Tuning Into The Planet: Scientists are collecting and archiving soundscapes before they disappear

by

Elizabeth Gamillo
B.S. in Biology and Creative Writing
Alverno College, 2018

Submitted to the Program in Comparative Media Studies/Writing in Partial Fulfillment of the Requirements for the degree of

MASTER OF SCIENCE IN SCIENCE WRITING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2023

Authored by: Elizabeth Gamillo

Certified by: M. R. O'Connor
Thesis Supervisor

Accepted by: Seth Mnookin
Director, Graduate Program in Science Writing

Acknowledgments

This thesis would not have been possible without the continued support of many people back home in Milwaukee, those I have met over the years in my budding professional career, and those in Cambridge during my time at MIT.

A huge thank you to all my sources who took time out of their day to explain their research to me and for their patience in answering my questions. Your work is the future.

Thank you, Seth Mnookin and the GPSW for giving me the opportunity of a lifetime to study science writing and the support to sharpen my skills. I am honored to have been part of this program. Thank you, Shannon Larkin for always having your door open to me and for your endless supply of chocolate in your office and thank you, Chris Couch for your guidance and reassurance when it got tough.

Thank you to my thesis advisor, M.R. O'Connor, for your support, encouragement, and thoughtful guidance in helping me get through the first drafts!

Thank you, Veronique Greenwood for inspiring me during our writing workshops.

Thank you, Justin LaManna and Amal El-Sheikh for your continued support and mentorship. It has been a long road and I appreciate you both for your guidance and for never giving up on me.

Thank you, Carole E. Barrowman for encouraging me to continue honing the craft of writing.

Thank you GPSW colleagues- Abdullahi, Allison, Phie, William, Daelin, and Vishva, for your friendship and for inspiring me with your talents. We did it!

Thank you, Luis for sticking with me through the hard parts of this journey and for believing in me.

My dearest friends, Maria, Selina, Karen, and Sarai, thank you for believing in me.

To my parents, Dora and Hector, and to my brother and sister, Isaiah and Jenny, thank you for supporting me on this journey.

Y a mis abuelos, Maria Estrada Garcia y Rodimiro Garcia, gracias por el apoyo y todos sus esfuerzos en esta vida. ¡Los quiero mucho!

Tuning Into The Planet: Scientists are collecting and archiving soundscapes before they disappear

By

Elizabeth Gamillo

Submitted to the in Comparative Media Studies/Writing on May, 24, 2023 in Partial Fulfillment of the Requirements for the Degree of Requirements for the degree of Master of Science in Science Writing at the Massachusetts Institute of Technology

ABSTRACT
Soundscapes of the world can reveal the status of an ecosystem to an ecologist, much like how a cardiologist can distinguish abnormal heart murmurs with an electrocardiogram. The effort to use the aural landscape to assess the recovery of fragile ecosystems and directly assist in those recoveries is becoming a movement within ecology. The audio recorder has become an increasingly powerful tool at a time when catastrophic heatwaves, wildfires, floods, and extreme weather increase in severity and occurrence. The soul-stirring calls of animals and the mechanical hum or the roar of cars and planes, all engulfed by the swift and rhythmic sounds of wind and water flow, generate a unique score that researchers collect to note unique rhythms and patterns in the cacophony of these landscapes.

Altered soundscapes are often the first detectable changes in an ecosystem facing threats. By strapping recorders onto trees or tripods, scientists can also track how ecosystems change in response to human disruptions, like air traffic and logging, or track biodiversity and shifts brought on by climate change. Collecting and archiving the baseline data of sounds that can be visited and studied, much like preserved specimens in a natural history museum, is crucial before they disappear or change forever. Together, these scientists are creating a record for the future. It's the sound of this moment, frozen forever as audio files. And they hope that someone can use it to travel back to the world as it was in this instant—and help preserve the ecosystems they love.

Thesis supervisor: M.R. O'Connor
Title: Thesis advisor

A haunting chorus of whistling announces dawn's break. Tiny trills chime in, calling to each other until the sound echoes through the forest. The caroling stops, and then quick squeaks break the quiet woods. In the distance, a kookaburra's shocking hooting call bursts like a wind instrument. Listen. Listen to the chattering birds. Listen to the landscape before it disappears.

This morning chorus, captured near Canberra, fell silent during the Black Summer, Australia's worst wildfire season on record. Between September 2019 and March 2020, the country experienced record-breaking temperatures, an extended drought, and fierce winds. These conditions created fires that rolled through 18.6 million hectares and singed southern Australian forests, woodlands, heathlands, grasslands, and farmlands.

In the aftermath, wallabies foraged in burnt forests, with black toothpick-like trees extending high above the ashen ground. It is estimated that regions impacted by the blazes were home to more than 800 native species. Seventy species had more than 30 percent of their habitat obliterated. Out of the 70 species, 21 were already threatened with extinction.

"You can still see where the fire has been. It's quite incredible, the scale of those bushfires, and you can still drive through areas now," said Elizabeth Znidersic, an ecologist and ornithologist at Charles Sturt University, Albury Wodonga. The university, situated between the borders New South Wales and Victoria in Australia, is where part of the fires occurred. "Literally, it'll take your breath away," she said of the destruction. Yet, Znidersic is now working towards restoring this lost land with a surprising tool: an audio recorder.

Znidersic realized the potential of using recorders to locate bird species while spying on elusive marshland birds as part of her research. "I found that technological approaches are the best way to actually detect secretive bird species such as rails, creeks, and bitterns," she said. "One of the methods that I was using was acoustic monitoring." In 2017, using a combination of acoustic monitoring and camera traps, Znidersic captured a rare and unusual purple gallinule on the Oak Ridge National Laboratory's reservation in Tennessee. The sighting was the first time it was spotted on the reservation, that had been thoroughly surveyed continuously for seven decades. The vibrant bird, known for its wandering, is native to South and Central America. Before that, Znidersic was using acoustics to track and monitor bird species without disrupting them and their environment in South Carolina and in Australia. After working on these types of projects for most of her career, it dawned on Znidersic that the recordings could be used for tracking, modifying, or restoring damaged ecosystems over time.

In a recent paper published in *Ecology Letters*, Znidersic and her colleague David Watson hypothesized that if the sounds of a thriving soundscape play in areas disturbed by wildfires, or other environmental and anthropogenic disturbances, scientists could lure animals back. Naming the new approach 'acoustic restoration,' Znidersic plans on broadcasting healthy and thriving soundscapes to encourage animals to recolonize these habitats. It's not as far-fetched as it sounds: Other researchers used the soundscapes of snapping shrimp to lure oysters back to degraded areas. In another study that illuminates the potential of sound as a conservation tool, researchers found that playing the aural bubbling and crackling drawl of a healthy coral reef increased fish settlement in degraded reef areas and grew the reef's species richness by 50 percent. Using audio recorders and machine learning algorithms to recognize what is heard in a far-off ecosystem, scientists could potentially preserve landscapes or even bring one back from the brink.

In a pilot study to explore the approach, Znidersic plans to place recorders in the area burned by the fires to listen in on how well the restoration works. Are animals inhabiting the area? Is it becoming noisier with bird songs or insects? Recorded sounds could also be used as archival data, where ecologists' decades from now can go back in time and compare if restorations were successful, if wildlife is thriving, or if an area has completely changed.

Soundscapes of the world can reveal the status of an ecosystem to an ecologist, much like how a cardiologist can distinguish abnormal heart murmurs with an electrocardiogram. The effort to use the aural landscape to assess the recovery of fragile ecosystems and directly assist in those recoveries is becoming a movement within ecology. The audio recorder has become an increasingly powerful tool at a time when catastrophic heatwaves, wildfires, floods, and extreme weather increase in severity and occurrence.

The soul-stirring calls of animals and the mechanical hum or the roar of cars and planes, all engulfed by the swift and rhythmic sounds of wind and water flow, generate a unique score that researchers collect to note unique rhythms and patterns in the cacophony of these landscapes.

Altered soundscapes are often the first detectable changes in an ecosystem facing threats. By strapping recorders onto trees or tripods, scientists can also track how ecosystems change in response to human disruptions, like air traffic and logging, or track biodiversity and shifts brought on by climate change. Collecting and archiving the baseline data of sounds that can be visited and studied, much like preserved specimens in a natural history museum, is crucial before they disappear or change forever.

Together, these scientists are creating a record for the future. It's the sound of this moment, frozen forever as audio files. And they hope that someone can use it to travel back to the world as it was in this instant—and help preserve the ecosystems they love.

In the 18th and 19th centuries, naturalists such as Charles Darwin and Alexander Von Humboldt voyaged around the world to collect observational data about the natural world with notebooks and writing utensils. In the 21st century, scientists are doing the same thing, but unlike those historical figures who largely ignored aural landscapes, they are focused on nature's melodies. While current-day scientists have been interested in collecting the sounds of the natural world for years, the capacity to do so arrived in the last decade. Current recorders, built to withstand the elements for years and transmit hourly data wirelessly, made it possible for scientists to preserve and archive sound.

At the University of Wisconsin-Madison's Sound Forest Lab, I sat in front of a computer screen on which a spectrogram, or picture of sound stretched across. "So, what can you hear?" says Zuzana Buřivalová, an ecologist and the lab's principal investigator as she shows me the images and plays the sound recordings. I looked at the picture of sound, a series of tight scribbles and waves running across the screen. Each sound overlaid on top of the other looked different. Some had higher peaks; some looked like swoops and whips of quick sound. Some were long, consistent waves. As the recording played, a chorus of hooting mammals and chirping birds calling out in a tropical forest in Indonesia filled the room like a symphonic arrangement. As the forest's music played, the morning's cacophony of birds transitioned into a mid-day burst of sound. Buřivalová started another recording of the day fading from dusk to night, and the insects and soft rhythmic rattle of cicadas took over the spectrogram. In healthy forests teeming with biodiversity, Buřivalová can see patterns commonly found across the globe, called the dawn and dusk peaks, along the spectrogram. These peaks show bird and insect activity, and by analyzing a soundscape's saturation in forests that have been disturbed, changes in species abundance can be spotted within 24 hours.

Spectrograms allow researchers to see sound frequencies and how long they last. The rising and falling of peaks along the pictures of sound can reveal the biodiversity found in forests. Buřivalová, with short blonde hair and bright blue eyes, is working towards using soundscapes to understand how the aural quality of forests changes as they are disturbed or logged. Using soundscape recordings obtained in 2016 from the Borneo rainforest with The Nature Conservancy, for instance, Buřivalová found that varying land-use changes within tropical forests affect species richness and compositions.

In protected forests, selectively logged and certified for sustainability, bird and insect sounds had two distinct peaks on the dawn and dusk chorus spectrograms. These peaks were smaller in selectively logged areas that were not certified for sustainability. In areas transformed into plantations, with little to no plant diversity, these peaks were almost absent, apart from some bird song early in the morning. Protected areas had lower bird and insect soundscape saturation during the night compared to the daytime. In selectively logged places, bird soundscape saturation was the same, but insect soundscapes were higher at night. The data Buřivalová and her team collected suggests that their soundscapes change as forests face disturbance and land use increases. The 24-hour sound cycle each bird community follows changes once forests are altered.

In disturbed forests, insect soundscapes are more apparent at night. Some birds are heard, too, but much less. And not only this but areas that were protected and undisturbed had more synchronized soundscapes than disturbed places, which may be attributed to human activity altering the acoustic habitat. "We're looking at…improving next big strategies that people use to protect biodiversity. And then the other focus area is looking at how we can improve the monitoring of biodiversity," Buřivalová says.

Other studies using acoustic monitoring have tracked how disturbance is noted through sound. For example, in a study published in *Ecological Indicators* using soundscape data, researchers tracked the six months before and four months after Hurricane Maria's landfall in 2017. They found that the storm negatively impacted forests more than coral reefs. Two of the three morning insect choruses and bird vocalizations declined by 50 percent in the weeks following the hurricane.

In a room across the hall from Buřivalová's office, brown shipping boxes are piled high in the right-hand corner of the bright lab space. Around the room, computer monitors sit next to bookshelves holding plants in decorated tin cans. Each shipping box is part of Sound Forest Lab's next project, collecting soundscape baselines of pristine areas in Gabon in West-Central Africa, Ecuador, and at the Manu Biological Station in Peru, with the hope that the data reveals how much biodiversity exists in these places. "[We are] measuring the biodiversity getting an indicator of that pristine areas, and kind of using it like an archive, and open to compare later on," Grace Ingram, Sound Forest Lab's research intern, explains. Ingram zips across the room, unpacking one of the sound recorders from the boxes. She opens it up and shows compartments where various batteries and SD cards fit. Next, she shows the camera traps that will take photos so the lab can compare the sounds with visual data.

Each package contains a sizeable boxy recorder designed to capture the sounds of natural forests, data sheets, a hard drive, camera traps to photograph the area, and spare parts. Sometimes the sound recorders are munched on by forest critters, or the microphones are chewed away, so extra parts are always needed. Collaborators with Sound Forest Lab in these areas will strap the recorders to trees, set up the camera traps to compare aural data with visual data in designated ecosystems, and tend to them as they collect data for one year. The data is also shared with researchers and locals in these areas.

Continuous monitoring can reveal patterns of sound saturation and the time of day or time of year animals are most active. It can also provide crucial data researchers need to compare a restoration before or after extreme weather events like fire and flooding. These recordings provide a baseline for researchers to know what used to exist when change comes.

Aldo Leopold, a wildlife ecologist and conservationist, followed a similar impulse to capture sound when he wrote down the soundscape of his rural shack in Baraboo, Wisconsin. In the 1940s Leopold would rise before dawn, sit on his bench outside with a pot of coffee and take detailed notes of the soundscape engulfing his rural shack. The notes included light intensity, which species of birds would begin to sing, the time, and where along the property the birds were when they started their pre-dawn chorus. In his notes from May 10th, 1941, Leopold listed the time and bird species breaking the hushed morning. At 4:00 am, a house wren's harsh rattle breaks the dawn's silence, followed by a wood thrush's flute-like notes. At 4:05 am, Leopold heard the American Robin's familiar tweets. Chorusing red wing blackbirds, field sparrows, pheasants, chipping sparrows, cowbirds, chickadees, and crows began their songs, and by 4:30 am, all within earshot of Leopold and his notebook.

By 1944, Leopold's writings were more detailed, and he included charts with the species of bird heard, timing, temperature, and daylight readings. Leopold also eavesdropped on birds in the evening and noted their sunset songs. Later, a paper using Leopold's notes on how birds' early morning and evening songs were influenced by daylight was published in *The Condor* in 1961, a peer-reviewed journal now known as *Ornithological Applications*.

Leopold didn't have a tape recorder. But, about seventy years later, Dr. Stan Temple, professor emeritus at the University of Wisconsin-Madison and senior fellow of the Aldo Leopold Foundation, brought the pre-dawn chorus to life. Using Leopold's unpublished manuscript, notes, and Cornell University's Macaulay Library, Temple and his team reconstructed Leopold's pre-dawn chorus to life as he heard it all those decades ago. The team used a total of 17 birds to recreate the song.

According to Temple, comparing the soundscape at the shack today with Leopold's writing revealed significant changes. Today, Leopold's shack is encroached upon by human noise, and if you were to rise before dawn and listen for the chorus, the song would be interrupted by noise from a nearby interstate highway and aircraft flying overhead. Different species of birds now inhabit the area around the shack because of changes to the landscape, Temple explained during a talk at the Museum of Wisconsin Art in December 2022.

Interest in noting soundscapes continued after Leopold. Sound was central to the argument of Rachel Carson's *Silent Spring*, published in the 1960s, which brought awareness of how sound is linked to an environment's quality. "It was a spring without voices," Carson wrote of a fictional town in her book she used to foreshadow what may happen when humans don't protect the environment. "On the mornings that had once throbbed with the dawn chorus of robins, catbirds, doves, jays, wrens, and scores of other bird voices, there was now no sound; only silence lay over the fields and woods and marsh."

The idea of collecting soundscapes continued to gain steam when Canadian composer Raymond Murray Schafer published his book *The Soundscape: Our Environment and The Tuning of the World*, which said, "Every natural soundscape has its own unique tones, and often these are so original, constitute sound marks." Schafer, in the 1970s and 1980s, wrote about and recognized ecological properties of soundscapes and used musical terms to describe them. "Every territory on earth will have its own bird symphony, providing a vernacular keynote as characteristic as the language of men who live there."

After Schafer, it became possible to think of recording entire soundscapes rather than collecting the calls of individual birds. In 1987, Bernie L. Krause, a soundscape ecologist who founded Wild Sanctuary, wrote in an essay, "We are beginning to learn that the isolated voice of a songbird cannot give us very much useful information. It is the acoustical fabric into which that song is woven that offers up an elixir of formidable intelligence that enlightens us about ourselves, our past, and the very creatures we have longed to know so well."

Individual recordings did not capture ambient noises or larger contexts about these animals' environments. When animals interact and call out to each other for mating or communication, they do so in a chorusing manner- their sounds interact, alternating and overlapping. Focusing on only one animal in an entire habitat would be like trying to listen to an orchestral arrangement but hearing only the first violins.

Still, the technology needed to catch up to researchers' ambitions. Even as, in the late 2000s, researchers grew interested in biophony, geophony, and anthrophony, or the biological, geophysical, and human-produced sounds each unique ecosystem has, they did not have the equipment needed to capture and handle the data of entire soundscapes. (The one notable exception was underwater soundscape recording, which had begun in the late 1970s, and uses different equipment.)

Laurel Symes, a bioacoustician at the Cornell Lab of Ornithology, recalled how difficult it was to record her surroundings on a trip to Central America in 2009. "We [Symes and her colleagues] were using equipment that was made to record for a few minutes, like vocal recording equipment that you walk around with," Symes says. They wired it to big batteries, used the biggest SD card they could find, and changed it every few hours. Symes and her group captured 19 hours of sound using this process but melted the battery compartment of the equipment in the process. "But the interest in the vision was there," Symes says.

A few years later, sweeping technological change made it possible for only $1000 to buy a recorder that could capture many hours of audio. Now, experts can purchase recorders ranging between $75 and $1200 (depending on the features of entry level and more advanced recorders), making it easier to mount the tool on tree trunks or tripods in remote landscapes for many months at a time. "That's been a game changer," says Symes. Methods of analysis using artificial intelligence to identify patterns have also exploded in recent years.

Recordings of soundscapes help establish baselines and may provide insights for restoration. But they can also have uses that people who captured them may never have imagined. For instance, researchers used motion-picture film to capture sounds of the only known recording of the Ivory-billed woodpecker in 1935. When ornithologists went to look for the bird again in 2004, they were trained using this recording. Researchers have used the original sound to train an algorithm to pick out the sounds most like the woodpecker in data collected by autonomous recording units.

The promise of preserving soundscapes is so great that many researchers are beginning to travel and collect baseline data of more pristine locations before anthropogenic activities alter them. Within the last decade, soundscape ecology crescendoed into an official field in science after Bryan C. Pijanowski, a professor of forestry and natural resources and director of the Discovery Park Center for Global Soundscapes at Purdue University, published a paper in *BioScience* that used the word "Soundscape" to detail a field in ecology in 2011. (Krause is also a co-author of the article.) Before, the term 'soundscape' had been used to describe associations between landscapes and sound. 'Soundscape' was not used in the scientific context of listening to the overall aural landscape.

Pijanowski, a pioneer of soundscape recording, made it his mission to record all thirty-two distinct significant biomes around the planet before they change or, worse, disappear. He and his team have placed recorders on trees in Patagonia and Denali and set up tripods holding recording equipment in Tanzania and the Borneo rainforest. So far, he has captured 28 out of the total 32 soundscape biomes in over six million recordings.

He brims with tales of the places he has recorded: "The Jamba woodlands in Africa, which are dominated by many species of primates, are so complex, especially, and there's this sequence that I call phases and transitions as you listen and you hear one group of animals, and then they stop. And very quickly, a next group of animals begins the chorus, all chorusing, so it's like an evolution. It's like different kinds of movements in a symphony," he says.

Vanishing Soundscapes, Pijanowski's most recent project, involves traveling to the Sundarbans, the largest mangrove forest in the world located within the borders of Bangladesh and India, to collect the forest's musical arrangement. "There are a lot of places in the world where the wild spaces are still pretty much intact. And I want to understand how each of these ecosystems sounds. What is the characteristic soundscape signature? What is the fingerprint of these? And then how do they change as humans change these places," Pijanowski says.

As Pijanowski races to grasslands in the Eastern steppes of Mongolia and other remote locations around the globe, he preserves each recording. "We don't know if [these places] are going to be completely lost, or if they're going to be slightly modified, or maybe even replaced," said Pijanowski. "So the big question is, what's going to happen to them? You have climate change that's going to alter every square meter of this planet. How is it going to affect the soundscape?"

Hidden in the reeds of wetlands skimming the forest's edge, the endangered and cryptic bittern, a heavy-set heron, lays low, its streaky brown and buff plumage camouflaging its body. It stalks the reedy areas, slowly lifting its feet and, at times stopping to lift its neck high to blend in with the grass. Since 2016, Liz Znidersic has monitored the bittern. There are an estimated 1300 Australasian bitterns nationally, with about 30% living within the forest, and it is considered one of the world's most endangered waterbirds.

Bitterns are like avian Goldilocks. Their wetland habitats must not be too deep or too shallow and must be flooded for just the right amount of time. The proper water levels produce the plant communities needed for nests, cover, and food.

In the Fall of 2022, eastern Australia underwent extreme heavy rainfall that flooded areas in New South Wales and Victoria, and soundscape recordings had another chance to prove their worth. October was recorded as the wettest October on record in the Murray-Darling basin, which includes Australia's longest system of rivers. Total rainfall numbers across the basin were near 150 millimeters (about 6 inches), or four times the average for the month, breaking records set in 1950—thousands of people evacuated from the flash floods.

Before the fall flooding event, Znidersic and her research team had deployed acoustic monitors in Spring 2022 onto trees while seated in kayaks and boats within the Barmah-Millewa Forest in Victoria on the edge of the Murray River. The forest mainly consists of floodplain marshes and has the largest river redgum forest in the world. The forest transforms in wet years into a swampy scene teeming with birds, like bitterns, egrets, cormorants, and spoonbills. Water levels rose dramatically during the flooding and then dropped 3-4 meters. During these flooding events, fieldwork is nearly impossible, so ecologists set up sound recorders to monitor the landscape while they wait for the waters to recede. In the process, Znidersic and her team captured remarkable Australasian bittern behaviors.

Last year, after the flood withdrew and they were able to retrieve the recorders, Znidersic, and her team found that the flood had changed the timing of the bittern mating season. "We could see how the birds started to vocalize, which is a proxy for their breeding. Then they became quiet because there was too much water. All of their habitats were underwater, then as the water level dropped, and we have this, you know, just by correlating very, very crude water level data, as the water level dropped, the birds started to vocalize again," Znidersic explained.

They realized that this year, the males started their breeding calls later than usual after the flooding slightly retreated, and they could access reeds, sedges, and rushes for nests. The bittern’s prey was also available and plentiful enough for the breeding season. In normal years, the birds' gasping, low booming calls begin in September, during Australia's spring and summer seasons. In 2022, they started their mating season three months later, in December.

Collecting data on the timing and sound of the birds' breeding season was enough for government water management agencies to collaborate and allocate water flow into the forest to ensure this year's chicks have enough time to fledge, says Znidersic. The wetlands must stay submerged to a specific level for a few months for bittern young to grow.

Before the acoustic monitoring, there had been limited monitoring of bitterns' response to water delivery and river operations. "We just don't have that baseline data to know kind of even basic questions about where things are, partly because the Australian environment is not a very kind of regular event, there aren't going to be regular seasons and things. And so it's very much driven by the availability of water and things like that when it rains, it's boom, bust sort of cycles," Paul Roe, a computer scientist and professor at Queensland University of Technology and the lead of the Australian Acoustic Observatory says.

If Znidersic and her team had not left the recorders during the intense flooding event, they might not have captured the relationship between flood waters and the mating season this year. And the bitterns may have found themselves high and dry. "That's why we set up things like the Acoustic Observatory to sort of understand how we can do long-term continuous environmental monitoring and use that to understand what's happening to the environment here," Roe says.

In 2017, Australia launched the Australian Acoustic Observatory (A2O), a project dedicated to listening to the unique and vast Australian landscape. It is the world's first terrestrial acoustic observatory of its size. Across the continent, it uses 360 solar-powered sensors to continuously record the sounds of wildlife and weather for the next five years. All its collected recordings are free to the public, citizen scientists, and researchers under an open-access or Creative Commons License. The observatory provides scientists with a direct and permanent record of terrestrial soundscapes through continuous recording across the continent, including those areas repeatedly hit with fire and floods, where manual surveys are nearly impossible or treacherous. The Observatory collects data from the permanent solar-powered listening stations in 90 sites that record data year-round, with the intention that the archived sounds will be used to understand ecosystems as they change over time. Data on the vegetation, landforms, and disturbances of each site where sensors reside are also collected by researchers. Recordings from the various spots range from roaring winds, downpours, and random tweets from nearby birds.
"The important thing is that we're collecting the data now because we want to understand the sort of trends and what's sort of happening [to biodiversity and phenology throughout Australia]," Roe says." So we might not fully analyze the data now, but by collecting it, we can analyze it in the future." Roe also says there is little baseline data for the type of diversity out there. Collecting recordings is one way to track it all.

Benchmarking an area before its disrupted can bring a lot of insight into what a place was like before and, in turn, guide restoration methods. For example, Znidersic says if a natural area is scheduled for mining, ecologists can record the soundscape before its altered. When mining practices stop, scientists can track the area's health based on how it sounds until it sounds like it did before the disruption occurred. "We can do a survey saying, yes, these species are here, or no, those species are missing. So, I think it's making the whole system more honest. The more metrics we have in there for a restoration, I think the better outcomes we will have," Znidersic says.

In the three years since the wildfires ravaged parts of Australia, Znidersic has seen some growth naturally come back. But because some areas were severely scorched, Znidersic will use acoustic recordings archived by the A2O before the fires for her pilot study's test sites. Soundscapes of healthy ecosystems are planned to be used as 'broadcast recordings' for the study sites.

For Znidersic's part, she and her team in Australia are negotiating the pilot study to test their proposed method for using soundscapes to drive restoration and assess its success. Znidersic does not expect animals that follow the sound will stay. But scientists suspect that when wildlife returns to an area, they won't be alone. They may bring fungi, seeds, spores, and microbes to the location that needs revitalization. "They poop, they scratch, they do all of those things, which actually will help the soil to recover," Znidersic says.

Znidersic will using a new tool called false-color spectrograms to detect changes within two years in her proof-of-concept study before investing in a more extensive study. The tool was developed by Znidersic's collaborators including Roe, at Queensland University. The use of false color spectrograms allows the team to easily look at the data of audio waves and spot various species within 24 hours of data. The method is easier to sifting through hours of gray colored spectrograms and gives researchers a full picture of an ecosystems sound. The false colors of each sound bit reveals hard to see birds, and frog sounds that get lost within a soundscapes cacophony. The method of using these false-color spectrograms are so powerful they can detect echolocation calls from bats. In the proof-of-concept study, Zindersic will identify which animals respond to the acoustic lures and how long it takes before the recolonization of disturbed habitats occurs to establish protocols that will work.

In Glacier Bay National Park, the soft drumming of raindrops falls onto the tops of alder leaves. Its rhythmic drumming creates a unique symphony scored by the distant calls of thrushes. In the Bartlett Cove Rainforest within the park, songbird's flute-like notes echo through, and an eagle's signature giggle pierces through the hermit thrushes singing. Listen closely and you can hear a whale's faint huffing coming from the remote waters of Southeastern Alaska.

In the United States, the National Park Service Natural Sound and Night Skies Division (NSNSD) collects the soundscapes of beloved National Parks. The endeavor that started in the early 2000s consists of collecting baseline data for ambient acoustic quality throughout the parks and night sky quality by identifying noise and light pollution sources. The teams record in remote areas like Denali National Park, Glacier Bay National Park, and other parks to restore and preserve natural acoustical soundscapes while developing new approaches to safeguard natural sounds and natural darkness. "These are some of our last great refuges for those kinds of experiences, you know, and if they were to cease to exist, we wouldn't be doing our job," Davyd Halyn Betchkal, an Alaska region soundscape specialist and biologist with the National Park Service's Soundscape and Night Skies Division. The NSNSD also monitors noise pollution and collects data on how human noises from crowds, and air traffic, can alter a natural soundscape.

Some of the collected sound recordings in Glacier Bay National Park have aided researchers in studying bird migration patterns. In 2016, Rachel Buxton, a Professor in Biology at Carleton University in Ottawa, Canada, published a study in *Ecology and Evolution* that found over the three year study, birds may have been arriving earlier. They also found that acoustic monitoring was a viable and rapid method to monitor shifts in bird arrival time in the spring. "We found that even throughout our study, birds were arriving earlier, by a couple of days," Buxton says. The trend overall was consistent with other research that found birds may be changing their flight patterns because of climate change, says Buxton.

Aside from the bird phenology study, Buxton has collaborated with Betchkal on other studies regarding noise pollution in the National Parks. Since Buxton's paper was published, the NSNDS team has collected more data and is looking to write an update on how bird phenology is changing in the park. The parks most recent data suggests that more acoustic monitoring has found that birds are vocalizing earlier than before, which might be linked to climate change. However, the team is still analyzing the data and has some speculations before it can be confirmed. "We have a couple of long-term research sites at parks where we are collecting data each spring, essentially looking at how bird bioacoustics might be shifting through time," says Cathleen Balantic, an acoustic biologist with the NSNSD. Balantic also says that her team has yet to have a clear answer on whether climate change may cause earlier vocalization. The observed differences in bird migration may also be because of varying weather patterns or degraded equipment used over the decade.

Balantic and her team use software that automates identifying which birds are calling and when. This kind of software is a crucial part of the toolkit for researchers in soundscape ecology, who must work through months and months of continuous recordings. The software, BirdNET they used in this study was trained using hundreds and hundreds of examples of bird calls through Cornell's Macaulay Library and other datasets from xeno-canto, a website dedicated to sharing wildlife sound datasets. Although this study only looked at bird song, the NSNSD also collects data using automated acoustic monitoring to examine the impact of management interventions on biodiversity, and understanding which species are present and found throughout the parks.

In principle, data collected by the NSNSD is available to anyone who requests it because it is public data. But, in the current state that the data is stored, there is no easy way for the public to access it. Asking park employees to sift through terabytes of data for one specific block of soundscape files is time-consuming. The Australian Acoustic Observatory, for example, has its data available online. The National Park Service is collaborating with NOAA's National Centers for Environmental Information's existing Passive Acoustic Data Collection to create an online database where anyone can access sounds from these treasured areas in the future.

In Norwegian forests, Sarab Sethi, a soundscape ecologist and postdoctoral research fellow at the University of Cambridge, is working on a project called The Sound of Norway. This biodiversity monitoring project listens in on ecosystems and machine learning automatically classifies bird vocalizations while tracking distribution and migration patterns on vast scales and periods. The recorders used for the project were developed by Sethi and other researchers at the Imperial College in London. The recorders, called BUGG, continuously record sound in realtime while uploading onto a cloud service using SIM cards. A smartphone or laptop can easily access data collected by BUGG once uploaded.

Currently, birds' movements in Norway are tracked by an army of volunteers sent to forests to follow and write down the birds they see or hear. But Sethi is hoping to gather more data using acoustic monitoring. "They don't know when these birds are arriving, when they're leaving, how that's changing with different climate patterns. So, we're hoping to complement those studies by providing longitudinal data of species occurrence alongside the more detailed data that the people—the volunteers—are getting," Sethi says. Aside from the Norway project, Sethi is also collaborating with Roe and other scientists on understanding how bird migrations can be tracked on a larger scale using acoustic recorders.

Outside our windows, soundscapes play their signature chorus too. Maybe a woodpecker is hammering away at an old oak tree, or yellow goldfinches' tweet as they rollercoaster away. Northern cardinals start an ensemble, and you may hear a lawnmower or car pass by. These sounds make up our everyday sounds. But our sounds, and the changes we've brought into the planet's ecosystems, are in danger of drowning out the individual scores of other places, plunging them into a soundless void or monotonous buzz.

As the planet grapples with the biodiversity crisis and disasters brought on by climate change, recording and collecting the musical symphony of our natural soundscapes is crucial to preserving the natural sounds of entire ecosystems before they disappear. "We need these sounds to be comforting to us, but also, we recognize that it's the voice of nature. So, we don't want to smother it. We don't want to quiet it," Pijanowski says.

Although no one knows how the collection of sounds will be used, scientists are racing against time to safeguard it before it is silenced forever. "They're acoustic fossils. My hope is to get this archive together and preserve it…have it curated so that maybe somebody 50 years from now or 100 years from now can go back to the same place as I did and ask the question, how have the sounds changed?" says Pijanowski.

Imagine a world where everyone stops and takes a moment to appreciate nature's orchestra. Every chirp, every swoop of wind, every squish of wet sand as hundreds of fiddler crabs burrow underneath, and every crash of waves against the coast is noted and recorded by us. Each rhythm and note are recorded, categorized, and preserved for future generations. Our soundscapes are ever-present but ever-changing. Take a moment to listen.

References

Abbott, M. (2020, March 18). *Fires left these wallabies nothing to eat. help arrived from above.* The New York Times. https://www.nytimes.com/2020/03/18/world/australia/wallabiesaustralia-fires.html

Ambrose, S., & Burson, S. (2004). Soundscape Studies in National Parks. *The George Wright Forum*, *21*(1), 29–38. https://www.jstor.org/stable/43597890?seq=5

Burivalova, Z., Maeda, T. M., Purnomo, Rayadin, Y., Boucher, T., Choksi, P., Roe, P., Truskinger, A., & Game, E. T. (2022). Loss of temporal structure of tropical soundscapes with intensifying land use in Borneo. *Science of The Total Environment*, *852*. https://doi.org/10.1016/j.scitotenv.2022.158268

Burivalova, Zuzana, Game, E. T., & Butler, R. A. (2019). The sound of a tropical forest. *Science*, *363*(6422), 28–29. https://doi.org/10.1126/science.aav1902

Burivalova, Zuzana, Purnomo, Wahyudi, B., Boucher, T. M., Ellis, P., Truskinger, A., Towsey, M., Roe, P., Marthinus, D., Griscom, B., & Game, E. T. (2019). Using soundscapes to investigate homogenization of Tropical Forest Diversity in selectively logged forests. *Journal of Applied Ecology*, *56*(11), 2493–2504. https://doi.org/10.1111/1365-2664.13481

Buxton, R. T., Brown, E., Sharman, L., Gabriele, C. M., & McKenna, M. F. (2016). Using bioacoustics to examine shifts in songbird phenology. *Ecology and Evolution*, *6*(14), 4697– 4710. https://doi.org/10.1002/ece3.2242

Buxton, R. T., McKenna, M. F., Clapp, M., Meyer, E., Stabenau, E., Angeloni, L. M., Crooks, K., & Wittemyer, G. (2018). Efficacy of extracting indices from large-scale acoustic recordings to monitor biodiversity. *Conservation Biology*, *32*(5), 1174–1184. https://doi.org/10.1111/cobi.13119

Carson, R. L. (2002). *Silent Spring 40th Anniversary Edition.* Mariner Books/Houghton Mifflin Company.

Cretois, B., Rosten, C. M., & Sethi, S. S. (2022). Voice activity detection in eco-acoustic data enables privacy protection and is a proxy for human disturbance. *Methods in Ecology and Evolution*, *13*(12), 2865–2874. https://doi.org/10.1111/2041-210x.14005

Devitt, T. (2012, September 23). Aldo Leopold’s Field Notes Score a Lost “Soundscape.” Retrieved from https://www.aldoleopold.org/post/aldo-leopolds-field-notes-score-lostsoundscape/.

Devitt, T. (2012, September 18). *Aldo Leopold's field notes score a lost "Soundscape."* University of Wisconsin-Madison News. https://news.wisc.edu/aldo-leopolds-field-notes-score-alost-soundscape/

Dunning, H. (2022, May 3). *Automatic audio loggers successfully used to map the sound of Norway: Imperial News: Imperial College London*. Imperial News. https://www.imperial.ac.uk/news/236077/automatic-audio-loggers-successfully-usedsound/

Filkov, A. I., Ngo, T., Matthews, S., Telfer, S., & Penman, T. D. (2020). Impact of Australia's catastrophic 2019/20 bushfire season on communities and environment. retrospective analysis and current trends. *Journal of Safety Science and Resilience*, *1*(1), 44–56. https://doi.org/10.1016/j.jnlssr.2020.06.009

Game, E., Purnomo, & Burivalova, Z. (2016). *The Nature Conservancy - Indonesia, East Kalimantan Province Soundscapes.* Ecosounds. https://www.ecosounds.org/projects/1064

Gaunt, S. L., Nelson, D. A., Dantzker, M. S., Budney, G. F., & Bradbury, J. W. (2005). New Directions for bioacoustics collections. *The Auk*, *122*(3), 984–987. https://doi.org/10.1093/auk/122.3.984

Gordon, T. A., Radford, A. N., Davidson, I. K., Barnes, K., McCloskey, K., Nedelec, S. L., Meekan, M. G., McCormick, M. I., & Simpson, S. D. (2019). Acoustic enrichment can enhance fish community development on degraded coral reef habitat. *Nature Communications*, *10*(1). https://doi.org/10.1038/s41467-019-13186-2

Gottesman, B. L., Olson, J. C., Yang, S., Acevedo-Charry, O., Francomano, D., Martinez, F. A., Appeldoorn, R. S., Mason, D. M., Weil, E., & Pijanowski, B. C. (2021). What does resilience sound like? Coral Reef and dry forest acoustic communities respond differently to Hurricane Maria. *Ecological Indicators*, *126*, 107635. https://doi.org/10.1016/j.ecolind.2021.107635

Hansen, K. (2022, November 21). *More flooding in Australia's Soggy Southeast*. NASA Earth Observatory. https://earthobservatory.nasa.gov/images/150625/more-flooding-inaustralias-soggy-southeast

Herring, M. (2022, April). *Saving The Australasian Bittern: A Guide to Wetland Management and Bittern-friendly Rice Farming*. Riverina Local Land Services, Griffith, New South Wales. https://www.lls.nsw.gov.au/__data/assets/pdf_file/0006/1410954/20220603-Saving-theAustralasian-Bittern_accessible.pdf

Jones, A. (2020). *Bush Sounds, birdsong in Australia- sleep music (2 hours) Nature Track. YouTube*. YouTube/ ABC Science. Retrieved from https://www.youtube.com/watch?v=uXuvLjIulU&t=284s.

Kahl, S., Wood, C. M., Eibl, M., & Klinck, H. (2021). BirdNET: A deep learning solution for avian diversity monitoring. *Ecological Informatics, 61,*101236. https://doi.org/10.1016/j.ecoindustria.2021.101236

Krause, Bernard L. (1993). The Niche Hypothesis: A virtual symphony of animal sounds, the origins of musical expression and the health of habitats. *The Soundscape Newsletter (World Forum for Acoustic Ecology)*.

Krause, Bernie L. (1987). The Niche Hypothesis: How Animals Taught Us to Dance and Sing. Retrieved from http://xenopraxis.net/readings/krause_nichehypothesis.pdf.

Lentfer, H. (2020, October 14). *Bartlett Cove Soundscape Gallery*. National Parks Service. https://www.nps.gov/glba/learn/nature/bartlett-cove-soundscape-gallery.htm

Leopold, A. (1941). Aldo Leopold Papers: Diaries and Journals: Shack Journals 1935-1948: Journal for 1941. Madison.

Leopold, A., & Eynon, A. E. (1961). Avian daybreak and evening song in relation to time and light intensity. *The Condor*, *63*(4), 269–293. https://doi.org/10.2307/1365621

Lin, T.-H., Akamatsu, T., Sinniger, F., & Harii, S. (2021). Exploring coral reef biodiversity via underwater soundscapes. *Biological Conservation*, *253*, 108901. https://doi.org/10.1016/j.biocon.2020.108901

Lindenmayer, D. B., Kooyman, R. M., Taylor, C., Ward, M., & Watson, J. E. (2020). Recent Australian wildfires made worse by logging and associated forest management. *Nature Ecology & Evolution*, *4*(7), 898–900. https://doi.org/10.1038/s41559-020-1195-5

Martínez-Vilalta, A., Motis, A., & Kirwan, G. M. (2020). Australasian bittern (Botaurus Poiciloptilus). *Birds of the World*. https://doi.org/10.2173/bow.ausbit1.01

McAfee, D., Williams, B. R., McLeod, L., Reuter, A., Wheaton, Z., & Connell, S. D. (2022). Soundscape enrichment enhances recruitment and habitat building on new Oyster Reef Restorations. *Journal of Applied Ecology*, *60*(1), 111–120. https://doi.org/10.1111/13652664.14307

Moss, S. (2005, August 24). *Cornell researchers say double knocks may be "soundprints" of ivory-bills the public is invited to join in, listen and help decipher the sounds of the ivorybilled woodpecker*. Cornell Chronicle.

https://news.cornell.edu/stories/2005/08/newivory-billed-woodpecker-recordings-released

Nolan, R. H., Boer, M. M., Collins, L., Resco de Dios, V., Clarke, H., Jenkins, M., Kenny, B., & Bradstock, R. A. (2020). Causes and consequences of eastern Australia's 2019–20 season of mega-fires. *Global Change Biology*, *26*(3), 1039–1041. https://doi.org/10.1111/gcb.14987

Oak Ridge National Laboratory is managed by UT-Battelle LLC for the US Department of Energy. (2017, June 30). *Fowl play caught on film: ORNL*. Oak Ridge National Laboratory. https://www.ornl.gov/news/fowl-play-caught-film

Pijanowski, B. C., Villanueva-Rivera, L. J., Dumyahn, S. L., Farina, A., Krause, B. L., Napoletano, B. M., Gage, S. H., & Pieretti, N. (2011). Soundscape ecology: The science of sound in the landscape. *BioScience*, *61*(3), 203–216. https://doi.org/10.1525/bio.2011.61.3.6

Roe, P., Eichinski, P., Fuller, R. A., McDonald, P. G., Schwarzkopf, L., Towsey, M., Truskinger, A., Tucker, D., & Watson, D. M. (2021). The Australian Acoustic Observatory. *Methods in Ecology and Evolution*, *12*(10), 1802–1808. https://doi.org/10.1111/2041-210x.13660

Ross, S. R., O'Connell, D. P., Deichmann, J. L., Desjonquères, C., Gasc, A., Phillips, J. N., Sethi, S. S., Wood, C. M., & Burivalova, Z. (2023). Passive acoustic monitoring provides a fresh perspective on fundamental ecological questions. *Functional Ecology*, *37*(4), 959–975. https://doi.org/10.1111/1365-2435.14275

Schafer, R. M. (1977). *The Soundscape: Our Sonic Environment and The Tuning of the World*. Destiny Books.

Sethi, S. S., Ewers, R. M., Jones, N. S., Sleutel, J., Shabrani, A., Zulkifli, N., & Picinali, L. (2021). Soundscapes predict species occurrence in tropical forests. *Oikos*, *2022*(3). https://doi.org/10.1111/oik.08525

Sethi, S. S., Kovac, M., Wiesemüller, F., Miriyev, A., & Boutry, C. M. (2022). Biodegradable sensors are ready to transform autonomous ecological monitoring. *Nature Ecology & Evolution*, *6*(9), 1245–1247. https://doi.org/10.1038/s41559-022-01824-w

Sethi, S., Fossøy, F., Cretois, B., & Rosten, C. M. (2021). (rep.). *Management relevant applications of acoustic monitoring for Norwegian nature- The Sound of Norway. NINA Report 2064*. Trondheim: Norwegian Institute for Nature Research.

Smith, D. G., Truskinger, A., Roe, P., & Watson, D. M. (2020). Do acoustically detectable species reflect overall diversity? A case study from Australia's Arid Zone. *Remote Sensing in Ecology and Conservation*, *6*(3), 286–300. https://doi.org/10.1002/rse2.173

The Sounds of Borneo: What can a rainforest symphony tell us about biodiversity. The Nature Conservancy. (2016). https://tnc.maps.arcgis.com/apps/Cascade/index.html?appid=7bf8056343d24fbea1b929b267b826c4

Temple, S. (2022, December). *Aldo Leopold, Natural Soundscapes And "The Numenon" Of A Place. Badger Talks.* West Bend; Museum of Wisconsin Art.

Towsey, M., Znidersic, E., Broken-Brow, J., Indraswari, K., Watson, D. M., Phillips, Y., Truskinger, A., & Roe, P. (2018). Long-duration, false-colour spectrograms for detecting species in large audio data-sets. *Journal of Ecoacoustics*, *2*(1), 1–1. https://doi.org/10.22261/jea.iuswui

U.S. Department of the Interior. (2021, October 1). *Natural sounds and night skies division (U.S. National Park Service)*. National Parks Service. https://www.nps.gov/orgs/1050/index.htm

Center for Global Soundscapes, (2015). *Vanishing Soundscapes* https://centerforglobalsoundscapes.org/vanishing-soundscapes/

Vincelette, H., Buxton, R., Kleist, N., McKenna, M. F., Betchkal, D., & Wittemyer, G. (2020). Insights on the effect of aircraft traffic on avian vocal activity. *Ibis*, *163*(2), 353–365. https://doi.org/10.1111/ibi.12885

Ward, M., Tulloch, A. I., Radford, J. Q., Williams, B. A., Reside, A. E., Macdonald, S. L., Mayfield, H. J., Maron, M., Possingham, H. P., Vine, S. J., O'Connor, J. L., Massingham, E. J., Greenville, A. C., Woinarski, J. C., Garnett, S. T., Lintermans, M., Scheele, B. C., Carwardine, J., Nimmo, D. G., … Watson, J. E. (2020). Impact of 2019–2020 mega-fires on Australian Fauna Habitat. *Nature Ecology & Evolution*, *4*(10), 1321–1326. https://doi.org/10.1038/s41559-020-1251-1

Williams, Ben, Lamont, T. A. C., Chapuis, L., Harding, H. R., May, E. B., Prasetya, M. E., Seraphim, M. J., Jompa, J., Smith, D. J., Janetski, N., Radford, A. N., & Simpson, S. D. (2022). Enhancing automated analysis of marine soundscapes using ecoacoustic indices and machine learning. *Ecological Indicators*, *140*, 108986. https://doi.org/10.1016/j.ecolind.2022.108986

WWF. (2020). *Australia's 2019-2020 bushfires: The wildlife toll*. World Wildlife Fund Interim Report AUS 2020. https://media.wwf.no/assets/article_images/Animals-ImpactedInterim-Report.pdf

Zniderisc, E. (2023, April 3). *Patience and Technology Provide Insights on How to Save Threatened Birds*. Retrieved from https://news.csu.edu.au/latest-news/patience-andtechnology-provide-insights-on-how-to-save-threatened-birds.

Znidersic, E., & Towsey , M. (2022). (rep.). *The Living Murray-Intervention Monitoring: Australasian Bittern and Australian Little Bittern presence and breeding surveys, 2021-22:*

Intervention monitoring in Barmah-Millewa Forest 2021. Moama, NSW: NSW National Parks and Wildlife Service.

Znidersic, E., Towsey, M., & Watson, D. (2021). *Eavesdropping on Wetland Birds Soundscapes.* Ecosounds. https://www.ecosounds.org/projects/1131

Znidersic, E., & Watson, D. M. (2022). Acoustic restoration: Using soundscapes to benchmark and fast-track recovery of ecological communities. *Ecology Letters*, *25*(7), 1597–1603. https://doi.org/10.1111/ele.14015

Znidersic, E., Towsey, M., Roy, W. K., Darling, S. E., Truskinger, A., Roe, P., & Watson, D. M. (2020). Using visualization and machine learning methods to monitor low detectability species—the least bittern as a case study. *Ecological Informatics*, *55*, 101014. https://doi.org/10.1016/j.ecoinf.2019.101014

Interviews

Balantic, Cathleen. M. (2023, February 14). Zoom Web Follow-up Interview. personal.

Betchkal, Davyd., & Balantic , Cathleen. (2023, January 13). Zoom Web Interview with the Natural Sounds and Night Skies Division (NPS). personal.

Burivalova, Zuzana, & Ingram, Grace. (2023, January 9). In person Interview at Sound Forest Lab-University of Wisconsin-Madison. personal.

Buxton, Rachel. T. (2023, February 14). Zoom Web Interview. personal.

Pijanowski, Bryan. C. (2r023, February 21). Zoom Web Interview. personal.

Roe, Paul. (2023, March 15). Zoom Web Interview. personal.

Sethi, Sarab. (2022, October 27). Zoom Web Interview. personal.

Symes, Laurel. B. (2023, February 22). Zoom Web Interview. personal.

Williams, Brittany. (2022, December 14). Zoom Web Interview (Oyster Reefs). personal.

Znidersic, Elizabeth. (2022a, October 24). Zoom Web Interview. personal.

Znidersic, Elizabeth. (2022b, December 18). Telephone/Web Interview (Quick Check-in). personal.

Znidersic, Elizabeth. (2023, February 21). Zoom Web Interview (Follow-up). personal.