continuum crowd density and velocity starting from mass and momentum conservation. To gather the necessary information to constrain these equations, they made a series of observations of a large number of people in a confined space—in this case, runners at the start of major marathons who are strongly constrained by geometry (along a street) and by the control of race officials. Runners are typically allowed to start the race in small groups according to their expected speed. The authors quantitatively analyzed videos of runners at the start of races and found that each starting event (when officials let runners start to advance toward the starting line) triggered an upstream-propagating wave of density and velocity perturbations through the crowd. In other words, the crowd supported a wave-like transmission of information (in this case, the start of the race). The properties of this wave provided the information needed to constrain the equations of motion, which in turn enabled predictions about the dynamics of other crowds without resorting to any assumptions about human behavior. That's a very important outcome, including for those interested in modeling potentially dangerous situations such as crowd panic.

The approach of Bain and Bartolo opens many avenues for future work for collective behavior researchers more generally. For example, it should inspire studies that pinpoint a group response to perturbations—such as the traveling waves launched by the starting events of a marathon race—to constrain continuum models. Some studies along these lines have already been done, such as characterizing the response of starling flocks to predators (*10*), of ants to mechanical stresses (*11*), and of midge swarms to sensory cues (*12*). More work is necessary to incorporate these findings into dynamical continuum models that avoid the need for a priori assumptions about animal behavior. Ultimately, such models may even be an effective way to determine the local interactions themselves because any agent-based model must approach the continuum model as a limiting case. ■

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CONSERVATION

The sound of a tropical forest

Recording of forest soundscapes can help monitor animal biodiversity for conservation

By **Zuzana Burivalova[1], Edward T. Game[2,3],** *and* **Rhett A. Butler[4]**

Conservation areas around the world aim to help conserve animal biodiversity, but it is often difficult to measure conservation success without detailed on-the-ground surveys. High-resolution satellite imagery can be used to verify whether or not deforestation has occurred in areas dedicated for conservation (*1*). Such remote sensing analyses can reveal forest loss and, in some cases, severe forest degradation, such as through fragmentation and intensive selective logging, especially if it includes the construction of roads or camps. However, conservation benefit is determined not only by forest loss but also by the level of degradation in those forests left standing. Bioacoustics—specifically the recording and analysis of entire soundscapes—is an emerging tool with great promise for effectively monitoring animal biodiversity in tropical forests under various conservation schemes (*2*, *3*).

Even forests that appear intact in satellite imagery can have low biodiversity conservation value because of effects such as canopy simplification, understory fires, invasion by exotic species, or overhunting. These forms of degradation are difficult to monitor remotely with satellite imagery, resulting in a common but faulty assumption that conserving forest cover is necessarily equivalent to conserving biodiversity. Continuing advances in spectral imagery and lidar (light detection and ranging) reveal progressively finer levels of forest change, but they still remain a proxy for animal biodiversity rather than a direct measure of it (*4*).

Repeated on-the-ground surveys can provide the required information to assess animal biodiversity. However, such surveys are expensive, cover limited ground, and may be affected by the biases of individual experts. One possible alternative is the use of bioacoustics, which can detect animals by their vocalizations. Depending on vegetation structure and the vocalizing species, acoustic recorders can detect animal calls and song from several hundred meters away (*5*). Autonomous sound-recording devices are now available from several companies as small units that are inconspicuous to humans. They can be programmed to record either continuously, if there is sufficient solar power or cellular network signal for direct transmission of data to cloud storage, or at given intervals, if battery power and data storage are limiting factors (*6*). Several multiyear recordings have now been completed (*7*).

Selected times of the day can convey a disproportionately large amount of information about the resident biodiversity; for example, mornings and evenings have been found to be particularly important for detecting differences between forests that are used in different ways by humans (*8*). With further developments in energy and data storage and transmission, continuous recording is likely to become the norm.

Relative to on-the-ground surveys, bioacoustics is inexpensive, making it more

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Hornbills, such as this rhinoceros hornbill in Bukit Tigapuluh National Park, Sumatra, Indonesia, have prominent vocalizations that can be identified in soundscapes.

feasible to repeat measurements over time. Also, the results are not influenced by individual researchers' biases or simply by the presence of observers in the field. The method offers the possibility to monitor multiple taxonomic groups at the same time (all vocalizing birds, mammals, insects, and amphibians), as opposed to, for example, camera traps. Finally, the data can be reanalyzed in the future with improved algorithms or to search for specific acoustic features. Analysis of human-made sounds can help to clarify how sounds from machinery (such as tractors, bulldozers, and chainsaws) affect habitat quality and to track illegal human activities, such as gunshots from poachers or chainsaws in illegal logging (*9*).

Acoustic data from soundscapes can be analyzed in many ways (*10*). Various indices can be calculated that characterize the soundscape for each time and frequency unit (*11*, *12*). Alternatively, individual species can be identified by experts, algorithms (*13*), or deep learning (*14*).

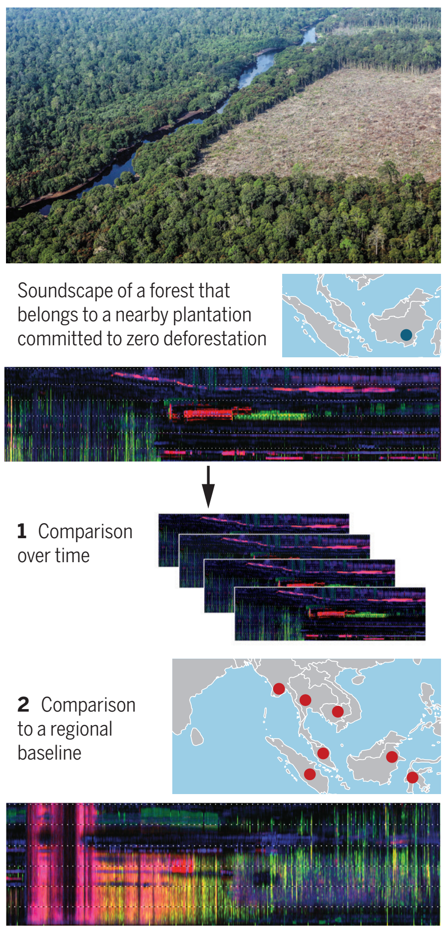
Soundscape analysis using indices appears most suitable to monitor the general state and recovery of forests, because it does not require site-specific species lists (*8*). Random forest models based on multiple acoustic indices can predict species richness with very high accuracy (*11*). However, further studies linking on-the-ground biodiversity surveys to soundscape indices are needed from a wide variety of forest types and human disturbances to determine whether such indices can be generalized. In areas where hunting is important, the recordings could also be used to determine the presence or absence of the hunted species (typically large mammals and birds) using individual species recognition algorithms.

Bioacoustics has particular potential in the context of industry sustainability certification and zero-deforestation commitments, both of which have become popular, widely publicized conservation strategies (*1*, *15*). Companies involved in such industries as palm oil, beef, soy, and pulp and paper production commit to not cause any deforestation through their industrial development. Typically, this means that any new plantation, ranch, or farm can only be developed in an area that is already deforested or heavily degraded. In some countries, such as Brazil, companies are legally obliged to protect parts of their concessions from deforestation. However, precise definitions of zero deforestation are often missing (*15*). The conservation benefit of such industry-protected forests should be determined not just by how much forest loss has been avoided, but also by the level of biological integrity of those forests left standing. Bioacoustics has the potential to provide this information (see the figure).

Advances in bioacoustics, as well as the robustness and affordability of sound-recording devices, make it possible for companies or independent consultants to deploy sound recorders in areas of forest maintained by a company under legal requirements, certification, or a zero-deforestation commitment. If the soundscape of a forest spared from conversion were becoming more impoverished and altered beyond the natural variation of the soundscape baseline, on-the-ground survey would be warranted. Slow, gradual changes in soundscape composition due to climate change might be beyond the direct control of the companies, but abrupt and quick change in soundscapes is more likely to be attributable to management. In these cases, other measures (such as prevention of hunting, reforesting edges or the degraded areas of the conserved zone with native species, or curbing fires) would be called for by auditors, who are typically involved in independent verification of a company's commitments.

How soundscape monitoring can aid conservation

This diagram shows how bioacoustics monitoring could be implemented in a concession governed by a corporate conservation commitment or sustainability certification. Soundscape recordings would be compared to each other over time, as well as to regional baselines from the closest available intact forest landscapes.



Because of the enormous size of the acoustic datasets and the computational power required to analyze them, there is a need for a global organization to host a global acoustic platform, which would allow direct, on-the-fly analysis. The development of such a data hosting and analysis platform should be a priority, together with the collection of regional soundscape baselines by scientists. Such baselines would be especially useful for understanding and accounting for the natural seasonal and interannual variation of soundscapes, as well as for comparison of the industry-protected forest soundscapes with the closest available undisturbed sites.

Nongovernmental organizations and the conservation community need to be able to truly evaluate the effectiveness of conservation interventions. Many (but not all) companies want to be able to provide objective, consistent, and easy-to-share evidence documenting their conservation efforts, at a low cost. Environmentally aware consumers may feel more confident about purchasing from brands that can show the results of their conservation efforts, on top of their certification logo or zero-deforestation commitment. The scientific community will benefit from a huge tranche of data on ecological communities across the tropics. It is therefore in the interest of certification bodies to harness the developments in bioacoustics for better enforcement and effectiveness measurements of their schemes. ■

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