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Editorial

Chatlogs

A Repair Manual for Spaceship Earth

by Alyssa Battistoni

A failed experiment in the Arizona desert holds valuable lessons for earthly survival.

On September 26, 1991, surrounded by the cameras of the world media, eight people dressed in bright red jumpsuits sealed themselves inside a three-acre steel-and-glass dome in the Arizona desert filled with over three thousand species of animals and plants. They planned to remain inside for two full years, aiming to show that the structure—known as Biosphere 2—was capable of sustaining life while completely sealed off from Biosphere 1, also known as Earth.

Amidst Biosphere 2's seven biomes—desert, rainforest, savannah, marsh, ocean, city, farm—the Biospherians would grow their own food and conduct research on the workings of the closed system. They would rely on the plants and animals they lived alongside to produce oxygen, absorb carbon dioxide, fertilize the soil, and consume waste. Lessons from the experiment were expected to advance the prospects of human life in space and on other planets.

Biosphere 2 may seem to be little more than a bizarre episode in the annals of extravagant scientific undertakings. But we should take its history seriously as we think about the future of life on Biosphere 1, which today appears fairly dire.

In the summer of 2019, Greenland's ice sheet lost nearly 200 billion tons of ice—three times the regular amount—while peat fires blazed across the Arctic. Two hundred reindeer starved to death in Norway while nearly two hundred gray whales have washed up dead on the western shores of North America since January. And that's just in the past year in one part of the world. The UN warns that a million more species are threatened with extinction in the next few decades as a result not only of climate change but overfishing, deforestation, and unsustainable agricultural patterns.

You can understand why someone might want to build another world.

> *"Is there a substitute for the work of nature—the work on which all other work depends?"*

Everything You Can Do, I Can Do Better

These incidents suggest that the ecological systems we usually take for granted—sometimes referred to as Earth's "life-support systems"—are starting to break down. Healthy ecosystems are generally self-renewing. They operate without humans having to do much. They are, in a sense, already automated, at least from our perspective. But climate change and other ecological pressures are interrupting their normal function.

Climate change has caused more rain in the Arctic, which then freezes into ice, making it hard for reindeer and herbivores to find food. Melting Arctic sea ice, meanwhile, may have reduced the amount of algae in Arctic seas, which feeds the amphipods that feed the whales. The prospect of further disruption raises a question: Is there something we could do to fill in the gaps? Is there a substitute for the work of nature—the work on which all other work depends?

The fear that we're running down nature's abundance has a long history, of course. For economics—which is, after all, the study of scarcity—it's nothing to worry about. Conventional economic theory holds that natural resource scarcity can be solved through substitution. When resources become scarce, they become more expensive, which leads people to use them more efficiently or to use other, more plentiful materials in their stead.

As the growth economist Robert Solow once quipped, "The world has been exhausting its exhaustible resources since the first cave-man chipped a flint." In the eighteenth century, Thomas Malthus had worried about the ability to produce enough food; in the nineteenth, William Jevons had worried that the world would run out of coal. But new techniques, technologies, and resources overcame existing limits: petroleum replaced whale oil; steam engines replaced horses.

In the twentieth century, our capacity to create substitutes grew immensely. Many synthetic products were invented to take the place of natural ones. Declining soil nutrients could be replaced with artificial fertilizer; aluminum could replace copper; plastic could replace just about everything—wood, stone, metal, glass.

Nuclear power appeared poised to offer cheap, near-limitless energy supplies in place of fossil fuels extracted from the earth.

These advances gave rise to a way of thinking that we might call "substitution optimism": the belief that humans can find substitutes for anything that nature does. But substitution optimists tend to neglect two problems. First, the development of substitutes assumes that the price of scarce goods will rise. What about scarce goods that don't have a price? In particular, what about the services freely provided by nature? The services of atmospheric cycles and pollution-absorbing forests cost nothing—which mean that as they grow scarcer they do not get more expensive, and do not spur the development of technological replacements. Today, those resources—what we might think of as the earth's *reproductive* rather than productive functions—are the ones most under threat. Like human reproductive work, they operate in the background of economic production, providing the basic functions necessary for life.

But it's also an open question as to whether those kinds of resources actually have substitutes. Plastic chairs can substitute for wooden ones, or plastic bags for paper—but can you build a substitute for an entire forest? Can human technologies or human labor substitute for the nonhuman work done by other organisms? Or are there certain kinds of work that only nature can do?

Today's substitution optimists remain bullish. A group called the Ecomodernists, whose members include famed cultural entrepreneur Stewart Brand, geoengineering researcher David Keith, and Breakthrough Institute founders Ted Nordhaus and Michael Shellenberger, has taken up Brand's famous injunction from the *Whole Earth Catalog*: "We are as gods and might as well get good at it." Despite the signs of destruction all around, they assure us that human powers can yet be channeled to produce a “good Anthropocene.”

In their view, resource scarcity isn’t a problem: the Ecomodernist Manifesto of 2015 declares that “substitutes for other material inputs to human well-being can easily be found if those inputs become scarce or expensive.” There are no real limits to growth: the sun provides more energy than we can hope to use, and any other given physical resource can be replaced with something else. That implicitly includes nature’s reproductive functions. Carbon capture-and-storage technologies can replace a forest’s capacity to absorb carbon. Injecting aerosols into the sky to make clouds more reflective mimics volcanic eruptions that spew sulfur into the atmosphere, helping to cool the earth.

> *“Plastic chairs can substitute for wooden ones, or plastic bags for paper — but can you build a substitute for an entire forest?”*

If Ecomodernists represent one extreme, the other end of the spectrum is occupied by those who spurn any kind of substitution. “Deep ecologists” see all of nature as intrinsically valuable: it’s simply impossible to substitute for the unique and irreplaceable value of any given organism. For other ecologically minded thinkers, including proponents of “degrowth,” the prospect of substituting technology for complex natural processes that we don’t even fully understand is a typical demonstration of human arrogance, one that’s certain to result in unintended consequences. In this view, technology is synonymous with the “techno-fix,” a futile attempt to avoid deeper social and economic change through innovation.

Neither of these positions is satisfying. It’s true that the Ecomodernists are wildly optimistic about human capacities and willfully obtuse about their limits. But it’s not enough to smugly tut-tut at human hubris while the planet burns. Given how quickly the effects of climate change are materializing, even drastic decarbonization is unlikely to stop more mass die-offs and other forms of ecosystem dysfunction. We should hope that at least some ecosystem activities have substitutes, even if they can’t be perfect ones.

> *“The question posed by Biosphere 2 was whether the entire Earth was substitutable”*

In her 1970 book *The Dialectic of Sex*, best known for advocating artificial wombs as a substitute for biological ones, the feminist thinker Shulamith Firestone also called for a revolutionary ecological program. Such a program should seek to seize “control of the new technology for human purposes, the establishment of a new equilibrium between man and the artificial environment he is creating, to replace the destroyed ‘natural’ balance,” she wrote.

Firestone, to be sure, had too much confidence in the possibility of liberation through technology, and too much fondness for the project of dominating nature. We have yet to automate human reproduction, and we’re similarly unlikely to exert total technological control over Earth’s reproductive functions. But we should nevertheless take seriously Firestone’s impulse to see technology as part of the project of making a liberatory and livable planet rather than aiming for an impossible return to a natural balance that's everywhere in shambles and that in any case was never so harmonious as we imagine. We don't have to build the equivalent of an artificial womb for the entire Earth. But we should think about how to use our technologies for purposes both human and nonhuman, in a world where nature and human artifice are now so thoroughly entangled as to be inseparable.

The story of Biosphere 2 offers a way of thinking through what that might look like—both its possibilities and limitations.

The Garden and the Aircraft Carrier

The question posed by Biosphere 2 was whether the entire Earth was substitutable. The biosphere, a concept first developed by the Soviet scientist Vladimir Vernadsky, refers to the thin layer of the planet capable of supporting life. Biosphere 2 sought to replicate those life-support systems. The countercultural figure behind it, John Allen—an eccentric visionary with a degree in engineering, an MBA from Harvard Business School, and an enthusiasm for theater, poetry, and alternative living—saw the project as simultaneously an experiment with utopia and a backstop against dystopia.

"We poise ready now [sic] not only to cooperate consciously and creatively with the evolutionary potential of our present biosphere," he proclaimed, "but also to assist in its mitosis into other biospheres freeing our earth-life to participate in the full destiny of the cosmos itself, both by giving the possibility to voyage and live throughout space." Biosphere 2 would help bring about a new age of space exploration, Allen believed, by developing a way to sustain human life in hostile environments. It would also help protect human life against looming existential threats on Earth: Biosphere 2 would be a prototype of what Allen called "Refugia," self-contained living spaces that could serve as "insurance" against the calamity of a nuclear winter.

Before Biosphere 2, Allen had managed an intentional community outside of Santa Fe organized along ecological principles. There he met Edward Bass, an eccentric child of the Bass oil dynasty who got into ecology in the 1970s. By the 1990s, Bass was the largest private sponsor of environmental research in the United States. He funded an Institute for Biospheric Studies at Yale and smaller research projects around the world. He also poured an estimated $150 million into Biosphere 2 through his company Space Biosphere Ventures.

Bass saw these contributions as investments in projects that would one day become profitable: in the early days of the biotech boom in the 1990s, it seemed eminently plausible that "ecotech" would take off too. The initial income from Biosphere 2 was to come from tourism—they charged people $12.95 to visit, and half a million people did—which would support the longer-term development of technologies that Bass expected "would have a very significant commercial application."

Biosphere 2 was, as one of its inhabitants called it, "the garden of Eden on top of an aircraft carrier." Underneath the rainforest and desert landscapes was a massive technosphere, comprising three acres of electrical, mechanical, and plumbing systems. The technology was intended, as a Biospherian put it, "to replicate many of Earth's free services"—the reproductive functions. On Earth, various planetary processes keep air and water moving, and nutrients and waste along with them. In Biosphere 2, that work was mechanized.

Some machines treated wastewater and desalinated water from the miniature ocean to make rain. Others created breezes, mists, and ocean waves. Giant air handlers heated and cooled the air, running off generators powered by natural gas and diesel. To prevent the domes from exploding as the air inside warmed and expanded in the heat of the desert sun, a giant pair of rubber "lungs" acted as a safety valve.

These innovations drew on two decades of research on how to keep humans alive in space, most notably a proposal by the twentieth-century ecologists Eugene and Howard Odum to build "bioregenerative life support systems" in spacecraft. Most spaceships were all technosphere: everything humans needed to survive was provided by a machine. The Odums' idea was to replace some of those technological functions with organisms that could perform the necessary functions of oxygen generation, waste removal, and food production. Bioregenerative systems would bring down the cost of space travel, reduce the need for astronauts' labor, and make it possible for astronauts to live longer in space without continually receiving supplies from Earth.

Biosphere 2 would be the most ambitious embodiment of these ideas to date. When it opened, it was heralded by many in the press as a marvel of both technological and ecological engineering—*Discover* magazine called it "the most exciting scientific project" since the moonshot—even as many scientists looked on skeptically. The crew that entered Biosphere 2 in 1991 was to be the first of many: Allen imagined that new crews would enter every two years for an entire century, each building on the knowledge of those who had gone before. Cumulatively, they would inaugurate a new era in the understanding of life on Earth—and the possibilities of life beyond.

The Bubble Bursts

Things didn't go as planned. If the technology of the "aircraft carrier" was cutting-edge, what lay above wasn't exactly the garden of Eden. Once the Biospherians were sealed inside, everything began to go drastically wrong. Though they had attempted to carefully calibrate the equilibrium of the internal ecosystem, an artificial balance was hard to strike.

Cramming seven biomes into just three acres led to some unexpected effects: the desert picked up condensation from the forest and became more like a shrubland. Nor had Biosphere 2 managed to replicate all of Earth's services: many trees in the rainforest and the savannah that would usually grow "tension wood" in response to winds failed to do so in the calm Biosphere, leaving them weaker. Most troublingly, the Biosphere began to lose a huge amount of oxygen, while carbon dioxide and nitrous oxide levels rose dangerously. The Biospherians tried to sequester carbon by growing plants, and stopped tilling the soil to prevent carbon stored in the soil from being released into the air. But they couldn't figure out how to actually stop carbon from accumulating.

It turned out that microbes in the soil were producing carbon dioxide faster than plants were producing oxygen, while the structure's concrete foundations were absorbing a surprising amount of oxygen. Some speculated that the El Niño event of 1991–1992 also contributed to more cloud cover than usual, decreasing the amount of sunlight for plants to photosynthesize. Some of the vines that the Biospherians had planted to absorb carbon started to overtake food crops, requiring intensive weeding. Algae consumed the ocean, requiring Biospherians to clear it away by hand so the coral reefs below could receive sunlight.

The complications multiplied. An estimated 30 percent of the 3,800 enclosed species died off, including all pollinators. The Biosphere was overrun by ants and cockroaches, stowaways inside the sealed system that soon outcompeted and outlasted other insects. By the time oxygen levels had dropped from 20.9 percent to 14.2 percent—the equivalent of living at an elevation of 15,000 feet—it became difficult to breathe, at which point the Biospherians broke the closed system to pump in oxygen and keep the crew alive.

> *"Once the Biospherians were sealed inside, everything began to go drastically wrong."*

The first crew left Biosphere 2 in September 1993, on schedule and underweight. The second crew of eight entered in March 1994. But by then Biosphere 2 was looking more like a boondoggle than a breakthrough: it cost a great deal to maintain, and seemed unlikely to develop a commercially viable product anytime soon. Bass began feuding with Allen and then fired most of the Biosphere 2 staff while the second crew was still inside. He hired Steve Bannon, at the time an investment banker experienced with company takeovers, to manage Space Biosphere Ventures's financial affairs. Amidst the turmoil, the second crew left the structure six months later. They would be the last people ever to live inside Biosphere 2.

Bannon brokered a deal with Columbia University, which agreed to take the facility over. (Columbia eventually gave it up, citing exorbitant expenses; in 2005, Bass gifted Biosphere 2 to the University of Arizona, which now runs it as a research facility.) Space Biosphere Ventures ended up facing multiple lawsuits. Though the irresistible spectacle of Biosphere 2 had made it a media darling at the outset, as the project faltered it was decried as a stunt, a hoax, a fraud. *The Village Voice* described Biosphere

2 as the product of "an authoritarian—and decidedly non-scientific—personality cult." The fact that the closed system had been breached to restore oxygen levels rendered the scientific value of the grand experiment dubious. Academic scientists, vindicated by the downfall of a flashy for-profit interloper, set about diagnosing the causes of the disaster.

The most obvious lesson was that replicating the reproductive functions of Earth was much more complicated than anyone had imagined. As a pair of Columbia researchers wrote in an assessment shortly after Columbia took over the facility, "isolating small pieces of large biomes and juxtaposing them in an artificial enclosure changed their functioning and interactions rather than creating a small working Earth as originally intended."

> *"If we're going to do more than mourn or panic, we have to take the idea of substitution seriously."*

You could not simply treat ecosystems as mechanical pieces to be assembled and slotted in and out. Ecologists didn't even know what all the pieces of an ecosystem were, let alone how exactly they worked together. "At present there is no demonstrated alternative to maintaining the viability of Earth," they concluded. "No one yet knows how to engineer systems that provide humans with the life-supporting services that natural ecosystems provide for free." Ecosystems did not appear to be very substitutable at all.

Jury-rigging Spaceship Earth

The story of Biosphere 2 seems to prove the substitution skeptics right: we can't replace ecosystems and we shouldn't try. But I can't muster much schadenfreude about the failures of Biosphere 2. After all, the misfortunes of the Biospherians look worrisomely like our own.

Even if we manage to stop climate change from reaching truly cataclysmic levels, rising temperatures will transform Earth's systems in ways that will make it difficult for many species to survive. Under the circumstances, pious affirmations of ecological holism can quickly tilt into premonitions of doom: if ecosystems are beyond human understanding and entirely irreplaceable, collapse is only a matter of time.

The biologists Paul and Anne Ehrlich once compared species to rivets on an airplane wing. If you were in a plane and looked out the window and saw a rivet fall off the wing, you might be a little concerned but not too worried—after all, the wing has thousands of rivets, enough to make any single one redundant. But if lots of rivets started popping off, you would probably start to freak out. Similarly, losing a species or two might be worrisome but not a sign of doomsday. Losing a lot of species, however, suggests that Spaceship Earth might be in trouble.

We are going to lose more rivets. I hope we can jury-rig something to keep the plane in the air. Our lack of control over the biosphere is genuinely terrifying. But if we're going to do more than mourn or panic, we have to take the idea of substitution seriously.

Instead of treating substitution as the frictionless replacement of one kind of thing for another, as if matter were totally commensurable, however, we could recognize that substitutes might be rough around the edges but can nevertheless help prevent total breakdown. In some cases, substitution might mean using one kind of organism in place of another; in others, it might mean substituting human labor or technology for the work of nature.

The idea that one species could do the same work as another was one of Charles Darwin's great insights. As the environmental historian Donald Worster relates, when Darwin went to the Galápagos, he noticed that giant tortoises did the grazing work that bison did in North America. Different creatures, that is, held "the same place in Nature"; they could fill the same "office" within an ecosystem—what ecologists would eventually come to call a niche. Different organisms would do the job differently, of course: a tortoise would have different predators and reproduction patterns than a bison, even if they both grazed. But ecosystems weren't fixed, timeless orders wherein each organism performed its appointed role for eternity. They were struggles to stay ahead of the competition or be replaced by something else.

This principle animated the selection of species in Biosphere 2. The thousands of species sealed in the dome were chosen not to faithfully replicate the exact relationships of existing ecosystems, but to provide particular functions: to serve as pollinators, to supply food crops, to recycle air, to decompose waste. If a particular species didn't fit the practical needs of the Biosphere, it was replaced with another.

Of course, human efforts to achieve particular ends by introducing new species don't always go well. The genre of stories about "invasive species" is one of the most reliable sources of cautionary tales about unintended consequences of human meddling in nature. The East Asian vine kudzu, for example, was widely planted in Southern states to help address soil erosion in the aftermath of the Dust Bowl; it became the weed that ate the South.

But not every story of introduced species is a warning. Rewilding projects, for example, attempt to restore land domesticated and cultivated by humans into ecosystems operating without human presence. This usually means reintroducing species that have been driven out of their former habitats or killed off by human settlement. In some cases, species have gone fully extinct, yet some other kind of creature may be able to do the same work.

In the rewilded nature reserve of Oostvaardersplassen in the Netherlands, for example, the roles of extinct aurochs and tarpans—wild ponies and cattle—are filled by physiologically similar breeds that eat the same grasses and have similar roaming patterns. In the American Great Plains, meanwhile, sustainable cattle raising practices have tried to replicate the grazing patterns of bison. Since cattle tend to roam less extensively, doing so requires more intensive human labor to direct herds.

This raises an important point: natural systems that now operate automatically may require *more* human labor to function as nonhuman species disappear. Life in Biosphere 2 was a lot of work. As one participant later recalled, “Farming took up 25 percent of our waking time, research and maintenance 20 percent, writing reports 19 percent, cooking 12 percent, biome management 11 percent, animal husbandry 9 percent.” As Biosphere 2’s nonhuman life support systems started to falter, its human inhabitants had to work harder to keep them functioning, from chasing pests that had no predators to pollinating plants when the bees died off. As scientists observed in the aftermath, “Biospherians, despite annual energy inputs costing about $1 million, had to make enormous, often heroic, personal efforts to maintain ecosystem services that most people take for granted."

Of course, Biosphere 2 didn't just rely on human labor to help nature function. Its vast technosphere was built expressly to fill in for Earth systems like ocean currents and water cycles. Biosphere 1 now has a rather substantial technosphere of its own, currently constituting 30 trillion tons of human artifacts, from computers to undersea cables to houses to lightbulbs. Most of it supports human life and pursuits. But some of it could also be put to use tending to the biosphere, as in Biosphere 2.

The garden of Eden and the aircraft carrier aren't our only options. Most of our world is some combination of the two. Using technology to support ecological functions doesn't have to involve building a giant array of machinery to replace Earth systems or trying to technologically manipulate the entire atmosphere, a la the Ecomodernists. But nor should it mean attempting to remove human activity and artifacts from ecosystems altogether. As Donna Haraway reminds us, "There is no Eden under glass." Technology can play an important role in actively maintaining ecosystems rather than replacing them wholesale, in conjunction with human labor.

Some of this work is already happening. Drones are being used to reseed land for restorative purposes, effectively performing the work of birds while reducing human presence in remote areas. In the Great Barrier Reef, a robotic vessel protects indigenous coral species by killing the crown-of-thorns starfish that is suffocating the reef.

Paradoxically, these unmistakably human interventions often occur in the absence of actual humans. Robots can offer ways to preserve nonhuman ecosystems without more direct forms of human intrusion. They aren't total replacements for organisms, of course. A drone can drop seeds but can't lay eggs; a robot fish can kill starfish but can't grow new coral. Indeed, none of the options available to us—nonhuman proxies, technological tools, human labor—is a perfect substitute for what they replace, and none ever will be. At best, they can provide rough approximations of certain functions. But these jury-rigged rivets might be our best hope for making a future on a damaged planet.

> *"The garden of Eden and the aircraft carrier aren't our only options. Most of our world is some combination of the two."*

How Are You Going to Pay for It?

Nature, Raymond Williams once said, is the most complex word in the English language. But I've come to think that "natural" mostly means "freely given." Nature offers the "free services" on which human life depends. More generally, nature describes what we take for granted, what we expect to happen of its own accord. From "natural birth" to "natural beauty," nature hides a lot of work done behind the scenes. As the scholar Merve Emre reminds us, "all reproduction, even reproduction that appears 'natural,' is assisted." Emre is concerned with human reproduction, but it holds just as true for the reproduction of nature itself.

We can no longer take the reproduction of our world for granted, or assume that the work of nature will take place automatically. Reproducing life on Earth will require a great deal more assistance from us, in our simultaneously extraordinary and limited capacities as a single species on a planet of millions. It will also require a great deal more recognition of the assistance provided by all those other species. What the feminist theorist Sophie Lewis calls "full surrogacy"—a call to distribute labor more broadly, to cultivate reciprocal practices of kinship and care—is as applicable to our nonhuman relationships as to our human ones.

While we may be able to perform some work on nature's behalf in order to stabilize our biosphere, however, the expense will be enormous. Indeed, the biggest barrier to developing substitutes for certain ecological services may turn out to be cost.

The ecologist John Avise observed that the true lesson of Biosphere 2 was an economic one. In the late twentieth century, economists had tried to estimate the value of Earth's freely provided services, but had usually stumbled over the technical difficulties of doing so. Biosphere 2 made it possible to construct "a more explicit ledger," Avise wrote. All told, it had cost over $150 million to keep eight humans alive for two years. As Avise pointed out, "if we were being charged, the total invoice for all Earthospherians would come to an astronomical three quintillion dollars for the current generation alone!" Replacing human labor with machines usually saves money. Replacing the work of nature with machines or human labor is the opposite: it makes what was free expensive.

This means that substitution is rarely economical. In China's Hanyuan County, for example, where pesticides have wiped out many bee colonies, human workers have subbed in, using feather dusters to pollinate pear trees by hand. But human pollination is only viable in Hanyuan because it's cheaper than renting beehives. In a system (capitalism) that aims to keep costs down above all else, the cost of human labor has to be approaching zero for it to compete with nature's gifts.

So as we ask who, or what, will do the work of nature, we should also ask another question: Who will pay for it? Earthly survival will require new ways of organizing not only our social and technological relationships, but our economic ones. As Biosphere 2 demonstrates, filling in for the work of nature is unlikely to be a profitable enterprise. Capitalism is unlikely to pay the extra costs. The question of what can replace it may be the biggest substitution problem of all.

Alyssa Battistoni is a political theorist and postdoctoral fellow at Harvard University. She is the coauthor of *A Planet to Win: Why We Need a Green New Deal*.

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the official doge of Logic.

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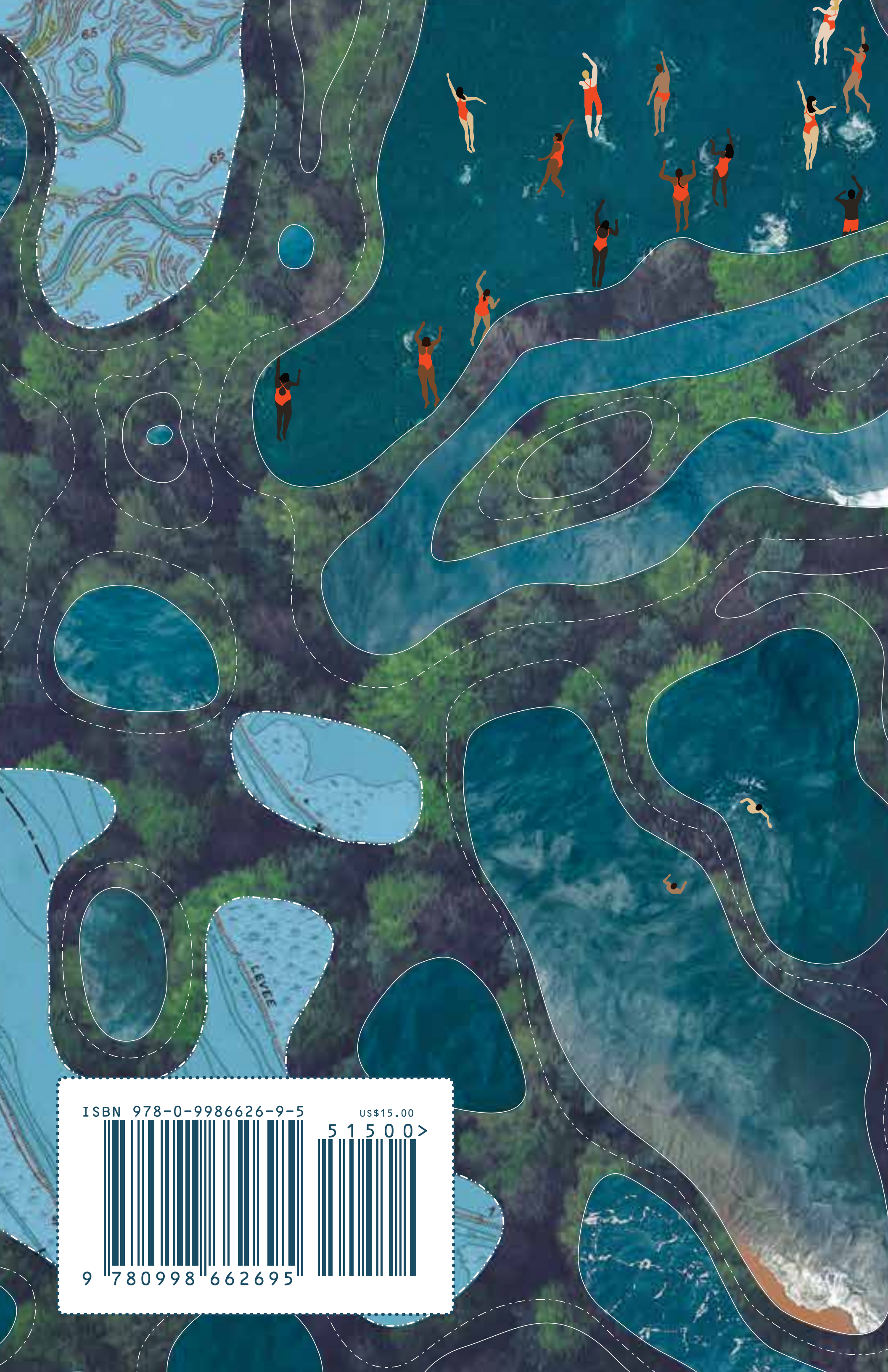

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