



Eavesdropping on Ecosystems

Researchers are collecting terabytes of recordings, from bird chirps to chainsaw roars. The emerging field of soundscape ecology has a lot to offer ... and a lot to prove

MICHAEL SCHERER-LORENZEN WAS ONE of 80 scientists appealing for funding from the German Science Foundation at a review meeting in Potsdam, Germany, last November. But his pitch was the only one that began with the harsh, throaty sounds of barking roe deer.

The midnight recording lasted just a few seconds, but it demonstrated exactly the kind of data the University of Freiburg researcher proposed to collect with a network of 300 microphones scattered across Germany. Each would record 1 minute of sound every hour for a year, he explained, capturing nearly 44,000 hours in all. The payoff: detailed “soundscapes” that could help researchers relate bird, insect, and

other animal populations to patterns of land management in Germany’s forests and grasslands. “It would be really cool,” he says, to use sound as a convenient proxy for measuring biodiversity.

Scherer-Lorenzen isn’t the only researcher enticed by the emerging field of soundscape ecology. Advances in cheap, tough automated recorders and powerful sound-analysis software are inspiring scientists to launch increasingly ambitious efforts that use sound to document and analyze ecosystems. Rather than focus on the calls of one or a few species at a time—as in many traditional bioacoustics projects—

soundscape ecologists are trying to describe the cacophony of entire landscapes, including nonbiological sounds such as rushing water, thunderclaps, and even the drone of cars and airplanes.

They hope to find more efficient ways to characterize an ecosystem than spending countless hours tromping through, and potentially disturbing, the landscape. Instead, they aim to find unique patterns hidden in the acoustic realm—and then track how they change in response to disruptions, such as increasing air traffic or construction projects, the arrival of invasive species, or the gradual effects of climate change.

Online

sciencemag.org

S Sound clips and podcast interview with author Kelly Servick (http://scim.ag/pod_6173).

Ears in the sky. Soundscape ecologist Bryan Pijanowski installs a fuzzy microphone on a research tower in Borneo earlier this year.

Researchers want to quantify “what we experience ourselves as we go through the day and listen,” says soundscape ecologist Bryan Pijanowski of Purdue University in West Lafayette, Indiana.

But studying whole soundscapes poses major technical and conceptual challenges. Researchers are struggling to find practical ways to boil down huge collections of digital recordings into something they can use. Converting complex soundscapes into relatively simple numerical indices of biodiversity is proving difficult. And soundscape ecologists have sometimes strained to persuade their colleagues, who may see little original in the approach, that large-scale networks of microphones can tell a meaningful story. Not that long ago, “there were many in the bioacoustics community that just said ‘No, no, no! This is not a new idea at all,’” Pijanowski says.

Sound foundations

Scientists have long observed how animals produce and perceive sound, and analyzed their communication patterns. The first field recordings of birdsong date back nearly a century. But for the most part, bioacoustics studies focused on individual species, mining a recording for particular calls of interest.

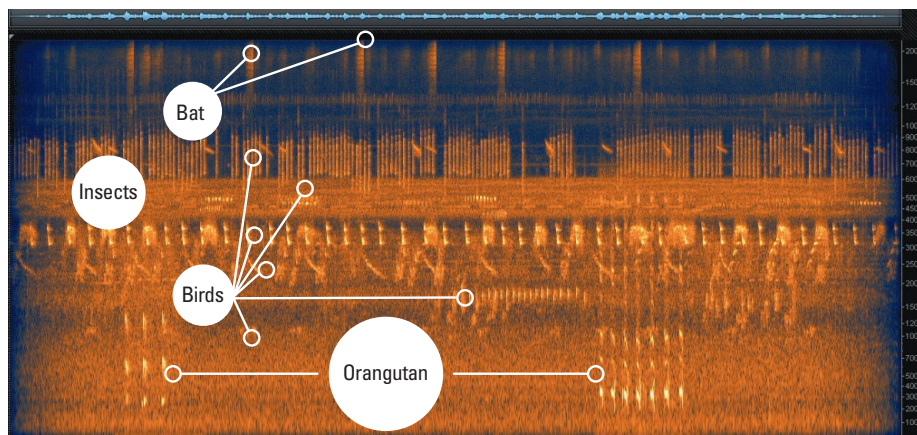
That species-level approach misses the forest for the trees, says Bernie Krause, a studio musician-turned-natural sound recordist who is often credited with developing the concepts behind modern soundscape ecology. “This reductionist, detached, and fragmented way of looking at the world is really incoherent,” he says.

Instead, Krause has proposed a theory of “acoustic partitioning,” which he first published in the magazine *Whole Earth Review* in 1987. Inspired by the complex soundscapes he heard in Kenya while collecting sound for a science museum exhibit, he suggested that natural sound be viewed as a resource shared among vocal organisms, like a nesting habitat or a food supply. An animal must carve out its own aural niche, he wrote, for example by using a signature frequency or by signaling at a particular time of day, to

avoid interference from other sounds.

In Krause’s view, a healthy ecosystem would be clearly partitioned into niches by frequency or time. In contrast, a disrupted area would have gaps at some frequencies, where species had been lost. And when

of frequencies in their recordings, the pair broke the soundscape into three components: “biophony,” or wild animal sounds (usually found at high frequencies); “geophony,” or geophysical sounds like wind, rain, and rushing water (which



Everything in its place. A recording from the Sumatran rainforest illustrates the acoustic niche hypothesis, in which different kinds of animals utilize different parts of the sound spectrum. Bats, for instance, call at higher frequencies while orangutans use lower frequency sound.

invasive newcomers or human-generated sounds intrude on a niche, the existing patterns might shift.

Many scientists were skeptical, seeing only anecdotal evidence for the theory. “It was completely rejected as a nice, aesthetic idea,” Krause recalls. “But then, to be fair, I really didn’t have, at the time, a way to express what I was finding . . . in the language of [scientific] publications.”

But the idea intrigued some researchers, including Stuart Gage, a soundscape

stretch across a wide frequency range); and “anthrophony,” or human-produced sounds (generally lower frequency).

Gage developed computer programs that quantified the amount of acoustic energy within certain frequency ranges; then he and Krause set out to compare natural and human-created sounds in a landscape. The effort was labor intensive. The pair gathered their soundscapes in California’s Sequoia National Park using nearly 5 kilograms of recording equipment, which

they had to babysit in the field. Its drawbacks became abundantly clear one evening, Gage recalls, when he found himself standing alone in a meadow waiting for a curious black bear to finish molesting the recorder he’d placed on a nearby rock. “He smelled it, he licked it, he slobbered all over it,” Gage says. “Then he whacked it.”

Luckily, the bear didn’t break it; his muffled snorts and loud smack were immortalized in the recording.

But Gage and others were already dreaming of systems that would be less likely to draw a bear’s attention: small recorders that could be hidden in the field for weeks or months at a time, collecting hours of high-fidelity sound with almost no human supervision. He began experimenting

“This is a science that’s plagued by the big data challenges that you see in, say, genetics.”

—Bryan Pijanowski,
Purdue University

ecologist and professor emeritus at Michigan State University in East Lansing and one of the field’s earliest champions. In the early 2000s, he worked with Krause to develop what he calls “a taxonomy of sound.” By analyzing the distribution

of frequencies in their recordings, the pair broke the soundscape into three components: “biophony,” or wild animal sounds (usually found at high frequencies); “geophony,” or geophysical sounds like wind, rain, and rushing water (which

with automated setups, connecting recording gear to laptop computers, but these were prohibitively bulky, power-hungry, and fragile.

Such problems caught the attention of Ian Agranat, an entrepreneur and technologist with an interest in birdsong. In 2003, Agranat had founded a company called Wildlife Acoustics, planning to make hand-held recorders for amateur bird enthusiasts. But he soon spotted a more promising market: scientists. Field recording equipment was “cobbled together by biologists who ... knew a little bit about technology,” he recalls. In 2007, he offered something better: the Song Meter, a \$600 weatherproof recorder in a lunchbox-sized metal case. When Gage first saw one, he decided he could “stop being an engineer and go back to being an ecologist.” Agranat has since sold more than 12,000 of the devices to researchers in some 60 countries.

The Song Meter now has plenty of company. Researchers can deploy a variety of powerful yet affordable sensors, some emphasizing portability, others designed for specific frequency ranges or extreme environments. Such technologies mark “the start of the story” for soundscape science, says Jérôme Sueur, an ecologist at the National Museum of Natural History in Paris.

A magic number?

Sueur was among the first researchers to seize on the new recorders to scale up his studies, hoping to show that sound could be a proxy for biodiversity. Sueur and his colleagues weren't interested in exactly which species were calling. Instead, he says they wanted “to take a global measure of the



Planting ears. Engineer Philippe Gaucher uses a crossbow to hang a microphone from the forest canopy in French Guiana. A recorder (blue box, right) is mounted on a tree.

acoustic output of the community.” Their goal was an algorithm that could boil hours of acoustic data down to a single number describing how an ecosystem's acoustic energy is distributed across the frequency spectrum and over time.

Sueur's team named their measure the Acoustic Entropy Index. It is based on what's called a Shannon index, which turns an inventory of the animals sighted in an

area into an estimate of species diversity. In Sueur's index, sounds at various frequencies take the place of animal species. A single, pure tone, for example, scores close to zero, representing low acoustic diversity. A noisy, chaotic, and more diverse soundscape should approach the highest possible score of 1.

In 2007, Sueur's team ran their first real-world test of the index in Tanzania, recording dawn and dusk sounds over several days in two coastal forests that are separated by 50 kilometers—and a lot of history. Loggers had exploited one for decades, but had been cutting trees in the other for just a few years. Sure enough, in a 2008 paper the team reported that the less disturbed forest had significantly higher acoustic entropy scores than the logged forest.

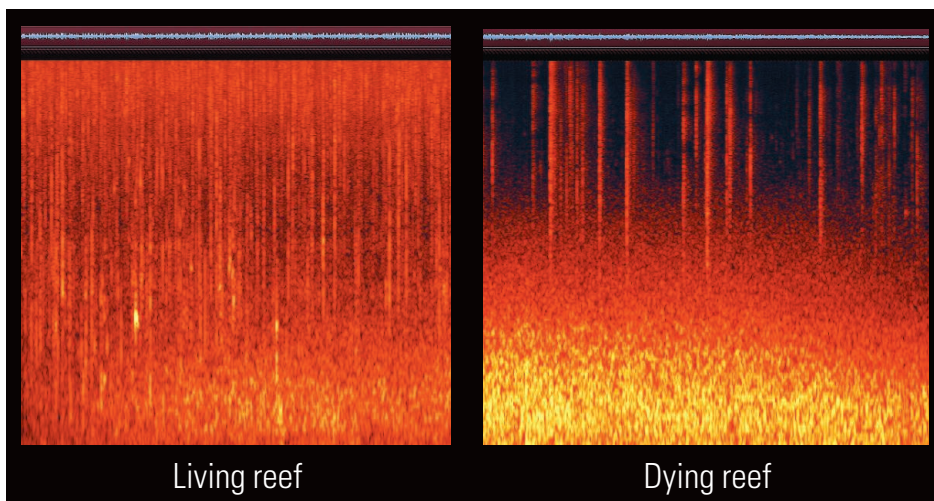
Since then, soundscape ecologists have developed a bouquet of indices based on different properties of the soundscape. At the University of Urbino in Italy, Almo Farina has developed an Acoustic Complexity Index based on sound qualities that can distinguish animal vocalizations from human-generated noise: Many animal sounds exhibit quick spikes in intensity (think of the abrupt crescendo of a bird's song) while many human-generated sounds, such as a droning engine, remain flat.

From Sueur's group came an Acoustic Dissimilarity Index, which compares two ecosystems based on differences in the timing and frequency of their sounds. In field tests, the index provided a ready way to estimate the number of species found in one community but not in the other.

The acoustic arsenal

Such acoustic measures can be powerful tools, but have their pitfalls, says Aaron Rice, director of the Bioacoustics Research Program at Cornell University. Many indices assume that biological sounds have shorter durations than humanmade ones. But in Rice's own marine acoustics research, the punctuated bursts of seismic air guns used for oil and gas exploration were a problematic exception. His conclusion: Indices are most useful when researchers have a good sense of the sources of sound they are likely to encounter. “Going into a place where you're recording somewhat blindly may not work,” he warns.

Similar limitations plague Sueur's Acoustic Entropy Index, which turned out to be highly sensitive to humanmade background noise. In fact, Sueur no longer believes he can create a single



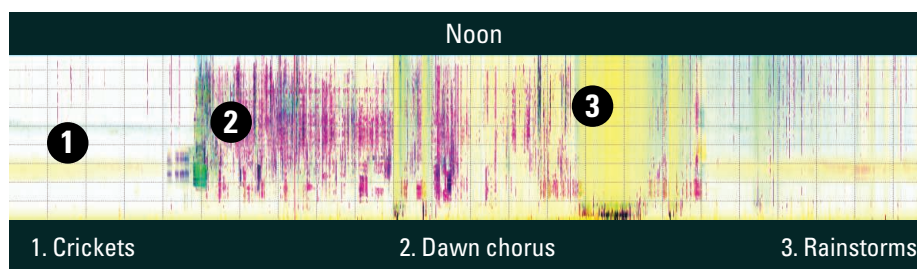
Visible decline. In visualizations of underwater recordings from Fiji, the spectrum from a healthy reef includes fish activity in the top half of the image. A nearby dying reef features mostly low-frequency ocean waves.

CREDITS (TOP TO BOTTOM): JÉRÔME SUEUR AND AMANDINE GASC; BERNIE KRAUSE (2)

acoustic measure that is a reliable proxy for biodiversity. The “index is not a miracle,” he says. “It would be stupid to try to summarize everything with a single value.”

Sueur does believe, however, that acoustic indices could become a useful element of a complete ecosystem portrait, especially when they are correlated with other indicators. For instance, Purdue’s Pijanowski—once a graduate student under Gage—has discovered a relationship between acoustic diversity and vegetation structure. His team planted sound recorders at 14 sites in the Costa Rican rainforest and compared features of the soundscape with vegetation data from light detection and ranging (LiDAR) surveys. Hot spots for vocal species turned out to correlate with patches of forest with large gaps in the upper canopy and dense foliage in the lower canopy, the researchers reported in a 2012 paper.

Such results make Pijanowski optimistic that sound recordings could someday shape management decisions by highlighting especially rich habitats or helping explain



Day in the life. A false-color spectrogram made from a recording in the Australian bushland highlights the daily variation in the soundscape. Colors indicate values drawn from three acoustic indices, each sensitive to different types of sound. The chirps of crickets dominate between dusk and dawn. As the sun rises, a bird call chorus fills the air. Rainstorms strike in the afternoon; the black, low-frequency marks at the bottom of the image are produced by waterdrops hitting the recorder.

Perils of the long view

The boom in sound-recording studies poses a challenge familiar in other fields: a glut of data. Pijanowski’s lab alone has amassed about 85 terabytes of sound—more than 100,000 hours—in just 5 years. “This is a science that’s plagued by the big data challenges that you see in, say, genetics,” he says. Many researchers already have libraries of field recordings that, if played in real time, would be longer than their careers.

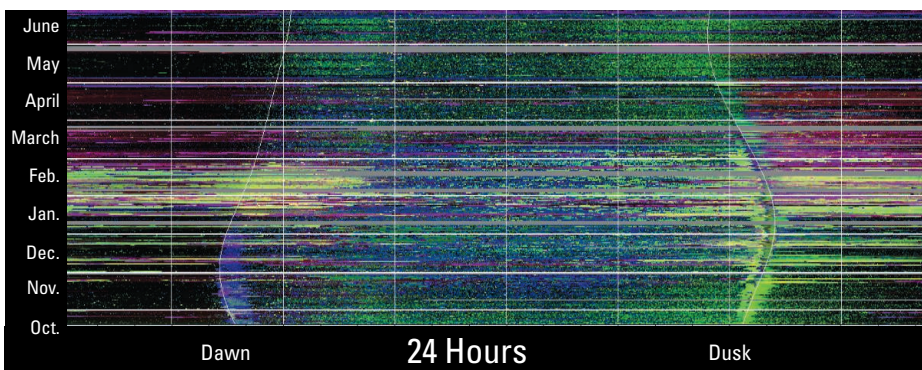
akin to studying the “acoustic climate,” he notes. And “when we start thinking about the acoustic climate, then we can start thinking about acoustic climate change.” Year-to-year comparisons could eventually highlight subtle and potentially problematic changes, he predicts, such as changing rain patterns or shifts in bird activity.

Proving grounds

To enable such long-term efforts, some soundscape researchers are eager to piggyback on existing ecological surveys, which can be large and relatively well funded. In the United States, biological oceanographer Susan Parks of Syracuse University in New York hopes to get acoustic sensors installed at the 106 sites planned for the National Ecological Observatory Network—an ambitious monitoring effort by the National Science Foundation that will fully launch in 2017. So far, however, Parks has the go-ahead to put her own recorders at just four sites. “The onus is upon me to show people that it would be a valuable research tool,” Parks says. To do so, she will spend 2 years gathering and analyzing recordings to measure human-generated sound and find seasonal patterns in birdsong.

Meanwhile, in Germany, Scherer-Lorenzen is strategizing about his first acoustic project. Thirty years after Bernie Krause first advanced his niche hypothesis, many soundscape experiments remain isolated case studies. Scherer-Lorenzen plans to take a broader view. By recording at locations where researchers funded by Germany’s Biodiversity Exploratories have already collected data on flora and fauna, he aims to see how well soundscape indices describe biodiversity across multiple landscapes. He expects the German Science Foundation to reach a verdict on his proposal in March. By April, he hopes to be out sprinkling microphones across the German countryside.

—KELLY SERVICEK



Zoom out. Computer scientist Michael Towsey combines 8 months of continuous recordings at a research station in Brisbane, Australia, into a single image. Colors indicate different acoustic indices. At dawn (*left curve*), a morning bird chorus (blue) is obvious during the Australian spring and early summer (October through December), but fades later in the year. Horizontal green streaks indicate heavy rainfall in January and February. At dusk (*right curve*), cicada activity is evident in the spring and summer months (green); by winter, the night is increasingly silent.

which features of a landscape support particular animal communities. In the last year, he says, there’s been an “explosion of people who are willing to think like this—more holistically.” One recent convert, Anne Axel of Marshall University, Huntington, in West Virginia, is using sound recordings to predict whether abandoned coal mines on Appalachian mountaintops still have potential value as habitats. She hopes to find out how the acoustic signatures of these pseudograsslands compare with their state “prior to people chopping off the tops of the mountains.”

“We know that we’re not going to be able to listen to it all,” says computer scientist Michael Towsey of the Queensland University of Technology in Brisbane, Australia.

To get around that problem, he’s developing ways to navigate soundscapes by sight, creating color-coded spectrograms that trained eyes can interpret at a glance (see graphic). Towsey describes the visualizations as “acoustic weather” charts. Some show how the spectrum of sounds shifts over a single day, while others assemble daily records into long-term snapshots to capture changes between seasons or years. That’s