

CONTRIBUTED PAPER

Audible bats provide opportunities for citizen scientists

Thomas J. Rodhouse¹  | Sara Rose² | Trent Hawkins² | Rogelio M. Rodriguez²¹National Park Service and Human and Ecosystem Resiliency and Sustainability Lab, Oregon State University-Cascades, Bend, Oregon²Human and Ecosystem Resiliency and Sustainability Lab's Northwestern Bat Hub, Oregon State University-Cascades, Bend, Oregon

Correspondence

Thomas J. Rodhouse, National Park Service (HERS Lab), Oregon State University-Cascades, 1500 SW Chandler Ave. Bend, OR 97702, USA.
Email: tom_rodhouse@nps.gov

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Abstract

Bat conservation has been impeded by a lack of basic information about species' distributions and abundances. Public participation in closing this gap via citizen (community) science has been limited, but bat species that produce low-frequency calls audible to the unaided human ear provide an overlooked opportunity for collaborative citizen science surveys. Audible bats are rare in regional faunas but occur globally and can be under-surveyed by traditional methods. During 2019–2020, we were joined by community members to conduct aural surveys and expand our knowledge of rare audible desert bats in western North America through a structured survey design broadly adaptable for practitioners across the globe where audible bats occur. Our study was integrated into a statistically robust but flexible master sample in use by the North American Bat Monitoring Program (NABat), ensuring representativeness of data contributions. We used survey results to update a Bayesian species distribution model for the rare spotted bat, *Euderma maculatum*, accounting for imperfect detection and including land cover occupancy predictors. Detection probability was estimated $\sim 0.7 \pm 0.1$. Informative priors from a previous attempt to model *E. maculatum* were leveraged with the new citizen science data to support spatial predictions of occurrence previously impeded by data sparsity and which reinforced the biogeographic importance of arid cliffs and canyons. Our results are preliminary but encouraging, and future surveys can scale up through the NABat design structure and Bayesian modeling framework. We encourage future surveys to use recording devices to obtain voucher calls and double-observer methods to address false-positive detection errors that arise with inexperienced volunteers. Our design and model supported approach to integrating citizen science surveys into bat conservation programs can strengthen both the scientific understanding of rare species and public engagement in conservation practices.

KEYWORDS

aural surveys, Bayesian hierarchical model, citizen science, echolocation, North American bat monitoring program (NABat), observation error, occupancy model, species distribution modeling

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1 | INTRODUCTION

The contemporary biodiversity crisis (IPBES, 2019) requires an “all hands on deck” approach to the collection, dissemination, and understanding of data via a public participation in citizen or community science (McKinley et al., 2017; Shirk et al., 2012). Public engagement through citizen science acts to crowd-source data collection and builds scientific literacy and trust. When done well, citizen science is seen as a scientifically valid way to help close information gaps (Dickinson, Zuckerberg, & Bonter, 2010; Kosmala, Wiggins, Swanson, & Simmons, 2016). Well-coordinated citizen science programs subtended by strong survey design and data collection and management protocols have advanced knowledge about distributions and abundances of multiple taxa, most notably for birds (e.g., Kabori et al., 2016; Sullivan et al., 2009; Tulloch, Possingham, Joseph, Szabo, & Martin, 2013), but increasingly for other taxa such as invertebrates (Ries & Oberhauser, 2015; Soroye, Ahmed, & Kerr, 2018; Ward, 2014), for processes like phenology and global change (Schwartz, Betancourt, & Weltzin, 2012), and for other components of biodiversity such as genomics (Garbarino & Mason, 2016). Aligning citizen science opportunities with recreational activities such as birdwatching has been a successful way to recruit and retain public participants (Sullivan et al., 2014; Tulloch et al., 2013). However, for cryptic or otherwise non-charismatic organisms and ecological topics (e.g., biological invasion, ecosystem function), public participation has lagged and data set biases persist (Boakes et al., 2016; Dickinson et al., 2010; Ward, 2014).

Until recently, bats (Chiroptera) were not considered a suitable target for citizen scientists. Bats have historically been maligned by many societies, feared as disease vectors, and are difficult to find and identify (Kingston, 2016). In general, bats are more threatened and disproportionately under-studied, in terms of basic knowledge about distributions and population trends, relative to other mammalian taxa (Frick, Kingston, & Flanders, 2019). However, the development of noninvasive survey methods that minimize direct contact between bats and surveyors are allowing for more public participation. Citizen science therefore has considerable potential to contribute to basic knowledge about bat ecology and their conservation. We recently (December 23, 2020) queried Web of Science using keywords *bats* and *citizen science* and only discovered 29 citations, several of which were nontopical erroneous inclusions, and none published prior to 2010 (Supporting Information). However, accessibility of bat field studies to citizen scientists has increased with the development of portable bat echolocation recording devices. Coordinated acoustic

monitoring programs in the United Kingdom (Barlow et al., 2015) and elsewhere (Lopez-Baucells et al., 2017) rely on public participation (e.g., Newson, Evans, & Gillings, 2015). However, purchase costs and proper uses of bat call recorders (“bat detectors”) can be a barrier to participation. Other non-technological survey methods being used with citizen science include collection of guano from buildings (Wray et al., 2018) and roadkill carcasses (Chyn, Lin, Chen, Chen, & Fitzgerald, 2019), and visual encounters of bats visiting fruiting trees (Taylor, Vise, Krishnamoorthy, Kingston, & Venter, 2020). Citizen science has contributed to advancements in wind farm bat risk assessment (Newson et al., 2017), to a better understanding of urban light pollution impacts to bats (Pauwells et al., 2019), and description of bat habitat preferences (Finch, Schofield, & Mathews, 2020).

An overlooked but potentially widespread and non-technical opportunity for public participation in the science and practice of bat conservation exists where bats that echolocate at low frequencies audible to the unaided human ear occur. Audible bats are infrequent within regional faunas but are found globally, especially, but not exclusively, within the Molossidae family (Barclay & Brigham, 1991; Jones, 1999; Jones, 2005). Audible bats tend to be fast-flying aerial hawkers of large moths (Jones, 2005; Rydell & Arlettaz, 1994) and are often not easily surveyed using traditional (e.g., Kunz & Parsons, 2009) capture methods and acoustic recording devices because they fly above survey equipment in wide open airspace (e.g., Best, Kiser, & Freeman, 1996; Luce & Keinath, 2007; Rodhouse, McCaffrey, & Wright, 2005; Strahan, 1995) at distances greater than the recording sensitivities of current commercially-available bat detector microphone technology (Adams, Jantzen, Hamilton, & Fenton, 2012). Notable species include the western North American member of the Vespertilionidae family, *Euderma maculatum* (Figure 1; Fenton, Tennant, & Wyszecski, 1987; Fullard & Dawson, 1997), and the Molossids *Tadarida teniotis* in Eurasia (Russo & Jones, 2002; Rydell & Arlettaz, 1994; Zbinden & Zingg, 1986), *Otomops martienssenii* in southern Africa (Fenton et al., 2002), and *Tadarida (Australomys) australis* in Australia (Barclay & Brigham, 1991). Each of these species routinely call at frequencies <20 KHz, the approximate upper limit of human hearing, and are locally known for being audible (e.g., <https://australian.museum/learn/animals/bats/white-striped-freetail-bat/> and <https://www.batcon.org/article/on-the-cover-25/>). These species can be surveyed by citizen scientists who are trained to listen for the distinctive audible calls of these species. Other species of bats that produce audible social calls may also prove to be appropriate targets for citizen science surveys. One intriguing possibility is with



FIGURE 1 A spotted bat, *Euderma maculatum*, captured near the study area in 2003. This species produces distinctive low-frequency calls audible to the unaided human ear which makes it a suitable target for aural surveys

Antrozous pallidus in western North America because it makes loud social calls in the vicinity of maternity roosts during summer (Hermanson & O'Shea, 1983). Encounter records of these distinctive social calls could prove invaluable for documenting pup-rearing habits of this rare species.

We developed a coordinated citizen science survey of the spotted bat, *Euderma maculatum*, and the pallid bat, *Antrozous pallidus*, in the desert canyons and adjacent foothills of central Oregon, U.S. We tested the survey design during 2019 and 2020 and used new encounter records produced through the survey to update a Bayesian distribution model and map (Rodhouse et al., 2015) that accounted for imperfect detection and leveraged prior information (Rodhouse et al., 2019). Our survey was structured to integrate seamlessly into the North American Bat Monitoring Program's (NABat) grid-based master sample currently in use across the continent for

structuring bat monitoring during summer with acoustic recording devices and during winter with visual surveys of bats in hibernacula (Loeb et al., 2015; Reichert et al., 2021). Our approach provides an additional survey methodology for NABat that is compatible with its flexible design and occupancy modeling framework, augments the program's omnibus acoustic and visual counting methods which can be inefficient for rare audible species, and provides a much-needed new way to increase public participation in bat conservation. Our approach may be adaptable to other regions of the globe where audible bats are found. We outline additional steps required to scale our approach up to broader regions, which include obtaining larger sample sizes and better quantification of false-positive error than what we were able to accomplish during our study.

2 | METHODS

2.1 | Survey design

We used our own (Rodhouse et al., 2005) and others (e.g., Fenton et al., 1987; Gitzen, West, & Baumgardt, 2001; Navo, Gore, & Skiba, 1992; Pierson & Rainey, 1998) reports of the efficacy of aural surveys over traditional capture and recording methods for *E. maculatum* to motivate our study design. *E. maculatum* is a strikingly-colored (Figure 1) but rarely seen obligate cliff-roosting bat ranging broadly across arid regions of western North America (Wai-Ping & Fenton, 1989; Watkins, 1977). The species routinely emits 10 KHz search-phase calls at >60 dB which can be heard by humans with undamaged hearing >60 m, whereas commercially-available bat acoustic recording units are limited to <40 m (Adams et al., 2012; Fullard & Dawson, 1997; Luce & Keinath, 2007). We also considered *A. pallidus* as an additional target species because it also roosts sympatrically in large desert cliffs and emits distinctive audible social calls in the vicinity of maternity colonies (Hermanson & O'Shea, 1983). We used a portion of central Oregon, U.S., encompassed by two national forest administrative boundaries, to focus our efforts, and overlaid the NABat grid-based master sample frame (Talbert & Reichert, 2018) with the target region in a Geographic Information System to establish the survey design (Figure 2). The master sample (Larsen, Olsen, & Stevens Jr., 2008; Reichert et al., 2021) provided a spatially-balanced randomization (Reichert et al., 2021; Stevens & Olsen, 2004) of all grid cell sample units within our study area. Our target sample size was 30 cells, following the master sample randomized rank order to ensure representativeness of the sample (e.g., mean and

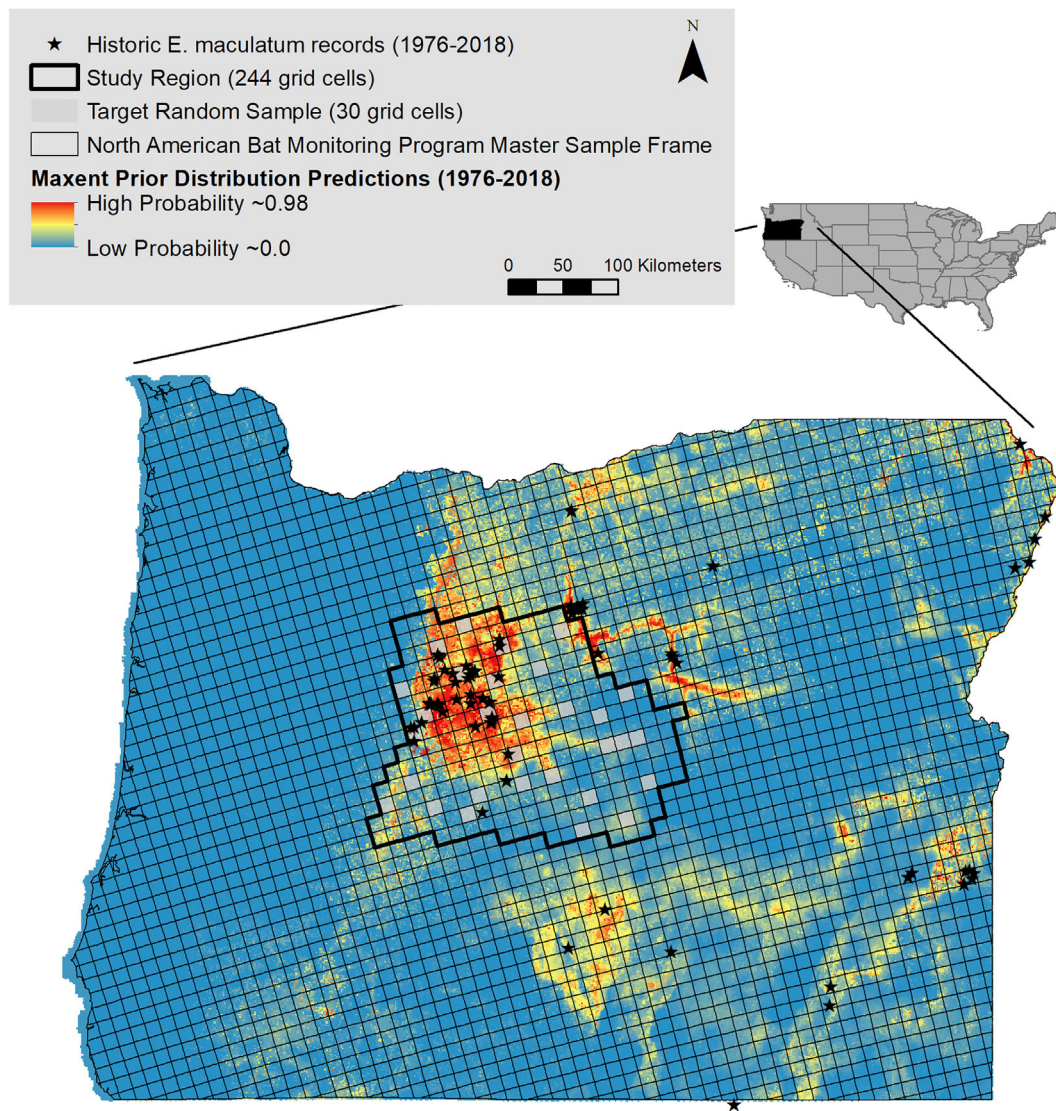


FIGURE 2 A map of Oregon (see inset) with historic *Euderma maculatum* records, the Central Oregon study region, the target random sample of 30 grid cells, and the background layers North American Bat Monitoring Program grid-based master sample frame overlaid on predictions from a presence-only *E. maculatum* distribution model produced using maximum entropy machine learning (Maxent). The high estimated *E. maculatum* occurrence probabilities correspond with the prominent aridland cliffs and canyon complexes of Eastern Oregon

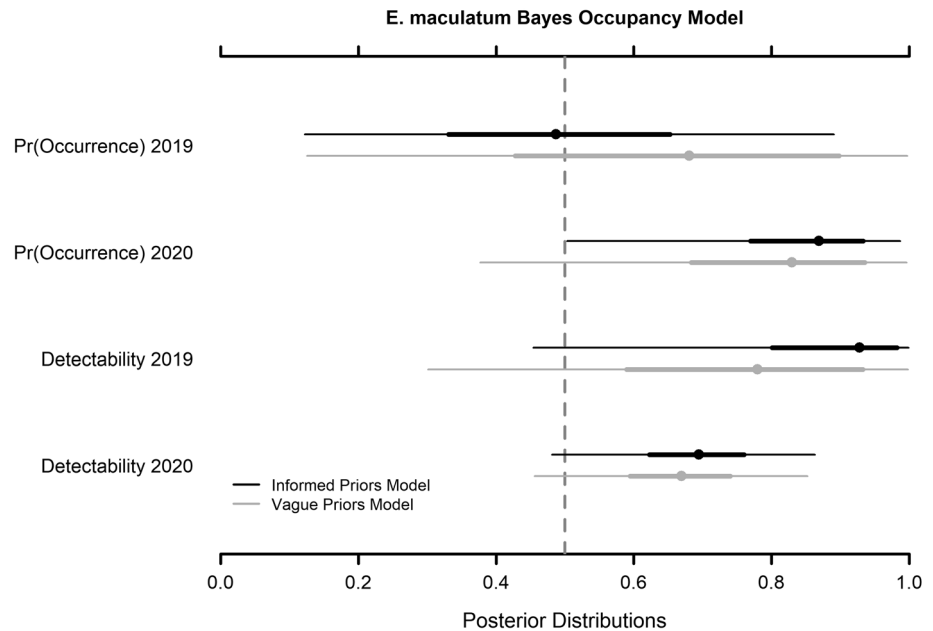
SD of cliff and canyon grid cell % cover for the sample was similar to the entire 244 grid cell region, 0.075 ± 0.24 vs. 0.084 ± 0.24). However, we also accepted additional encounter records from grid cells out of the randomized target sample in order to encourage volunteer participation and increase our pilot study data set size.

Using our project Geographic Information System, we examined each target grid cell for accessibility and land ownership, and to identify candidate listening sites at or near cliffs and open landscapes where encounters were most likely to occur. We used world wide web applications for mobile computing devices (i.e., smartphones) from CitSci.org, AvenzaMaps.com, and iNaturalist.org to enable participants to navigate to survey locations and to

record observations. These phone apps were accessible even when off-line in rugged terrain without cellular reception. Maps, training video and quiz, event calendar, and our field reference manual (Supporting Information) were provided through our CitSci.org project site (https://www.citsci.org/CWIS438/Browse/Project/Project_Info.php?ProjectID=2273).

Volunteers were recruited through a public outreach campaign involving news media and bat conservation lectures delivered at public libraries and other venues (Supporting Information). Volunteers were trained in the field where *E. maculatum* was certain to be heard and, during the Covid-19 global pandemic, via internet webinar using audio recordings of *E. maculatum*. We also

FIGURE 3 Probability of occurrence and detectability parameter estimates (posterior distributions) for hierarchical Bayesian multi-season occupancy models fit to an encounter history of the spotted bat *Euderma maculatum* in Central Oregon, from aural surveys conducted by citizen scientists. One model (black) used priors informed by a preceding model, the other model (gray) used vaguely informative priors. Vertical dashed lines reference 0 and 1 for visualizing occurrence and detectability probabilities (0–1 scale)



utilized an interactive display with audio feedback (Supporting Information) for testing participants abilities to hear and distinguish among different audible species and background noise (e.g., crickets). Volunteers unable to demonstrate the ability to hear spotted bats during trainings did not contribute to the survey, although to foster public participation they were encouraged to contribute in other ways (e.g., assisting with navigation and driving). We used the CitSci.org portal for data entry (Supporting Information). Participants were assigned grid cell sample units in order to facilitate adherence to the master sample randomization. Surveys were conducted from June to September in 2019 and 2020. Each survey lasted 1 hr, beginning after civil sunset, and consisted of quietly listening for *E. maculatum* and *A. pallidus* calls, noting the time of each encounter, and other ancillary details of each observation including site photographs uploaded to the project website for future reference.

2.2 | Data analysis

We used two regional species distribution models for *E. maculatum* developed prior to our study as articulated hypotheses to guide our study design and analysis. The Bayesian hierarchical multi-season occupancy model developed by Royle and Dorazio (2008) and applied by Rodhouse et al. (2015) to acoustic and capture encounter records for 14 bat species, including *E. maculatum* and *A. pallidus*, collected during 2003–2010, described regional relationships between species occurrence probabilities and environmental gradients at coarse grain (100 km² North American Bat Monitoring Program grid

cells). We included grid cell mean elevation, *SD* of elevation (as a measure of topographic roughness), 30-year mean annual precipitation, % forest land cover, and % cliff and canyon land cover as covariates (see Rodhouse et al., 2015 for additional details). Most notable for our target species was the strong association with arid land cliffs and canyons. Bat encounter data available from that study were sparse for *E. maculatum* and *A. pallidus* relative to other bat species and model predictions were not mapped by Rodhouse et al. (2015).

We also developed a finer-grained (30 m² resolution) distribution model (Figure 2) using maximum entropy machine-learning (Maxent; Philipps, Anderson, & Schapire, 2006) with bioclimatic and land cover predictor data and presence-only *E. maculatum* encounter records available for the state of Oregon over the period 1976–2018 from published sources including data used by Rodhouse et al. (2015) and others (Rodhouse et al., 2005; Verts & Carraway, 1998). Mapped predictions from this model reinforced low-elevation arid land cliffs and canyons as broadly important biogeographic predictors of *E. maculatum* distribution patterns and highlighted our topographically-rugged central Oregon study region as an area of above-average probabilities (Figure 2).

We used the new set of encounter records obtained through our citizen science study during 2019–2020 to update the *E. maculatum* multi-season occupancy model developed by Rodhouse et al. (2015), with some modifications to the detection-level model component, predicting occurrence probabilities for the 244 grid cells in our study region (Figure 2), a subset of the broader grid-based master sample. We included the same occupancy-level environmental covariates as were used by Rodhouse

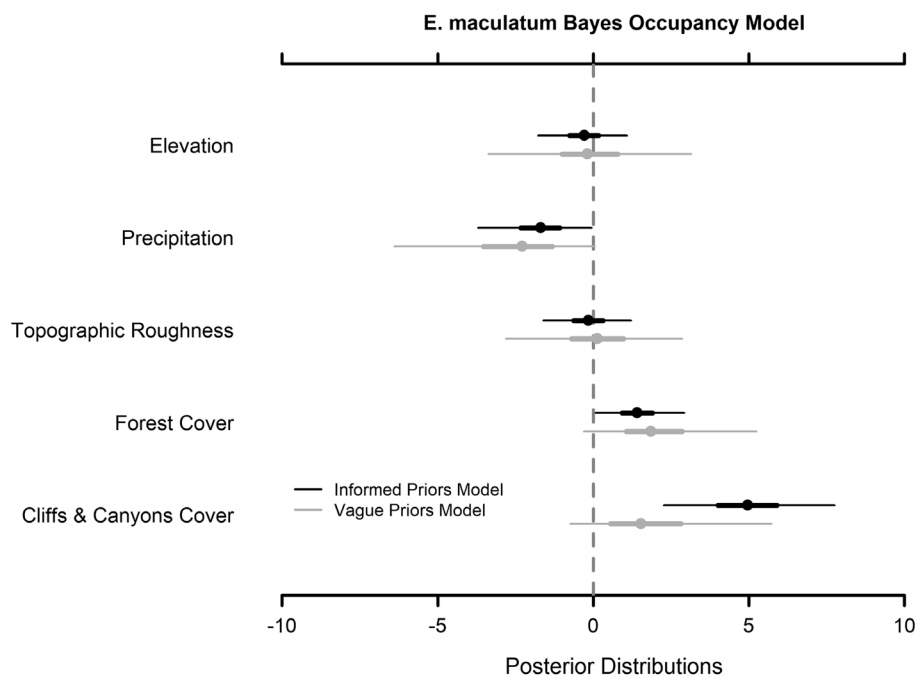


FIGURE 4 Environmental covariates parameter estimates (posterior distributions) for hierarchical Bayesian multi-season occupancy models fit to an encounter history of the spotted bat *Euderma maculatum* in Central Oregon, from aural surveys conducted by citizen scientists. One model (black) used priors informed by a preceding model, the other model (gray) used vaguely informative priors. Vertical dashed lines reference 0 and 1 for visualizing occurrence and detectability probabilities (0–1 scale)

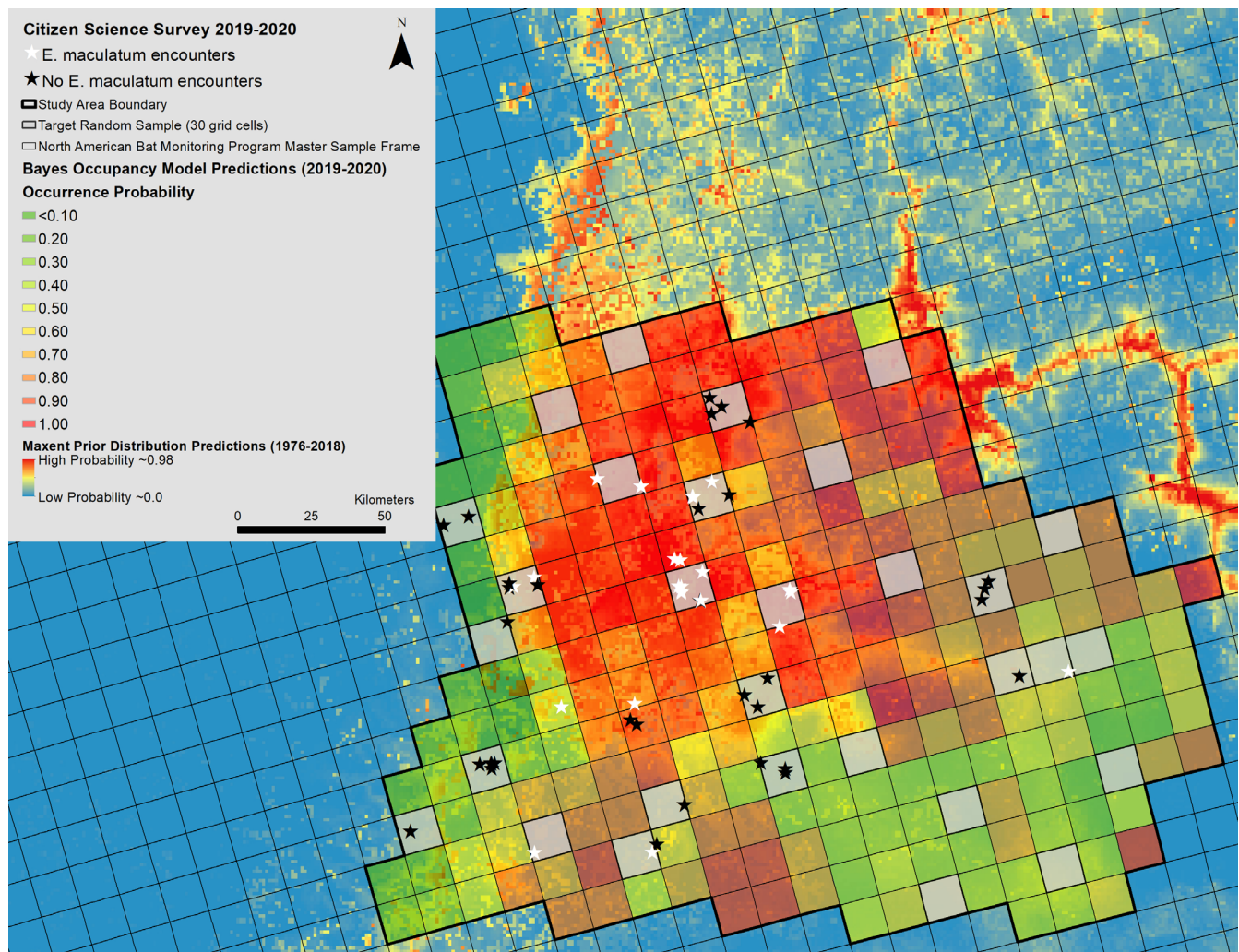


FIGURE 5 A map of *Euderma maculatum* occurrence probability predictions from a hierarchical Bayesian multi-season occupancy model across 244 grid cells covering the Central Oregon study region, a subset of the North American Bat Monitoring Program master sample frame

et al. (2015; grid cell mean % cover of forest, % cliffs and canyons, elevation, *SD* elevation, 30-year annual precipitation), and a simple intercept-only false-negative detection model, acknowledging that a richer observation process model that also accounts for false-positive error (e.g., because inexperienced observers may inadvertently record a spotted bat that is in fact another noise, crickets, etc.) will be more satisfying in future when more data are available. Notably, the COVID-19 pandemic limited our ability to complete our survey sample size goals.

We used the Bayesian modeling software JAGS (Just Another Gibbs Sampler; Plummer, 2003) run from R statistical computing software (R Core Team, 2020) to fit the model and generate predictions. We used posterior summaries from the 2015 model parameters as informative priors. We compared results (parameter posterior distributions) between the informative priors model and an alternative vague priors model, following the general approach described by Rodhouse et al. (2019) and Banner, Irvine, and Rodhouse (2020).

3 | RESULTS

We were assisted by 12 volunteers to conduct 61 surveys in 20 of the 30 targeted grid cell sample units. Encounters with *E. maculatum* were reported from 25 of the 61 surveys, and from 11 sample units. One encounter with *A. pallidus* was also reported from one survey. Several observers reported multiple simultaneous detections, suggesting multiple individual bats (i.e., “minimum number known alive”) that could add additional abundance information to audible survey results in future (e.g., using N-mixture models; Kery & Royle, 2021). Several observers noted uncertainty in their detection confidence, suggesting that observer confidence and experience could be combined with voucher recordings and double observation methods to support false-positive error estimation in future (Kery & Royle, 2021).

Our informative priors occupancy model for *E. maculatum* provided similar, but more precise estimates than the vague priors model (Figures 3 and 4). Inferences from both models suggested relatively high average detection and occurrence probabilities ($\sim 0.7 \pm 0.1$ and $\sim 0.8 \pm 0.1$ in 2020, respectively), with increasing posterior precision in the second year (2020) as additional information became available (Figure 3). Our models also demonstrated strong positive trends in *E. maculatum* occurrence probabilities along the forest and canyons land cover gradients (Figure 4). Occurrence probability also appeared to trend negatively with precipitation but no trend along the elevation and topographic

roughness (elevation *SD*) gradients (Figure 4). Prediction patterns from this model were similar to the a priori presence-only species distribution model, albeit at coarser aggregate resolution per the grid-based sampling frame (Figure 5).

4 | DISCUSSION

We developed and tested a new way for public participation in the science and practice of bat conservation via a vis aural surveys of audible bats. We recruited, trained, and coordinated community members to assist us in the survey of the geographically widespread but rarely encountered spotted bat, *Euderma maculatum*. We also listened for and encountered on one occasion the social calls of the pallid bat, *Antrozous pallidus*, suggesting that with additional effort this species could also be effectively surveyed using our method. We embedded our survey within the random master sample survey design and analytical framework of NABat (Loeb et al., 2015; Reichert et al., 2021), which added scientific validity and makes our approach scalable across western North America where these and other audible species (e.g., *Eumops perotis*; Best et al., 1996) occur.

Our 2-year study succeeded in generating new distributional insights about *E. maculatum* (Figure 5). By leveraging prior information in a Bayesian modeling framework (Banner et al., 2020; Rodhouse et al., 2019), we could map predicted probabilities of occurrence for the first time, overcoming past limitations from encounter data sparsity (Rodhouse et al., 2015). We found strengthened evidence from our updated model that in our study region *E. maculatum* occurs most often in dry woodlands and forested canyons, particularly in the north-central portion of the study region where several large river canyons confluence (Figure 5). We found no evidence of a strong elevational gradient and in fact several of our new encounter records extended the local distribution upslope into the Cascade Mountain Range farther than our previous understanding of the species' distribution. We also succeeded in estimating probability of detecting (1 minus false-negative detection error) the species using aural surveys. This is the first published attempt to do so, and although we consider ours a proof-of-concept study and our results provisional, our estimate of ~ 0.7 (Figure 3) is encouraging and considerably higher than when using traditional capture and acoustic methods (e.g., Rodhouse et al., 2015). Notably, we were not also able to generate enough replicate survey data to inform a false-positive detection model in order to estimate the probability that observers mistakenly recorded spotted bat encounters (e.g., if background noises were

thought to be spotted bats). However, our survey and modeling framework is readily extensible to do so and this will be a requisite advancement when scaling our approach up to broader regions and longer time frames. Double-observer methods (e.g., when pairing two or more observers within a single survey event) and use of voucher recordings can be used in a site- or observation-confirmation false-positive occupancy model survey design (Banner et al., 2018; Chambert, Miller, & Nichols, 2015; Kery & Royle, 2021).

There are global opportunities for public participation in the survey of audible bats, many of which remain rare and poorly described. Bats that call at low frequencies tend also to be fast, high-flying species, often of arid regions, that are not well surveyed using typical methods (Jones, 1999). For example, Lison et al. (2019) advocated for more citizen science survey efforts to better populate distribution and abundance data sets of rare desert bats, and our study provides a way forward to help address this need. We recognize several ways to improve on our own study that will benefit others. First, establish robust methods to train and screen observers' ability to hear the target species. This will be particularly important in areas where multiple audible species occur, or when audible bats are easily confused with background noises. Second, use recordings of voucher echolocation calls and/or paired double observers at a subset of surveys to support the estimation of false-positive error (Banner et al., 2018; Chambert et al., 2015; Kery & Royle, 2021; Santos-Fernandez, Peterson, Vercelloni, Rushworth, & Mengersen, 2020). Third, sample size, including in both the temporal (replicated within seasons) and spatial dimensions must be large and geographically extensive (e.g., in our case grid cell sample units ideally exceed $n = 100$ across the broader region of interest, see Banner, Irvine, Rodhouse, Donner, & Litt, 2019) in order to support analytical flexibility and desired inferences (e.g., richer observation process models supported by many within-season replicates to estimate both false-negative and false-positive error). Fourth, multiple coordinating teams (e.g., bat hubs; Reichert et al., 2021) need to collaborate and introduce incentives for public participation in order to establish regional or range-wide inferential extents and contribute meaningfully to broad-scale bat ecology and conservation (Callaghan, Rowley, Cornwell, Poore, & Major, 2019; Dickinson et al., 2010). Fifth, clearly-communicated coordination and data management is essential, and likely requires funding dedicated staff in the coordinating organization (Tulloch et al., 2013). Finally, embedding a citizen survey of audible bats as an augmenting method into an existing multi-method survey design such as we did with NABat will leverage resources and expertise, reduce the amount of non-random convenience sampling and associated biases (e.g., Dambly, Jones, Boughey, & Isaac, 2020),

and increase participant retention and long-term success. Participant retention can be aided by the integration of acoustic recorders (e.g., to obtain voucher recordings) and mobile data management technologies (e.g., smartphone apps) that will be particularly engaging to some potential participants (particularly youth; Newman et al. 2012).

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Conceptualization: Thomas J. Rodhouse. Data Collection: All authors. Data management and analysis: Thomas J. Rodhouse, Sara Rose, and Trent Hawkins. Original draft writing: Thomas J. Rodhouse. Review and editing: All authors.

DATA AVAILABILITY STATEMENT

Data and JAGS models are available online at: <https://irma.nps.gov/DataStore/Reference/Profile/2285244>.

ETHICS STATEMENT

This research did not involve capture and handling of animal subjects and only reported results from noninvasive aural (listening) surveys. We therefore did not require an animal ethics approval for this work.

ORCID

Thomas J. Rodhouse  <https://orcid.org/0000-0001-5953-9113>

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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