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Acoustic monitoring reveals a diverse forest owl community, illustrating its potential for basic and applied ecology

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For millennia, humans have attributed mystic powers to owls, and they remain a mysterious group. Nocturnality and silent flight have precluded extensive scientific study, notwithstanding a few species made prominent by their specialization, such as the spotted owl (*Strix occidentalis*; Noon and Franklin 2002), or global distribution, such as the barn owl (*Tyto alba*). Yet owls are the apex volant nocturnal predator guild globally, and thus likely play an important but poorly understood role in ecosystem dynamics (Whelan et al. 2008). Here, we report a species-rich owl community as revealed by passively recorded audio data, and describe how this type of bioacoustic data can greatly facilitate the systematic study of entire owl communities without conventional vocal-lure surveys that may alter owl behavior and vocalization patterns (Crozier et al. 2006).

The ongoing expansion of the barred owl (*S. varia*) into the western United States has raised the prospect of severe impacts to spotted owls, as well as the disruption of forest owl assemblages and entire forest ecosystems (Gutiérrez et al. 2007, Holm et al. 2016). Therefore, we conducted passive acoustic monitoring during May–August of 2017 and 2018 in the northern Sierra Nevada, California, within mixed-conifer forest to assess the distribution and density of barred owls at the leading edge of this species' range expansion. We deployed autonomous recording units (ARUs; Swift Recorder, Cornell Lab of Ornithology Bioacoustics Research Program) in >400 4-km^2 grid cells across ~6,000 km^2 and applied sliding window template detectors to the resulting audio data to identify potential barred owl and spotted owl territorial vocalizations (Raven Pro 2.0, Cornell Lab of Ornithology Bioacoustics Research Program; see Wood et al. 2019 for further details). While manually confirming or rejecting potential target vocalizations, we also noted the presence of other owl species' vocalizations in the audio data.

In addition to barred and spotted owls (Fig. 1a; Audio S1), we detected great horned owls (*Bubo virginianus*; Fig. 1b), western screech owls (*Megascops kennicottii*; Fig. 1c, d), flammulated owls (*Psiloscops flammeolus*; Fig. 1c), northern saw-whet owls (*Aegolius acadicus*; Fig. 1d), northern pygmy owls (*Glaucidium gnoma*; Fig. 1e), long-eared owls (*Asio otus*; Fig. 1f), and barn owls (Fig. 1g). Notably, we found high species richness at fine spatial scales. Six species (great horned, barred, spotted, long-eared, western screech, and flammulated owls) were found within 17 km of each other during a seven-night period in August, 2018 along a forested, midelevation (1,360–2,200 m) ridgeline near the eastern slope of the Sierra Nevada. Species richness was high at even finer scales: three ARUs deployed no more than 934 m apart recorded great horned, barred, spotted, and flammulated owls within a five-night period.

This is greater species richness than has been reported in other forest owl communities globally (Gutiérrez et al. 2007). It demonstrates the apparent coexistence of similarly sized owls (e.g., spotted and barn owls, flammulated and northern pygmy owls; Fig. 2), which is indicative of potentially complex spatiotemporal resource partitioning (Gutiérrez et al. 2007). More importantly, we believe that the high owl species richness we documented is indicative of a methodological turning point for the study of owls.

Crozier et al. (2003) documented almost as many owl species during 5 yr of vocal-lure surveys near our study area, but data generated from such surveys on nontarget species can be difficult to apply to ecological research. First, reports of nontarget species during vocal-lure surveys are inconsistent and identifications can be unreliable (authors' *personal observations*). Second, interspecific differences in response rates to vocal-lure surveys likely introduce bias to the data (Crozier et al. 2006). Third, data on nontarget species can be too sparse to estimate occupancy and detection (R. J. Gutiérrez *unpublished data*). These issues are inherent to vocal-lure survey data, albeit to varying degrees, and for these reasons, it is difficult to do more than report species richness. Passively collected audio data have none of these problems: Documenting high species richness is just the beginning.

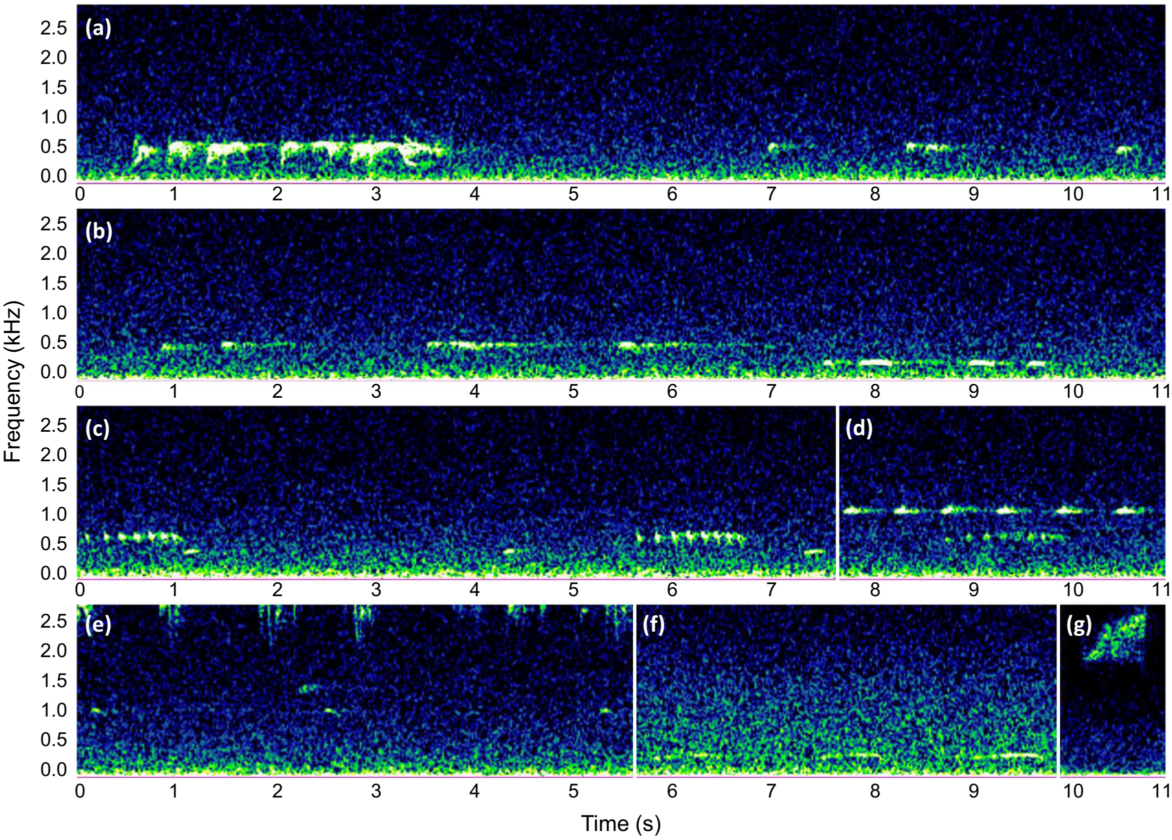

FIG. 1. Compilation of spectrograms of the vocalizations of (a) barred and spotted owls, respectively, (b) spotted and great horned owls, respectively, (c) western screech and flammulated owls, respectively, (d) northern saw-whet and western screech owls, respectively, (e) northern pygmy owl, (f) long-eared owl, and (g) barn owl recorded at various sites in the course of passive acoustic monitoring in the northern Sierra Nevada, USA (sample rate 32 kHz, Hann window, 3 dB bandwidth = 39 Hz, 2,048-sample DFT, hop size = 18.4 ms). An annotated audio file is available online (Audio S1).

Systematic detection and classification of vocalizations from all nine owl species is possible with the methods we used or with increasingly sophisticated artificial-intelligence–based programs (Kahl et al. 2017). Such a data set would be without precedent for owls.

The high species richness we documented across spatial scales (4–6,000 km^2) suggests that passively collected audio data such as this could support research on scale-dependent patterns in alpha, beta, and gamma diversity (Lira-Noriega et al. 2007) and on metacommunity assembly (Leibold et al. 2004). Spatial scale is also predicted to influence species coexistence (Kneitel and Chase 2004), and passively collected audio data could facilitate the study of competition, coexistence, and behavioral ecology in a previously inaccessible taxon. We frequently documented simultaneous vocalizations of pairs of owl species (Fig. 1a–d) that suggest at least occasional direct interspecific interactions, and the strength of such associations could be formally tested. Pairing acoustic data with dietary or other types of data could further elucidate the ecological mechanisms by which a rich community of owl species coexists at fine spatial scales (Basset and Angelis 2007). The degree to which coexistence is mediated by topographic and floristic heterogeneity could also be explicitly tested at different spatial scales and resolutions. Ultimately, community-level data sets for guilds like forest owls have the potential to contribute to a mechanistic understanding of the drivers of biodiversity.

Community-level data would also be a valuable asset for managers. Previous work indicates that passive acoustic surveys can be used to monitor population change and response to management of individual owl species at landscape scales (Wood et al. 2019), and our findings suggest that changes to the entire owl community could be monitored in a unified framework. Community occupancy models and multispecies occurrence models can be used to evaluate community-level ecological change (Dorazio and Royle 2005, Zipkin et al. 2010), such as the effects of forest management or invasive species on the forest owl community (Holm et al. 2016). Furthermore, the implementation of broad-scale passive acoustic monitoring provides a foundation for natural

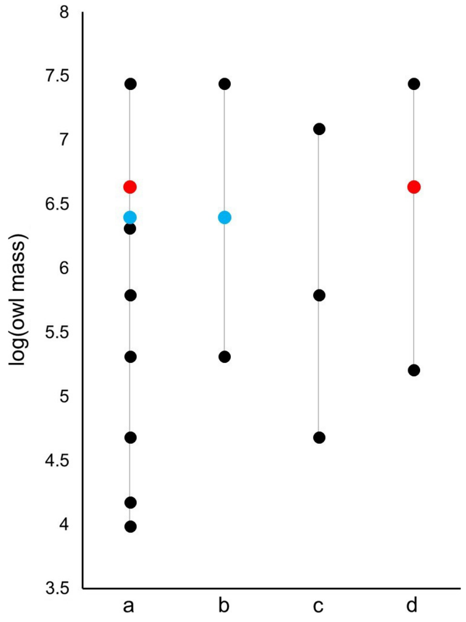

Fig. 2. Median size (log(mass (g))) of species in four North American forest owl communities: (a) the northern Sierra Nevada mixed-conifer forest (this study); (b) California oak–pine foothills; (c) Wyoming lodgepole pine forest; and (d) Missouri hardwood forest. In descending order of size, community (a) included the great horned, barred (red), spotted (blue), barn, long-eared, western screech, northern saw-whet, northern pygmy, and flammulated owl; communities b–d are reproduced from Gutiérrez et al. (2007).

Before-After-Control-Impact experiments at a much broader taxonomic scale than conventional vocal-lure surveys would allow.

Collectively, our findings reveal the tremendous latent potential of passively recorded acoustic survey data for studying otherwise cryptic species and biological communities. We are optimistic that advances in artificial-intelligence techniques such as convolutional neural networks (Norouzzadeh et al. 2018) will facilitate the extraction of monitoring and behavioral data not just on diverse owl assemblages, but on hundreds of species from this type of audio data, opening up exciting new possibilities in ecological research and biodiversity conservation.

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