentrated in the digestive system. Feeding in the lagoon, Bikini's biota had ingested products of the explosions, radioisotopes of elements necessary to life, such as phosphorus and calcium; and some species, feeding on others, had concentrated these radioisotopes in their bodies. Atomic weapons had thus made connections among species visible. It was a development that, like nuclear proliferation, would profoundly shape the future of the global environment.

"HAPPY MEETING GROUND ON THE CORAL REEF"

On the evening of June 24, 1954, Eugene and Tom Odum deplaned onto Enewetak Atoll with 155 pounds of scientific equipment and a desire to advance ecological theory.[34] Their opportunity to visit the Pacific Proving Grounds arose from Eugene's work surveying plants and animals at the AEC Savannah River Site.[35] In 1953 Eugene received a letter explaining that the Office of Naval Research and the Pacific Science Board were appraising the feasibility of establishing a permanent biological station on Enewetak Atoll (what would become the Eniwetok Marine Biological Station). The site was ideal for ecological studies, the letter explained, but the committee first wanted to gauge scientific interest in a permanent field station.[36] Eugene pitched two projects: an extension of his previous work on fat deposition in migratory birds, and an extension of the "community metabolism" studies that his brother, Howard T. ("Tom") Odum, was developing at Silver Springs, Florida.[37] Tom viewed the hot springs, a popular vacation spot, as "a ready-made natural laboratory" because they maintained a constant temperature. Unlike physiologists, Tom wrote, who could place individual organisms into laboratory equipment, ecologists were unable to "lift up a whole community, place it in a respirometer, measure the whole metabolism, and yet not disturb the normal influx and outflow of raw materials, energy, and waste products."[38] In his proposal to the AEC, Eugene echoed Tom's language, highlighting the "unique opportunity" that atomic testing created to study “entire ecological systems in the field.”[39] While the AEC had no interest in bird fat, it was enthusiastic about Tom’s methods, and they offered the Odums a grant to visit Enewetak for six weeks.[40] “It sure will be fun,” Tom wrote to Eugene as they prepared for the trip, “I think we can talk up some new theories too.”[41]

Scientists often describe theory as emerging from and responding to experimental data and, in the case of ecology, field observations. But as the quote by Tom Odum illustrates, the relationship between observation and theory is rarely straightforward. The Odums did not “discover” evidence of ecosystems at Enewetak; rather, they theorized Enewetak’s coral reefs as ecosystems years before they arrived. Beginning with his dissertation work in 1936, Eugene had advocated studying organisms in the field remotely, without “disturbing” them.[42] As the Odums planned their trip to Enewetak, Eugene was completing a textbook that reviewed recent work on species–environment relationships. Such work included Arthur Tansley’s 1935 article, “The Use and Abuse of Vegetational Concepts and Terms,” which coined the term “ecosystem” to refer to plants, animals, and the abiotic environment of a given area, and Raymond Lindeman’s work on how materials and energy moved through “trophic levels.”[43] Pitching the textbook to a publisher in 1944, Eugene wrote, “After the war there will be a great revival of interest in ecology [. . .]. With all the distruction [*sic*] now going on, it will be practically essential for us to give more thought to our shrinking environment in more ways than one!”[44]

That year Eugene secured a publishing contract, and in 1949 he asked his younger brother, Tom, to join him as a coauthor.[45] After serving in the Air Force, Tom had joined Yale University’s graduate program in zoology, intending to study bird physiology like Eugene, but he soon decided to work instead with the charismatic limnologist G. Evelyn Hutchinson.[46] Tom wrote to Eugene frequently, sharing lecture notes and laboratory gossip, as he worked on his dissertation. Although Tom declined coauthorship on the textbook, he wrote chapters on two topics that the Hutchinson laboratory had trained him in: population biology and biogeochemistry.[47] *Fundamentals of Ecology* was published in 1953, to positive reviews. Soon thereafter, the Odums set off for Enewetak, arriving mere months after the AEC had detonated its second thermonuclear weapon, a device that yielded 15 megatons.

While the AFL struggled to represent vast areas in their collections, the Odums sought to catalog one site exhaustively. The Odums’ primary goal was to represent the “trophic structure” of a coral reef as a “pyramid of mass.” Toward this end, they demarcated six 20 × 20-foot squares (“quadrats”) across a coral reef in a line parallel to the current. They then estimated the total mass of each species in each quadrat. But as AFL members had known for years, the atolls were difficult terrain to work in. They mapped one of the quadrats only by "brief glimpses from a helicopter" because they could not cross the breakers. Another they could sample only during a half-hour window of low tide. The other four quadrats they observed by snorkeling with acetate paper and pencils. In taking notes on what they saw, they were constrained by their lack of knowledge of local species and of marine species more generally. Their field notes included many question marks. On field maps they represented unknown species with letters, hatch marks, and descriptions like "greenish yellow coral." Later, they would attempt to match their notes with identifications of samples they had sent to experts at Cornell University and the Smithsonian Institution.[48]

Once the Odums began their fieldwork, they struggled to match the species and situations they encountered to their preconceived frameworks. To convert counts (in the case of large species) or area (in the case of small ones) into mass, the Odums dried and weighed one or a few samples of each species. By using mean values they ignored the substantial variation among samples. They also lost samples to overheating; they wrote in their field notes, "These values not good; specimens dried in oven too long."[49] Once they had estimated total mass per species, they sorted species (often guessing) into "producers," "herbivores," and "carnivores." The Odums also omitted information, intentionally or not, when producing published figures from their hand-drawn maps. In the final version of quadrat B (figure 4), the edges of coral boundaries are smoothed and a number of smaller colonies are missing.

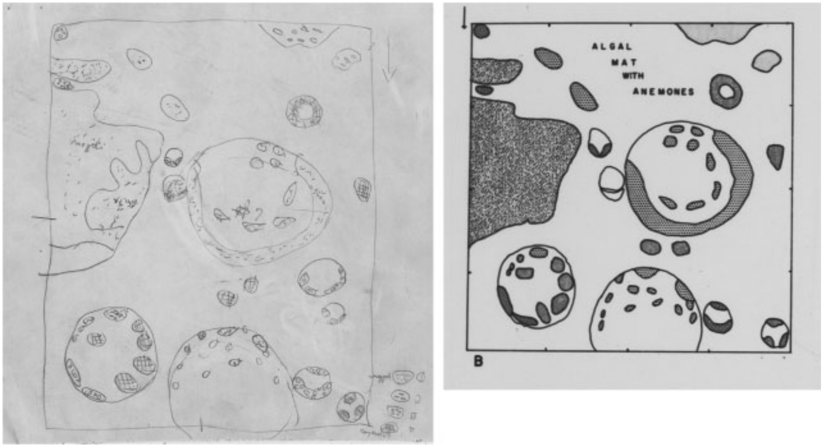

Figure 4. A map of "quadrat B" sketched in the field by the Odums (left) and the version of "quadrat B" published in Odum and Odum (1955). Note the differences in spacing and coral species identification (as indicated by shading). Credit: UGA 06-032, Box 1, Folder 9. Courtesy of Hargrett Rare Book and Manuscript Library / University of Georgia Libraries.

Before the trip, the Odums had also supported the contentious hypothesis that coral existed in a mutualistic relationship with photosynthetic algae.[50] Seeking evidence for their position, they developed radioautographs of algae collected from coral heads. They recorded that algae from dead coral heads produced bright radioautographs, suggesting they were "intensely radioactive," whereas those from live coral did not. The Odums speculated that the algae inside live coral were not receiving nutrients from the surrounding water, but only from the coral polyp. They concluded that this mutualism allowed for "cyclic use and reuse of food and nutrients" in a harsh, unproductive environment. Through this fieldwork, the fission products of the ten nuclear weapons that had been detonated at Enewetak became evidence of symbiosis.

Upon their return, the Odums quickly drafted a manuscript summarizing their trophic pyramid and coral symbiosis results. They employed the trophic pyramids as evidence that ecological communities shared an underlying structure, regardless of location. As Tom wrote to Eugene, "The pyramids are very gratifying and not too different from Silver Springs, Savannah River [. . .] etc. Thus it really looks like there is an underlying constancy in these things."[51] The coral radioautographs they used as an explanation for why communities in "nutrient-poor" tropical waters were nevertheless pyramid shaped. The article was published in *Ecological Monographs* in 1955 and won that year's Ecological Society of America award for best publication. Receiving the award, Eugene stated, "It was in connection with an AEC grant that my brother, with his interest in flowing water ecosystems, and I with my interest in sessile terrestrial and salt marsh systems, found a happy meeting ground on the coral reef." Tom, meanwhile, attributed his path to "the dream of abstract conceptualization from G. Evelyn Hutchinson" and "the fascination with the ecological from an older brother's early enthusiasm."[52] In describing the Enewetak paper as having arisen from the nebulous influence of mentors, Eugene and Tom omitted many other factors that influenced their work: the overwhelming number of species they encountered, the difficulty of working on the reef, and the multiple nuclear detonations that occasioned their fieldwork.

A "PERFECT AQUATIC LABORATORY"

In their manuscript, the Odums described Enewetak as an "isolated system," a "rather constant environment" that "as yet has been little affected by nuclear explosions."[53] Their language echoed that of other AEC-sponsored scientists and officials. In the AEC's promotional film *Operation Greenhouse* (1951), the narrator described

Enewetak as "secluded" and "primitive" while also likening it to a university campus:

> One of the proving grounds is an outdoor laboratory: Enewetak Atoll in the Pacific. This Trust Territory of the United States has been used before as a testing ground for Operation Sandstone. But three years have passed, three years to bring new and improved atomic weapons to this secluded equatorial land… . Since Enewetak is a distant and primitive area, men have to leave their stateside laboratories and homes for a period of months. [*Image of an American man with suitcase entering his car and waving goodbye to son and dog*.] Now the proving grounds come alive like a university campus when students return from a summer holiday … [*aerial view of islands from military plane*] these are the dormitories of "Enewetak university" … individual test islands, seemingly like so many science buildings on college grounds.[54]

In another film, *Bikini Radiobiological Laboratory* (1950), the AFL described the Proving Grounds as unchanging and secluded, a "perfect aquatic laboratory."[55] Elsewhere Donaldson extolled the "unparalleled scientific experiments" at the Pacific Proving Grounds—the atomic detonations that had enabled ecologists to visualize relationships among species in a "natural environment" and to make ecology "a more exact science."[56] As Elizabeth DeLoughrey has argued, through such rhetorical work, AEC scientists fashioned the atolls as laboratories uninhabited by humans and available for any conceivable experiment.[57]

In fact, the atolls were neither isolated nor pristine. Rather, they were globally connected, geopolitically central, and radically transformed. In the decade before the Odums' arrival, the landscape at Enewetak had been shaped and reshaped by military and scientific activity. The beaches were littered with barges, steel cable, scrap metal, beer and sake bottles, and abandoned furniture.[58] Beginning in 1950, the AEC constructed "semipermanent facilities" at Enewetak including medical offices, barbershops, chapels, and the marine laboratory (figure 5). At night, in the Back N' Atom Bar, the Odums mingled with AEC officers and other scientists from across the United States including AFL members. Although the Odums did not meet Donaldson during their 1954 visit, they met other AFL members who complained to Donaldson about their messiness and tendency to "borrow too freely."[59] Members of the AFL would return to the Pacific Proving Grounds regularly through the 1960s (figure 6). Scientific and military presence at Enewetak and Bikini during this period was sustained. For Operation Ivy (1952) alone, the United States

Figure 5. Eniwetok Marine Biological Laboratory, 1964. E. M. B. L. Jackson dissects a rat in the foreground; Lauren Donaldson stands second from the left in the far background. Credit: University of Washington Libraries, Special Collections, DON0352.

Figure 6. Applied Fisheries Laboratory member Ralph Palumbo collecting specimens with an onion sack in Bikini Lagoon, 1964. Credit: University of Washington Libraries, Special Collections, DON0041.

transported 75 million gallons of fresh water, 1 million meals, 89,968 square feet of tent, and 3 million board feet of lumber.[60] As one AFL member later reflected, "The statistics cannot give a picture of the work performed—of the massive bunkers constructed, of the causeways thrown between islands, of air-strips built, roads graded, heavy equipment carried by marine craft from island to island, structures aligned precisely for test instrumentation purposes, plus the normal community and housekeeping chores incidental to keeping a large group of men reasonably happy, healthy and satisfied."[61]

The atolls were not isolated and pristine; nor were they uninhabited. As the rest of the world worried about the possibility of atomic violence, Marshall Islanders lived it. Between 1946 and 1962, the AEC conducted 105 atmospheric and underwater nuclear weapons tests at the Pacific Proving Grounds, releasing the equivalent power of more than seven thousand Hiroshima bombs.[62] Marshall Islanders suffered forced relocations, destruction of ancestral lands, and radiation sickness.[63] In a tone less triumphant than that of many ecologists, E. B. White wrote in a review of AEC scientist David Bradley's 1948 book, *No Place to Hide,* "His laboratory was a paradise, and the experiment in which he was involved was an experiment in befouling the laboratory itself. [. . .] Bikini is the world in miniature; radioactivity is the disease that can knock it out."[64] Bikini did, indeed, become a model in miniature for the world, insofar as it is an originating landscape for ecosystem science.

"THE FIELD STATION AS PROVING GROUND"

It is easy to forget about ecology's Atomic Age because a number of ecologists and environmental scientists were involved in the antinuclear protests of the 1960s. Indeed, Frank Golley has reflected that by the 1970s, ecologists "seemed oblivious to the connection between ecosystem research and the military activity of the U.S."[65] But it was not until the 1960s that many ecologists began to frame nuclear technologies, and nuclear weapons in particular, as environmental threats. On the contrary, during the 1950s, ecologists emphasized the immense potential of nuclear technologies to enhance scientific understanding of the structure of the natural world, and, therefore, human ability to manage and restore the natural world. For their parts, Donaldson and Eugene Odum both downplayed the threat of nuclear weapons until late in their careers. Commenting on a panel at the 1963 American Institute of Biological Sciences meeting, Eugene Odum contended that nuclear detonations were no different from storms, forest fires, pest irruptions, "and other natural, accidental, or experimental stresses that mimic, in one way or another, nuclear war."[66]

During ecology's Atomic Age, the AEC provided ecologists with funding and with access to production sites and proving grounds, where ecologists were largely able to pursue their own research agendas. In their report to AEC headquarters on their work at Enewetak, the Odums admitted that they "were not primarily concerned with the effects of radiation," but rather with showing that the "basal metabolism" of a community could be "measured in certain very definite and precise ways, just as one can measure oxygen consumption, heart rate, etc., of an individual."[67] This does not mean that ecologists worked independently, however. The AEC vetted all of their scientific publications and often censored words like "fallout."

It was not until 1954, when the Atomic Energy Act set declassification into motion, that the work of the AFL, the Odums, and other AEC ecologists gained a broad audience. At this point AEC ecologists began presenting their findings at international meetings.[68] Richard Foster of the AFL first described the phenomenon of "bioaccumulation" to a public audience at the 1955 "Atoms for Peace" conference in Geneva, Switzerland, at which Eugene Odum also presented.[69] In his first revision of *Fundamentals of Ecology*, published in 1959, Eugene added a chapter on the new discipline of "radiation ecology" in which he described studies like those of Donaldson's laboratory that explored how ecological communities mediated the distribution of radioactive substances in the environment. In writing the chapter, he drew from his experiences at post-1954 international conferences and from a sabbatical year (1957–58) at the AFL and UCLA.[70] While at UCLA, Eugene regularly joined biologists for three-hour train trips to Nevada to observe weapons detonations at the Nevada Proving Grounds, which ecologists also studied, although less intensively. He wrote in a letter to his mother,

> On reaching observation ridge cars park in neat rows and everyone gets out to stand or sit on bleachers erected under searchlights. At 30 minutes before scheduled explosion a voice from the loudspeakers begins to count off the minutes "30 minutes before zero, 29 minutes before zero," etc. At five minutes the seconds are counted, and at one minute everyone is instructed to put on dark goggles or turn and face away from the site (the light for first few seconds is so bright that one could be blinded.) Then the count down 10-9-8-7-6-5-4-3-2-1-0.[71]

Also in that letter, Eugene noted that he was impressed by the "beautifully organized sampling systems" in the desert. The desert struck him as a "good system for our type of studies because it is [. . .] relatively uniform and simplified biologically."[72] Eugene's experiences at the Pacific and Nevada Proving Grounds would shape his later experiments with radiotracers at field sites across the southern United States. After the passage of the Atomic Energy Act, the AEC began mass-producing radioisotopes and distributing them to American researchers. As they did, ecologists were no longer constrained to sites where radioisotopes had been released accidentally or through detonations. By the early 1960s, ecologists were applying radioisotopes intentionally to their field sites in measured doses. Stanley Auerbach injected Cesium-137 into tulip poplar trees in Tennessee. Eugene Odum applied radioisotopes to abandoned agricultural fields in Georgia.[73]

As the United States and the Soviet Union increased the power and the range of their nuclear weaponry, it became possible to conceive of a catastrophic global-scale war. In 1946 the United States had nine weapons in its stockpile. By 1955, it had 2,422. And by 1961, it had 22,229.[74] Due in part to AEC ecologists' fieldwork, scientists and the public began to conceptualize radioactive fallout as a regional, even a global, health risk.[75] A comparison of the text of Eugene's second and third editions of *Fundamentals of Ecology* is telling. In the second edition (1959), Eugene wrote, "Man's opportunity to learn more about environmental processes through the use of radioactive tracers balances the possible troubles he may have with environmental contamination." In the third edition, published in 1971, Eugene revised the sentence to read, "Man's opportunity to learn more about environmental processes through the use of radioactive tracers balances to some extent the troubles he is having with environmental contamination."[76]

The period of the proving ground as ecological laboratory ended in 1963 when the United States, the Soviet Union, and Great Britain signed the Partial Test Ban Treaty, prohibiting all non-wartime detonations of nuclear weapons except for those conducted underground. At the same time, however, the RAND Corporation recommended to the Pentagon that they investigate the ecological dimensions of post–World War III recuperation.[77] Thus began a period in which ecologists purposefully destroyed "ecosystems," rather than warships or imported animals, to study if and how they recovered. By 1970 ecologists had purposefully irradiated deciduous forests in New York, tropical rain forests in Puerto Rico (a project led by Tom Odum), and agricultural fields in Georgia and Tennessee.[78]

Although always conducted someplace in particular, this research was oriented toward developing generalized transposable strategies for the survival of American citizens. Through this fieldwork, ecologists framed particular ecosystems as objects less or more vulnerable to attack, a development that contributed to the emergence of the "diversity-stability hypothesis," the idea that the greater the number of species in an ecosystem, the better that system will be at "adjusting to stress."[79] World War III simulations also contributed importantly to the idea that there is a threshold of damage beyond which an ecosystem can no longer repair itself. Destruction thus became a standard method of studying ecosystems, and ecologists began clear-cutting, burning, and applying biocides to their field sites.[80] As

Eugene Odum put it in an article in the *Southern Biologists Bulletin,* "ecologists need not feel bashful about attacking ecosystems so long as they observe the rules of good science."[81]

The boundaries of ecosystems were quite different from the boundaries that had in the past delimited ecological study sites. Instead of delimiting field sites by visual observation ("The oaks end here!") or by the demarcation of quadrats or property lines, ecologists increasingly relied on radioisotopes to mark out a study's limits. In a revealingly titled talk, "The Field Station as Proving Ground," Eugene Odum argued that "[e]cosystems, such as lakes, forests, or cities where the real world problems lie cannot be put into a test tube, dissected into small pieces or enclosed within laboratory walls; they must be studied *in situ*."[82] And yet it is important to note that these boundaries, seemingly external to the experimentalist, were determined as much by experimental design—and the human production of radioisotopes—as by intrinsic properties of species and their interactions. Ecosystems may seem natural and universal, but their delineation depended on the tools of a particular time and place. Destruction was the enabling condition for understanding life as interconnected.

MATTER, AND WHY ECOSYSTEMS MATTER

By 1970 ecosystems had materialized. That year the poet William Stafford reflected, "Thoreau's concept of Concord was what we now call a 'model ecosystem,' though he formulated and studied it in advance of all the technology we believe to be necessary in such studies."[83] Ecosystems were not discovered; nor were they constructed entirely by scientists. Rather, along with ecologists, the activities of nonhumans at different scales (atomic bombs, radioisotopes, hydroids, corals, and wrasse, to name a few) enabled ecosystems to materialize. With ecosystem studies, ecologists claimed that fieldwork conducted in one place could be used to understand other distant and different places. The Pacific Proving Grounds became a model for lakes in Wisconsin, rain forests in Panama, deserts in China—and, ultimately, even for corporate relations and gut microbes.

Ecosystems' materialization altered not only ideas about the order of nature, but also material environments themselves across the world. Beginning in the 1970s, many types of environmental management were reorganized as ecosystem management, including wilderness protection.[84] Between 1970 and 2016, the amount of global protected area increased from 4 million km^2 to more than 26 million km^2.[85] Today myriad restoration projects attempt to restore ecosystem functions or ecosystem composition.

As Paul Sutter has observed, environmental history's "troubled categories of analysis" include "not only the freighted and now thoroughly problematized 'nature,' but also the encompassing and surprisingly undertheorized 'environment.'"[86] We can and should add "ecosystem" to the list. Ecosystems are frequently employed as metaphors for well-balanced and well-functioning societies, as when James Scott contrasts the "homogenization, uniformity, grids, and heroic simplification" of states with the "*resilience and durability of diversity*."[87] But the making of ecosystems entailed injustice, and even horror: the disposession of Marshall Islanders; the radiation sickness of thousands of soldiers and civilians; simulations of World War III; and the creation of the massive US nuclear complex, which by the end of the Cold War occupied more than 8,500 km^2 and whose radioactive legacy will persist for at least ten thousand years.[88]

Environmental historians are well situated to recover such unsettling histories that are sometimes embedded within what seems most natural. The Pacific Proving Grounds were a place of destruction and exclusion—"the latitude of doom," as *Newsweek* called it—where ecologists wondered if the world could survive hydrogen bombs. But through the work of Donaldson and other ecologists, the Proving Grounds also became an originating landscape of conservation and restoration.[89] Starting in the 1960s, Pacific Islanders mobilized the ecosystem concept and many of the ideas that underpin restoration ecology when developing their own narratives of anticolonial struggle.[90] Ecosystem theory facilitated grassroots environmentalism, holistic ecology, conservation biology, and restoration ecology, movements of the "Age of Ecology" that are typically contrasted with the "Atomic Age." The rise of ecology, however, was not a response to the perception of environmental decline but one of its preconditions, with roots in powerfully destructive technologies.

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Notes

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1. Definition from Kathleen Weathers, David Strayer, Gene Lickens, *Fundamentals of Ecosystem Science* (New York: Academic Press, 2013), 3; Joyce Chaplin, "Can the Nonhuman Speak? Breaking the Chain of Being in the Anthropocene," *Journal of the History of Ideas* 78 (2017): 509–29.
2. Orie Loucks, "Systems Methods in Environmental Court Actions," in *Systems Analysis and Simulation in Ecology*, ed. Bernard Patten (New York: Academic Press, 1972): 419–72.
3. See, for example, Donald Worster, *Nature's Economy: A History of Ecological Ideas* (Cambridge: Cambridge University Press, 1977); Peter Taylor, "Technocratic Optimism, H. T. Odum, and the Partial Transformation of Ecological Metaphor after World War II," *Journal of the History of Biology* 21 (1988): 213–44; Joel Hagen, *An Entangled Bank: The Origins of Ecosystem Ecology* (New Brunswick: Rutgers University Press, 1992); Frank Golley, *A History of the Ecosystem Concept in Ecology: More Than the Sum of the Parts* (New Haven: Yale University Press, 1993).
4. Chunglin Kwa, "Representations of Nature Mediating between Ecology and Science Policy: The Case of the International Biological Programme," *Social Studies of Science* 17 (1987): 413–42; Paolo Palladino, "Defining Ecology: Ecological Theories, Mathematical Models, and Applied Biology in the 1960s and 1970s," *Journal of the History of Biology* 24 (1991): 223–43; Stephen Bocking, "Ecosystems, Ecologists, and the Atom: Environmental Research at Oak Ridge National Laboratory," *Journal of the History of Biology* 28 (1995): 1–47; Sharon Kingsland, *The Evolution of Ecology, 1890–2000* (Baltimore: Johns Hopkins University Press, 2005), chap. 7.
5. DeLoughrey analyzes how the U.S. AEC rhetorically rendered the Marshall Islands "isolated" in films and texts. She argues that the ecosystem concept "drew from the grammar of the AEC and its nuclear tests," thereby upholding the concept of isolated spaces – an idea that was "perpetuated by the aerial view utilized by AEC films" (168). Elizabeth DeLoughrey, "The Myth of Isolates: Ecosystem Ecologies in the Nuclear Pacific," Cultural Geographies (2012): 167–84. Others connecting the rise of the environmental sciences with American militarism include Scott Kirsch, "Ecologists and the Experimental Landscape: The Nature of Science at the U.S. Department of Energy's Savannah River Site," *Cultural Geographies* 14 (2007): 485-510; Ronald Rainger, "Science at the Crossroads: The Navy, Bikini Atoll, and American Oceanography in the 1940s," *Historical Studies in the Physical and Biological Sciences* 30 (2000): 349-371; Edmund Russell, *War and Nature: Fighting Humans and Insects with Chemicals from World War I to Silent Spring* (New York: Cambridge University Press, 2001); Ronald Doel, "Constituting the Postwar Earth Sciences: The Military's Influence on the Environmental Sciences in the USA after 1945," *Social Studies of Science* 33 (2003): 635-666; Jacob Darwin Hamblin, *Arming Mother Nature: The Birth of Catastrophic Environmentalism* (Oxford: Oxford University Press, 2013). Joseph Masco argues that the global reach of nuclear crisis enabled new visions of planetary threats, especially climate change, in Joseph Masco, "Bad Weather: On Planetary Crisis," Social Studies of Science 40 (2009): 7-40.
6. For an overview of this intersection, see Sara Pritchard, *Confluence: The Nature of Technology and the Remaking of the Rhone* (Cambridge: Harvard University Press,

2011), Introduction; Dolly Jørgensen, Finn Arne Jørgensen, and Sara B. Pritchard, eds., *New Natures: Joining Environmental History with Science and Technology Studies* (Pittsburgh: Pittsburgh University Press, 2013).

7. On environmental history and fieldwork, see Robert Kohler, *Landscapes and Labscapes: Exploring the Lab-Field Border in Biology* (Chicago: University of Chicago Press, 2002); Stephen Bocking, "Science and Spaces in the Northern Environment," *Environmental History* 12 (2007): 868–95; Jeremy Vetter, ed., *Knowing Global Environments: New Historical Perspectives on the Field Sciences* (New Brunswick: Rutgers University Press, 2011); Raf De Bont and Jens Lachmund, eds., *Spatializing the History of Ecology: Sites, Journeys, Mappings* (New York: Routledge, 2017); Megan Raby, *American Tropics: The Caribbean Roots of Biodiversity Science* (Raleigh: University of North Carolina Press, 2017).
8. For an introduction to these concerns, see Bruno Latour, *Reassembling the Social: An Introduction to Actor-Network Theory* (New York: Oxford University Press, 2005); Diana Coole and Samantha Frost, *The New Materialisms: Ontology, Agency and Politics* (Durham: Duke University Press, 2010); S. Eben Kirksey and Stefan Helmreich, "The Emergence of Multispecies Ethnography," *Cultural Anthropology* 25 (2010): 545–76. Recent environmental histories that engage this literature include Michelle Murphy, *Sick Building Syndrome and the Problem of Uncertainty* (Durham: Duke University Press, 2006); Paul Sutter, "Nature's Agents or Agents of Empire? Entomological Workers and Environmental Change during the Construction of the Panama Canal," *Isis* 98 (2007): 724–54; Edmund Russell, *Evolutionary History: Uniting History and Biology to Understand Life on Earth* (Cambridge: Cambridge University Press, 2011); Timothy LeCain, "An Impure Nature: Memory, Geese, and Neo-Materialism at America's Biggest Toxic Superfund Site," *Global Environment* 11 (2013): 16–41. Particularly useful to this essay is Murphy's framing of materialization as a process that involves actors of different kinds, "the effect of power as exercised through the concrete arrangements of objects, actions, and subjects" (*Sick Building Syndrome*, 181).
9. On war and environment, see Richard Tucker and Edmund Russell III, eds., *Natural Enemy, Natural Ally: Toward an Environmental History of War* (Corvallis: Oregon State University Press, 2004); J. R. McNeill and Corinna R. Unger, eds., *Environmental Histories of the Cold War* (Cambridge: Cambridge University Press, 2010); Edwin A. Martini, ed., *Proving Grounds: Militarized Landscapes, Weapons Testing, and the Environmental Impact of U.S. Bases* (Seattle: University of Washington Press, 2015). The topic nests into an emerging literature in the environmental humanities on violence. See, for example, Rob Nixon, *Slow Violence and the Environmentalism of the Poor* (Cambridge: Harvard University Press, 2013).
10. Peter Galison and Bruce Hevly, eds., *Big Science: The Growth of Large-Scale Research* (Stanford: Stanford University Press, 1992). New funding structures, technologies, and understandings of war contributed to the emergence of a number of scientific disciplines including molecular biology, atmospheric science, and oceanography. See Ronald E. Doel, "Constituting the Postwar Earth Sciences: The Military's Influence on the Environmental Sciences in the USA after 1945," *Social Studies of Science* 33 (2003): 635–66; Jacob Darwin Hamblin, *Oceanographers and the Cold War: Disciples of Marine Science* (Seattle: University of Washington Press, 2005); Joseph Masco, "Bad Weather: On Planetary Crisis," *Social Studies of Science* 40 (2009): 7–40; Emory Jerry Jessee, "Radiation Ecologies: Bombs, Bodies, and Environment during the Atmospheric Nuclear Weapons Testing Period, 1942–1965" (PhD diss., Montana State University, 2013).
11. Angela H. Creager, *Life Atomic: A History of Radioisotopes in Science and Medicine* (Chicago: University of Chicago Press, 2013).

12. Ibid., chap. 10.
13. Historians of ecology have focused on production sites, with the notable exception of Jessee, "Radiation Ecologies," who explores how studies of atmospheric fallout played a critical role in the development of ecology, meteorology, and oceanography and how it reshaped what was known about radiological health risks.
14. In 1971 AEC funding for environmental and biological studies was $72 million. Total funding for ecology from NSF that year was less than $20 million. David C. Coleman, *Big Ecology: The Emergence of Ecosystem Science* (Berkeley: University of California Press, 2010), 7. NRDC Nuclear Notebook: Known Nuclear Tests Worldwide, 1945–1998. For an excellent overview of the spatial footprint of the US nuclear program, see Joe Masco, *The Nuclear Borderlands: The Manhattan Project in Post-Cold War New Mexico* (Princeton: Princeton University Press, 2006), chap. 1. On ecological work conducted at AEC production sites, see Stephen Bocking, *Ecologists and Environmental Politics: A History of Contemporary Ecology* (New Haven: Yale University Press, 1997), chaps. 4 and 5; Matthew Klingle, "Plying Atomic Waters: Lauren Donaldson and the 'Fern Lake Concept' of Fisheries Management," *Journal of the History of Biology* 31 (1998): 1–32; Scott Kirsch, "Ecologists and the Experimental Landscape: The Nature of Science at the U.S. Department of Energy's Savannah River Site," *Cultural Geographies* 14 (2007): 485–510; Creager, *Life Atomic,* chap. 10.
15. In *Fish of Rare Breeding: Salmon and Trout of the Donaldson Strains* (Washington, DC: Smithsonian Institution Press, 1976), Neal O. Hines recounts that Donaldson received a telegram around August 15, 1943. I believe the date of the telegram to be August 18 based on a transcript of a call between Mr. Wensel and Mr. Hanford Thayer found in Box 9, Folder 18, Lauren R. Donaldson Papers, University of Washington Special Collections [hereafter, LRDP].
16. Fisheries biology and ecology were separate disciplines with their own societies and journals. But many biologists identified as both fisheries biologists and ecologists, and the two disciplines deeply influenced one another. As Klingle (1998) notes, the subdiscipline of population ecology grew out of early studies of fisheries. See also Sharon Kingsland, *Modeling Nature: Episodes in the History of Population Ecology* (Chicago: University of Chicago Press, 1985). On Hanford, see John Findlay and Bruce Hevly, *Atomic Frontier Days: Hanford and the American West* (Seattle: University of Washington Press, 2011); Kate Brown, *Plutopia: Nuclear Families, Atomic Cities, and the Great Soviet and American Plutonium Disasters* (New York: Oxford University Press, 2013).
17. Neal O. Hines, *Proving Ground: An Account of the Radiobiological Studies in the Pacific, 1946–1961* (Seattle: University of Washington Press, 1962), chap. 1. For archival material on the establishment of the AFL, see Boxes 3 and 9 of the Laboratory of Radiation Ecology Records, 1948–1984, University of Washington Special Collections [hereafter, LRER]; and Leslie R. Groves to Donaldson, March 10, 1961, Box 12, Folder 46, Laboratory of Radiation Biology Records, 1944–1970, University of Washington Special Collections [hereafter, LRBR].
18. Jonathan Weisgall, *Operation Crossroads: The Atomic Tests at Bikini Atoll* (Annapolis: Naval Institute Press, 1994); Scott Kirsch, "Watching the Bombs Go Off: Photography, Nuclear Landscapes, and Spectator Democracy," *Antipode* 29 (1997): 227–55.
19. On nuclear colonialism in the Pacific, see David Hanlon, *Remaking Micronesia: Discourses Over Development in a Pacific Territory, 1944–1982* (Honolulu: University of Hawai'i Press, 1998); Jeffrey S. Davis, "Representing Place: 'Deserted Isles' and the Reproduction of Bikini Atoll," *Annals of the Association of American*

Geographers 95 (2005): 607–25; Holly M. Barker, *Bravo for the Marshallese: Regaining Control in a Post-Nuclear, Post-Colonial World* (Belmont: Cengage Learning, 2012).
20. Jessee, *Radiation Ecologies*, 161.
21. There were many military objectives of the scientific surveys, as enumerated in "Oceanographic Program at Bikini Atoll," Box 3, Folder 7, W. T. Edmondson Papers, Series 3, University of Washington Special Collections.
22. My account of Tests *Able* and *Baker* draws from Hines, *Proving Ground*, and trip logbooks, laboratory correspondence, staff meeting minutes, and AEC reports in LRBR and LRER.
23. Box 11, Folder 28, LRDP; also "Report on Able and Baker Effects," Box 6, Folder 4, LRBR.
24. Hines, *Proving Ground*, chaps. 2 and 3; "Appendix XIV," Box 6, Folder "Bikini 1946–1947," LRER.
25. Hines, *Proving Ground*. Press releases can be found in Box 2, Folder 7, Neal O. Hines Papers, University of Washington Special Collections [hereafter, NOHP]. The Resurvey scrapbook can be found in Box 21, LRDP. On the AEC, see Richard G. Hewlett and Jack M. Holl, *Atoms for Peace and War, 1953–1961* (Los Angeles: University of California Press, 1989); John Krige, "Atoms for Peace, Scientific Internationalism, and Scientific Intelligence," *Osiris* 21 (2006), 161–81.
26. Hines, *Proving Ground*, 61.
27. The previous summer, AFL member Richard Foster had collected samples of fish from the Columbia River and found them to have concentrations of radioactivity thousands of times higher than their environment. The AFL's findings at the Pacific Proving Grounds resonated with this finding and with Donaldson's earlier work on fish nutrition. Lauren R. Donaldson and Richard F. Foster, "Effects of Radiation on Aquatic Organisms," in *The Effects of Atomic Radiation on Oceanography and Fisheries* (Washington, DC: National Academy of Sciences, 1957).
28. Neal Hines, "Bikini Atoll and the Scientific Resurveys," Box 6, Folder 6, LRER.
29. On Marshall Islanders' continuing struggle for self-determination, see M. X. Mitchell, "Offshoring American Environmental Law: Land, Culture, and Marshall Islanders' Struggles for Self-Determination During the 1970s," *Environmental History* 22 (2017): 209–34.
30. Atomic Energy Commission, Second Semiannual Report (Washington, DC: Government Printing Office, July 1947), 7. More than fifty thousand people lived in the Trust Territory. Roger Gale, *The Americanization of Micronesia: A Study on the Consolidation of U.S. Rule in the Pacific* (Washington, DC: University Press of America, 1979).
31. Jessee, *Radiation Ecologies*, 94–96.
32. Andrew W. Rogers, *Techniques of Autoradiography*, 3rd ed. (North Holland: Elsevier, 1979).
33. Lauren Donaldson, "Speech" delivered at meeting of the Atomic Energy Project, University of California at Los Angeles, August 11, 1948, Folder 2, Box 3, LRDP.
34. "Logbook," Box 1, Folder 1, Series 1, Eugene Odum Research Files: Eniwetok Atoll (Accession UA06-032), Hargrett Rare Books and Manuscripts Library, University of Georgia [hereafter, ODUM-E]. The US government referred to the atoll as "Eniwetok" until 1974 when it changed its official spelling to "Enewetak" to reflect its pronunciation by Marshall Islanders.
35. My account differs from Donald Worster's, who writes that Tom Odum was recruited by the AEC because of his doctoral work on the biogeochemistry of strontium. Worster, *Nature's Economy*, 364.

36. Karl Wilbur (AEC) to Odum, April 6, 1953, Box 1, Folder 10, Series 1, ODUM-E.
37. Eugene Odum to Dr. Karl Wilbur, June 11, 1953, Box 1, Folder 10, Series 1, ODUM-E.
38. Howard T. Odum, "Community Metabolism of Silver Springs, Florida," *ESA Bulletin* 34 (1953): 67; Howard T. Odum, "Trophic Structure and Productivity of Silver Springs, Florida," *Ecological Monographs* 27 (1957): 55–112.
39. Eugene P. Odum to Dr. Karl Wilbur, June 11, 1953, Box 1, Folder 10, Series 1, ODUM-E.
40. Eugene Odum to W. Boss, April 27, 1954, Box 1, Folder 8, Series 1, ODUM-E; "A Proposal for Studies on the Productivity of Coral Reef Atolls," Box 1, Folder 8, Series 1, ODUM-E. Howard Odum to Sidney Galler, August 14, 1953, Box 1, Folder 8, Series 1, ODUM-E.
41. H. T. to Gene, undated (ca. 1954), Box 1, Folder 8, Series 1, ODUM-E.
42. Eugene Odum, "Variations in the Heart Rate of Birds: A Study in Physiological Ecology," *Ecological Monographs* 11 (1941): 299–326.
43. Arthur Tansley, "The Use and Abuse of Vegetational Concepts and Terms," *Ecology* 16 (1935): 284–307; Raymond Lindeman, "The Trophic-dynamic Aspect of Ecology," *Ecology* 23 (1942): 399–417.
44. E. Odum to J. Bennett Jr., February 7, 1944, Folder 14, Carton 3, Series III, Eugene P. Odum Papers (MS 3257), Hargrett Rare Books and Manuscripts Library [hereafter, EPOP].
45. Tom to Eugene, fall 1949, Folder 25, Carton 3, Series III, EPOP.
46. Tom to Eugene, summer 1948, Folder 25, Carton 3, Series III, EPOP.
47. H. T. to Eugene and Martha, Summer 1951, Folder 25, Carton 3, Series III, EPOP; H. T. to Eugene, undated (ca. spring 1953), Box 60, Eugene Odum Papers – Institute of Ecology (Accession UA97-045), Hargrett Rare Books and Manuscripts Library [hereafter, EOPI]. Tom edited the book and wrote much of chaps. 4–7.
48. Eniwetok Atoll Log, Folder 1, Box 1, UGA 06-032. ID information in Folder 11.
49. "Quadrat B," Eniwetok Atoll Log, Folder 1, Box 1, UGA 06-032.
50. On the history of coral science, see Alistair Sponsel, "Coral Reef Formation and the Sciences of Earth, Life, and Sea, c. 1770–1952" (PhD diss., Princeton University, 2009).
51. Tom to Gene, November 1, 1954, Folder 4 Box 1, ODUM-E.
52. "The George Mercer Award for 1956," *Bulletin of the Ecological Society of America* 38 (1957): 2–3.
53. Howard T. Odum and Eugene P. Odum, "Trophic Structure and Productivity of a Windward Coral Reef Community on Eniwetok Atoll," *Ecological Monographs* 25 (1955): 291–320.
54. *Operation Greenhouse* (Lookout Mountain Laboratory, US Air Force, Hollywood, California, 1951), as cited in DeLoughrey (2012), 174.
55. Script for *Bikini Radiobiological Laboratory,* in Paul Pearson to Lauren Donaldson, May 17, 1950, Box 6, Folder 20, LRBR.
56. Lauren Donaldson, "Biological Cycles of Fission Products in Aquatic Systems as Studied at the Pacific Atolls of Bikini and Eniwetok," Report AECU–3412, Box 3, Folder 7, LRDP.
57. DeLoughrey (2012) further argues that Odum's ecosystem concept "positions laboratory space outside of history (i.e. human presence) and accountability," and that we must "raise the vital question as to how, as a methodology and system of thought, it sustained the concept of isolation, despite all evidence to the contrary" (178).
58. Neal O. Hines, "Bikini Atoll and the Scientific Resurveys," Box 6, Folder 6, LRER.

59. Lauren R. Dolandson to Art and Frank, August 11, 1954, Box 6, Folder 8, Laboratory of Radiation Ecology Records, 1948–1984, LRER.
60. Undated draft of Joint Office of Test Information, "Background Information on U.S. Nuclear Tests in the Pacific," p. 34, Folder 46, Box 12, LRBR.
61. Ibid.
62. Robert Jackson, *Guide to U.S. Atmospheric Nuclear Weapons Effects Data* (Alexandria: Defense Nuclear Agency, 1993).
63. See note 19; Jane Dibblin, *Day of Two Suns: US Nuclear Testing and the Pacific Islanders* (London: Virago, 1988); International Campaign to Abolish Nuclear Weapons, *Banning Nuclear Weapons: A Pacific Islands Perspective* (Duluth: ICAN, 2014), http://www.icanw.org/wp-content/uploads/2014/01/ICAN-PacificReport-FINAL-email.pdf. For environmental histories of the Pacific, see J. R. McNeill, ed., *Environmental History in the Pacific World* (New York: Routledge, 2001); Matt Matsuda, *Pacific Worlds: A History of Seas, Peoples, and Cultures* (Cambridge: Cambridge University Press, 2012); Gregory Cushman, *Guano and the Opening of the Pacific World: A Global Ecological History* (Cambridge: Cambridge University Press, 2013).
64. E. B. White, "Journal of a Contaminated Man," *The New Yorker*, December 4, 1948, 171–77.
65. Golley, *A History of the Ecosystem Concept in Ecology*, 105.
66. E. P. Odum, "Summary," in G. M. Woodwell, ed., *Ecological Effects of Nuclear War* (Upton: Brookhaven National Laboratory, 1965). For Donaldson's views, see Lauren Donaldson, Draft of "Biological Effect of Atomic Warfare," Folder 20, Box 17, Lauren R. Donaldson Papers, University of Washington Special Collections, Seattle, Washington.
67. Rough drafts, Folders 2-7, Box 1, ODUM-E.
68. Ira Chernus, *Eisenhower's Atoms for Peace* (College Station: University of Texas Press, 2002); Jacob Darwin Hamblin, "Exorcising Ghosts in the Age of Automation: United Nations Experts and Atoms for Peace," *Technology and Culture* 47 (2006): 724–56; John Krige, "Atoms for Peace, Scientific Internationalism, and Scientific Intelligence," *Osiris* 21 (2006): 161–81.
69. J. Davis and Richard Foster, "Bioaccumulation of Radioisotopes through Aquatic Food Chains," *Ecology* 39 (1958): 530–35. Eugene Odum's folder on the Geneva conference can be found in Carton 22, Series 1, EPOP.
70. Odum, *Fundamentals of Ecology,* 2nd ed. (Philadelphia: Saunders, 1959), 452–86. Drafts in File 4, Box 13, Series I, EPOP.
71. E. P. Odum to "folks," September 27, 1957, Folder 9, Carton 3, Series III, EPOP.
72. Ibid.
73. See, for example, Eugene Odum and Edward Kuenzler, "Experimental Isolation of Food Chains in an Old-Field Ecosystem with the Use of Phosphorus-32," *Radioecology* 113 (1963): 120; Stanley Auerbach, Jerry Olson, and M. Waller, "Landscape Investigations Using Caesium-137," *Nature* 201 (1964): 761.
74. Robert Watson, *History of the Office of the Secretary of Defense IV: Into the Missile Age, 1956–1960* (Washington, DC: Office of the Secretary of Defense, 1997), 457, Table 6.
75. On fallout and environmental science, see Laura Bruno, "The Bequest of the Nuclear Battlefield: Science, Nature, and the Atom During the First Decade of the Cold War," *Historical Studies in the Physical and Biological Sciences* 33 (2003): 237–60; Masco, "Bad Weather: On Planetary Crisis"; Jessee, *Radiation Ecologies*.
76. Eugene P. Odum, *Fundamentals of Ecology*, 3nd ed. (Philadelphia: Saunders, 1971), 451–67.

77. H. H. Mitchell, *Ecological Problems and Post-War Recuperation: A Preliminary Survey from the Civil Defense Viewpoint*, RM-2801 (Santa Monica: The RAND Corporation, 1962).
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88. Valerie Kuletz, *The Tainted Desert: Environmental and Social Ruin in the American West* (New York: Routledge, 1998); Joe Masco, *The Nuclear Borderlands: The Manhattan Project in Post-Cold War New Mexico* (Princeton: Princeton University Press, 2006): 311–15.
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