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RESEARCH ARTICLE

Using autonomous recording units to identify and monitor western yellow-billed cuckoo habitat

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Abstract

Autonomous recording units (ARUs) paired with signal classification software can be used to detect species-specific calls, making them useful for evaluating patterns in avian occurrence and activity. However, classification of target signals is not always reliable and may be especially challenging for species that vocalize infrequently. We assessed the use of ARUs to identify and monitor habitat for a cryptic and federally threatened distinct population segment, the western yellow-billed cuckoo (*Coccyzus americanus*) in mountainous xeroriparian drainages. Using Kaleidoscope Pro, we developed a call-classifier and processed acoustic data collected in sites also surveyed using traditional human-observer methods, applying the same spatial and temporal detection criteria to estimate breeding territories for each method. The classifier detected a total of 4,061 true positive calls at 4 sites, had an overall precision score of 0.07, recall score of 0.09, and F-score (beta = 1) of 0.08, indicating high false positive and false negative classification rates. Our results were, however, consistent with other ARU studies of rare and cryptic species and ARUs estimated occupancy as effectively as human surveys with as little as 2 hours of daily recording. Total detections varied among sites, likely due to differences in cuckoo population densities and the interaction between topography and ARU detection space. Our results suggest that despite performance shortcomings of call-classifiers, ARUs can be effective for monitoring cuckoos, with potential for providing higher resolution temporal and spatial information on activity and habitat use and may be particularly effective in remote locations where cuckoos often occur.

KEYWORDS

acoustic monitoring, autonomous recording unit, bioacoustics, *Coccyzus americanus*, cryptic, xeroriparian, yellow-billed cuckoo

Use of autonomous recording units (ARUs) to passively survey and monitor birds has rapidly increased over the past decade (Shonfield and Bayne 2017, Gibb et al. 2019). With long battery life, customizable recording schedules, and high data storage capacity, modern ARU hardware offers the ability to obtain large amounts of acoustic data over long durations with minimal maintenance. Recent advances in data processing software allow for semiautomated detection and classification of target signals in large datasets (Potamitis et al. 2014). Together, ARUs and data processing software provide innovative methods for avian monitoring and research, which can complement or even outperform traditional human-observer methods such as point counts or playback surveys (Hutto and Stutzman 2009, Alquezar and Machado 2015, Darras et al. 2018). Acoustic monitoring programs have also been used to investigate temporal and spatial patterns in vocalization rates (Pérez-Granados and Schuchmann 2020, Bateman et al. 2021) and in occupancy studies of birds (Campos-Cerqueira and Aide 2016, Abrahams and Geary 2020). Increased use of ARUs has also revealed limitations and challenges (Shonfield and Bayne 2017, Gibb et al. 2019) such as variable performance among software platforms and time-consuming manual verification of classifier detections (Knight et al. 2017). In addition, the amount of data generated by ARUs can become very large depending upon how long ARUs are programmed to record, but few studies have assessed how reduced sampling schemes may affect detection capability (Clément et al. 2021).

The use of ARUs to evaluate occurrence or breeding status of rare or cryptic species may be especially important given those species often have the greatest need for improved monitoring programs to aid in conservation and recovery efforts (Sidie-Slettedahl et al. 2015, Bobay et al. 2018, Schroeder and McRae 2020, Manzano-Rubio et al. 2022). This is the case for the federally threatened distinct population segment of the western yellow-billed cuckoo (*Coccyzus americanus*). Historically found in riparian habitat from northern Mexico to southern British Columbia (Hughes 2015), populations of this species have declined due to habitat loss and degradation (U.S. Fish and Wildlife Service [USFWS] 2014), with most remaining populations located in Arizona, New Mexico, California, and Sonora (USFWS 2021). Traditional human observer call-playback protocols have been developed for surveying yellow-billed cuckoos and estimating breeding status based on the temporal and spatial patterns of detected cuckoos (Halterman et al. 2015), and this information has been used to estimate population size and designate critical habitat (USFWS 2021). Most of these survey efforts have focused primarily on riparian areas where cuckoos most commonly occur, but recent records and studies in southeastern Arizona confirm that cuckoos are also breeding in xeroriparian habitats (Griffin 2015, Corson 2018, eBird 2021, Beauregard 2023). Populations of cuckoos in xeroriparian habitats likely represent a large addition to the estimated western population segment, but the geographical extent of use of these habitats remains unclear due to limited survey data. If ARU methods can be developed to survey for cuckoos, biologists and land managers might add an important alternative tool to current human-based surveys, which can be resource intensive and infeasible in many remote locations.

Yellow-billed cuckoos are notably cryptic (Hamilton and Hamilton 1965, Johnson and Benson 2022) and vocalize relatively infrequently at approximately once per hour (Halterman 2009). Yellow-billed cuckoos may be strong candidates for ARU-based survey methods, however, given their distinctive vocalizations which may contribute to efficient detection by signal classification software. Yellow-billed cuckoos also maintain large home ranges, particularly while foraging, advertising for mates prior to nest initiation, and during pair interactions (Hamilton and Hamilton 1965, Halterman 2009, Sechrist et al. 2013). These behaviors, which often include vocalizing, increase the likelihood of detection by ARUs deployed in a fixed location, even if the ARU is not near the nest.

We investigated the utility of using ARUs to identify western yellow-billed cuckoo habitat by comparing the efficacy of ARUs and signal classification software to detect cuckoos to that of human observers at 5 field sites in southeastern Arizona xeroriparian habitat. In the process, we developed and evaluated the performance of a semiautonomous classifier for cuckoo calls using Kaleidoscope Pro (Wildlife Acoustics Inc., Maynard, MA, USA). We then examined seasonal and daily vocal activity based on detection results. Finally, we tested subsets of our full acoustic dataset to simulate commonly used ARU recording schedules to identify the optimal timing and duration of recording that would most efficiently identify cuckoo habitat.

STUDY AREA

Our study was conducted in southeastern Arizona, USA, within the Madrean Sky Islands Archipelago region (Warshall 1995). Temperature and precipitation in this region vary with elevation, ranging from an average annual temperature of 84°F (28.9°C) and average annual rainfall of 27 cm in Tucson at 730 m elevation, to 77.7°F (25.4°C) and 33 cm in Sierra Vista at 1,700 m (NOAA 2023). We chose 5 field sites located in drainage bottoms in the Coronado National Forest and Buenos Aires National Wildlife Refuge. Sites were chosen nonrandomly to ensure accessibility for surveyors and locations where cuckoos had been documented previously, while also representing the variation in geomorphology and vegetative structure and composition typical of areas used by cuckoos in xeroriparian habitat. All sites were in mid-elevation (~1,000–2,000 m) ephemeral drainages. Geomorphology ranged from a broad, shallow valley to a narrow, sinuous, steep-walled canyon. Habitat consisted primarily of Madrean oak woodland, semidesert grassland (Brown 1994), with xeroriparian and riparian vegetation interspersed along the drainage bottom, consistent with southwestern cuckoo breeding habitat as previously described (USFWS 2021).

METHODS

Protocol call-playback surveys

We surveyed sites using a standard survey protocol developed to monitor western yellow-billed cuckoos that requires 4 survey visits per site, spaced 10–15 days apart, within a survey season lasting from June 15–August 15 (Halterman et al. 2015). Each survey required the use of call-playback to elicit responses from cuckoos at 100-m intervals along a survey transect that follows a drainage bottom. Transects were 2 km in length and divided into 0.5 km segments for our analyses. If cuckoos were detected during survey visits, we made additional visits to confirm breeding status by searching for nests or other evidence of breeding including copulation, nest building, fledglings, or distraction displays. Nest searching effort varied among sites, and nests were not monitored intensively, therefore we were not able to determine a definitive number of nests in a site.

Yellow-billed cuckoo vocalizations

Adult yellow-billed cuckoos produce several call types (Hamilton and Hamilton 1965, Hughes 2015), but we focused on the 2 most commonly observed: coo and contact calls (Figure 1). Coo calls are hypothesized to be produced primarily by females advertising for mates (McNeil et al. 2013). Coo calls are often given as a series of

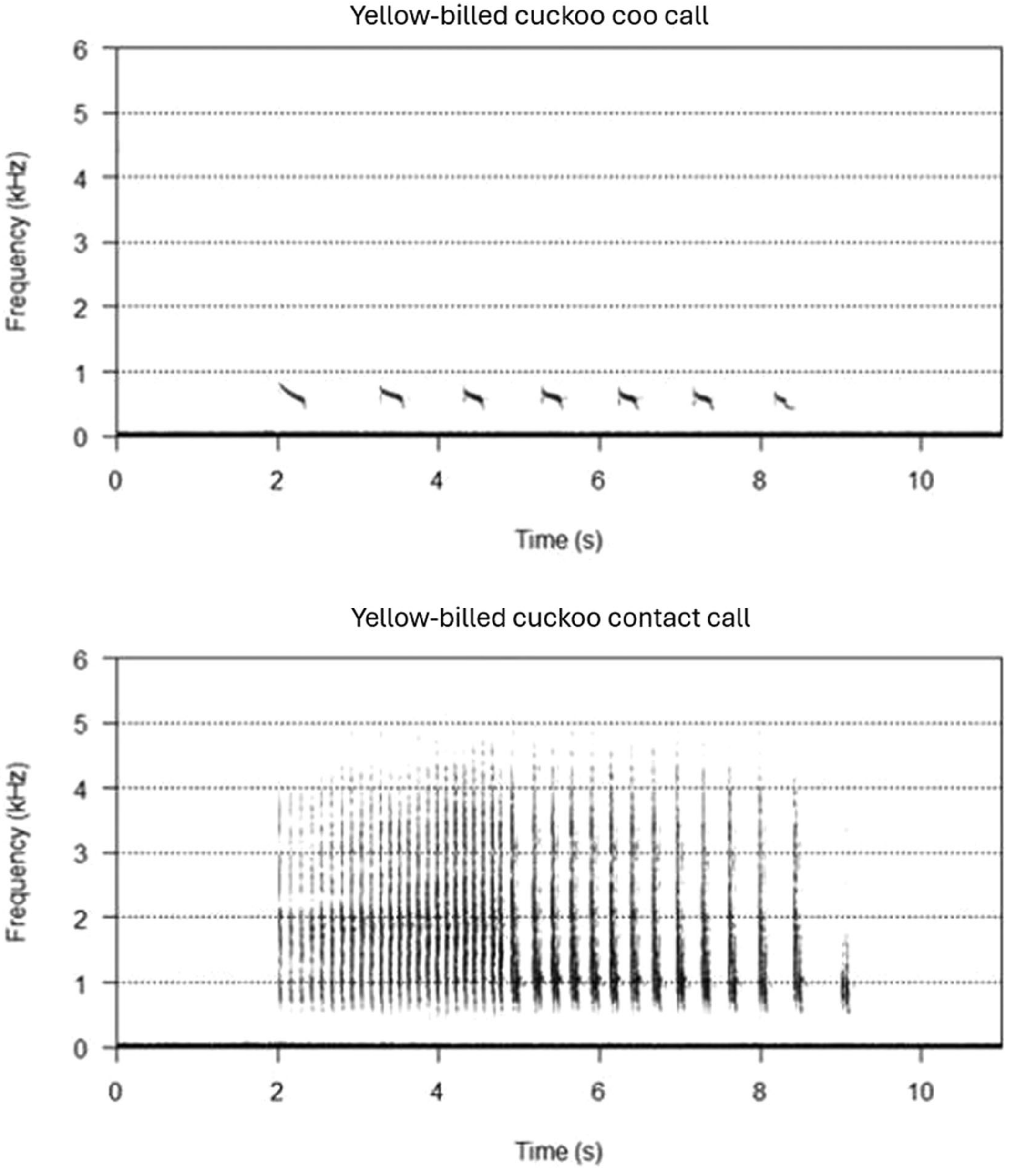

FIGURE 1 Spectrogram of the western yellow-billed cuckoo's (*Coccyzus americanus*) coo call (top) and contact call (bottom). Because coos are typically given as a series of repeated individual notes, the coo call shown here, consisting of a series of 7 individual coo notes, would have been considered a single coo call in our analysis. Likewise, the multiple notes given in rapid succession in the contact call shown here would be considered a single contact call in our analysis. Both vocalizations were recorded at Cherry Creek in the Canelo Hills in the Coronado National Forest, Arizona, USA, in 2018.

~5–11 individual coo notes. A cooing bout may last for only one series of coo notes, but more typically lasts for several minutes or more with repeated series of coos separated by a brief pause of approximately 0.5 seconds (Hughes 2015). For this analysis, each individual series of coo notes was counted as a single full coo call, rather than each individual coo note.

Contact calls are the call type used for playback during protocol surveys and are commonly observed but rarely given more than once per 10-minute period (Hughes 2015). More variable in structure than coo calls, contact calls typically consist of several introductory kuk notes followed by a series of kowlp notes (Figure 1), but variations are also given consisting of only kuk (often considered an alarm call) or only kowlp notes (Hamilton and Hamilton 1965, Hughes 2015).

Autonomous recording unit deployment

Within each site, 4 ARUs (Model SM4, Wildlife Acoustics, Inc., Maynard, MA, USA) were deployed along the transect at 500-m intervals, beginning 250 m past the initial start point of the transect and ending 250 m before the stop point. Thus, each transect was divided into 4 segments of 500 m in length with the ARU in the center of each. All ARUs were deployed prior to the start of the survey season (June 15) and were retrieved in October. Each unit was affixed to a small-diameter tree (<10 inches DBH) using nylon webbing at a height of approximately 2 m from the ground, and no further than 25 m from the drainage bottom. To avoid tampering or theft, ARUs were deployed away from trails or roads. All ARUs were set to record continuously every day from 04:00–11:00 at a sampling rate of 22,050 Hz and were inspected by surveyors during each site visit.

Determining ARU range

Detection probability varies among ARUs deployed at different locations due to the attenuating effects of environmental factors on sound detection space (Darras et al. 2016). Therefore, acoustic monitoring programs must account for potential variation in acoustic range when comparing results from different sites (Darras et al. 2016, Manzano-Rubio et al. 2022). To determine the approximate range of each ARU at our sites, we used a portable speaker (Model Clip 3, JBL, Los Angeles, CA, USA) to broadcast the recording of the cuckoo's contact call used for standardized playback surveys from distances of 1 m, 100 m, 200 m, 300 m, and 400 m from the actively-recording ARU. Calls were broadcast at 70 dB sound pressure level (SPL) at 1-m distance from a handheld sound level meter, as recommended by the survey protocol (Halterman et al. 2015). We then viewed the spectrograms of the recordings, isolated the clips of the recorded playback, and used the Kaleidoscope Pro SPL analysis feature to measure the maximum sound pressure level (in dB) and identified the distance at which playback calls were no longer detected. The pressure levels were plotted against the distance interval at which they were recorded, resulting in a distance attenuation curve for each individual ARU.

Acoustic analysis

Kaleidoscope Pro software (Wildlife Acoustics, Inc., Maynard, MA, USA) uses cluster analysis algorithms to process acoustic data and sort detected signals into individual clusters of statistically similar signals. Users can develop classifiers for target signals by reviewing the cluster analysis output and manually sorting target signals and non-target signals into separate clusters. Subsequent reprocessing of the data trains the algorithms based on these manual verifications, resulting in a classifier that can then be used to process new datasets. User-defined signal parameters such as frequency window, minimum and maximum duration of signals, and maximum intersyllable gap also act as data processing filters.

We developed a classifier to include clusters for both coo and contact calls. Building a classifier requires training data containing numerous examples of the target signals from which clusters can be formed, as well as background data containing examples of other signals present in the acoustic environment which are discriminated against. Cuckoos vocalize relatively infrequently, so we assumed that a given period of continuous acoustic data may contain very few cuckoo vocalizations relative to other signals, which may inhibit the software's ability to form distinct clusters around vocalizations. To address this, we used Raven Pro software (Cornell University, Ithaca, NY, USA) to view spectrograms from a subset of acoustic data from ARUs deployed near cuckoo nests in 2018 during a pilot study. We manually isolated 879 examples of cuckoo vocalizations that were clear and unobstructed by other species' vocalizations or background noise, which we then combined with 64 hours of background data audio files from our field sites to be used as a training dataset.

We manually inspected examples of spectrograms of coo and contact calls as well as the background data to inform our choices of signal parameters for data processing. We used a 350–1,250 Hz frequency range to process data, noting that both calls exhibit their peak amplitudes in the range of approximately 500–1,000 Hz. We also used 0.5–10 seconds of detection length, and 0.5 seconds maximum intersyllable gap, as both call types also vary in their duration, and the gap between individual coo notes is often similar to that of the gap observed between kowlp notes of the contact call. For cluster analysis settings, we used a 1.5 maximum distance from cluster center for outputs, FFT window size of 512, 12 maximum stats, 0.5 maximum distance from cluster center for building clusters, and 500 maximum clusters, following recommendations provided in the user manual (Wildlife Acoustics 2022). The cluster analysis resulted in 33 clusters, which were manually reviewed and edited before subsequent reprocessing of the data to train the classifier. Finally, we processed all 2019 ARU data using the classifier.

Classifier performance assessment

To assess the performance of our classifiers, we used methods outlined in Knight et al. (2017). All signals that the classifier reported in the coo or contact clusters were manually reviewed to separate true positive calls from false positive signals. Manual review consisted of a visual inspection of the spectrogram of each reported signal in the coo and contact clusters. Additionally, all detected signals with spectrograms that superficially resembled cuckoo vocalizations (and which could not be confidently identified as another known signal by visual inspection) were reviewed auditorily to ensure that faint, obscure, or atypical cuckoo vocalizations were not mislabeled as false negatives. Reported signals confirmed to contain yellow-billed cuckoo vocalizations were counted as true positives and labeled either coo or contact. Signals not containing yellow-billed cuckoo vocalizations were labeled false positive.

To estimate a false negative rate, we manually reviewed a benchmark dataset (Knight et al. 2017), which was a subset of data consisting of 4, randomly-selected full days of data for each site. We calculated the number of coo and contact calls present within the benchmark dataset and compared these totals against the results of the classifier's true positive totals for the same data. This results in rates of false negatives that can be used as estimates for the overall dataset. We then used the rates of true positives, false positives, and false negatives for the coo and contact clusters to calculate precision, recall, and F-score of the 2 call types. Precision is a measure of the proportion of detections that are true positives. Recall is the proportion of calls present in the data that are detected by the classifier. F-score combines recall and precision to measure classifier performance as a single metric. To calculate these metrics, we used the following equations:

$$\text{Precision} = \text{TP}/(\text{TP} + \text{FP}) \tag{1}$$

$$\text{Recall} = \text{TP}/(\text{TP} + \text{FN}) \tag{2}$$

$$F = (\beta^2 + 1)\text{TP}/((\beta^2 + 1)\text{TP} + \beta^2\text{FN} + \text{FP}) \tag{3}$$

where TP is the rate of true positives (calls accurately classified in the coo or contact cluster), FP is the rate of false positives (non-cuckoo signals classified in the coo or contact cluster), and FN is the rate of false negatives (calls not accurately classified in the coo or contact cluster). In the F-score, β is a user-defined metric that allows for the prioritization of either precision or recall based on specific analysis goals. Precision is favored when $\beta > 1$ and recall is favored when $\beta < 1$, and precision and recall are balanced when $\beta = 1$ (Sokolova et al. 2006). We used a β value of 1.

Temporal call patterns

We used the true positive results of our classifier to evaluate the temporal patterns of calls detected. Total detected true positive calls were calculated for each call type at each ARU and plotted by date, with the goal of identifying patterns in activity before, during, or after estimated nesting cycles. We also calculated the total number of each call type detected during each hour of the morning to identify trends in peak vocal activity, which was used to guide development of optimized recording schedules.

Estimating occupancy

At the end of the field season, locations of cuckoo detections for each protocol survey were plotted in ArcGIS v. 3.2 (Esri, Inc., Redlands, CA, USA). Following protocol guidelines, we identified occupied territories as areas where cuckoos were detected during 2 or more survey periods, with survey visits separated by at least 10 days, with detection locations between surveys no greater than 500 m apart (Halterman et al. 2015). Importantly, we use the term occupancy here as an estimation of breeding status of detected cuckoos, as is defined by the Halterman et al. (2015) survey protocol, and not in the context of occupancy modeling (MacKenzie et al. 2002). Each 500 m segment was categorized as occupied according to protocol surveys if it contained at least one detection from an occupied territory. Therefore, multiple segments may be categorized as occupied from a single territory, but a site may only have a maximum of 4 occupied segments, even if greater than 4 occupied territories are estimated based on protocol surveys.

We then estimated occupancy in each segment using our true positive detection data obtained through ARUs and classifiers and applying the same spatial and temporal detection criteria. Detected cuckoo calls were grouped according to the ARU at which they were detected, and the survey period in which they occurred. If cuckoos were detected by the classifier at the same ARU during 2 or more survey periods (with the detections a minimum of 10 days apart), that ARU's segment was estimated to be occupied according to the acoustic data. We then plotted the occupancy estimates for both human-based surveys and ARU data in a table, allowing us to directly compare the 2 methods at individual sites and segments and determine whether the classifier results estimated occupancy at greater, fewer, or different sites and segments than traditional protocol surveys.

Optimizing deployment parameters

To determine whether reduced amounts of ARU data could yield reliable occupancy estimates, we compared occupancy estimates from protocol surveys against multiple subsets of our acoustic dataset (Table 1). We first used the results from our call patterns analysis to identify peak hours of call activity and reduce our full, 7-hour daily recording dataset to 2 new datasets of 3 hours daily and 2 hours daily. To each of these 3 datasets, we then applied 2 customized, intermittent recording schedules commonly used in research and management to further subset the data. These included a 5-minutes, on-off recording interval, and a 15-minutes-on, 45-minutes-off interval beginning

TABLE 1 Autonomous recording unit recording schedule simulations used to evaluate whether reduced recording times could yield accurate occupancy estimates of western yellow-billed cuckoos (*Coccyzus americanus*) compared to occupancy determined by human observers in southeastern Arizona, USA, field sites, 2018.

Begin/end times	Sampling	Hours of daily recording	Total hours of data per ARU
04:00–11:00	Continuous	7	420
05:00–08:00	Continuous	3	180
05:00–07:00	Continuous	2	120
04:00–11:00	5-min on-off	3.5	210
05:00–08:00	5-min on-off	1.5	90
05:00–07:00	5-min on-off	1	60
04:00–11:00	First 15 min/hr	1.75	105
05:00–08:00	First 15 min/hr	0.75	45
05:00–07:00	First 15 min/hr	0.5	30

at the top of each hour. This resulted in 9 separate recording schedules ranging from 0.5–7 hours of daily recording. We then compared the total number of segments estimated to be occupied for each recording schedule to identify the most efficient recording schedules that estimate occupancy as reliably as protocol surveys.

RESULTS

Protocol call-playback surveys

Yellow-billed cuckoos were detected in all 5 sites during protocol surveys, with a total of 46 detections during the 4 required protocol surveys between June 15–August 15. Based on protocol guidelines, 4 of 5 sites were considered occupied, with a total of 13 occupied segments, while the fifth site, Hunter Canyon, had detections during one survey and no evidence of breeding. Follow-up nest searching confirmed breeding at all 4 occupied sites. Detections at Hunter Canyon were presumed to be from nonbreeding, migrant, or transient birds. We therefore excluded data from this site for further analysis.

Determining ARU range

Contact calls played back at 70 dB were recorded at all ARUs in all 4 occupied sites when at 200 m distance, but the number of ARUs detecting calls varied from 0–4 across sites at 300 m distance, while no ARUs in any sites recorded playback calls at 400 m (Figure 2), indicating varying sound attenuation rates between sites and within sites.

Acoustic analysis

All ARUs were functional for the entirety of the field season and collected a total of 12,880 hours of acoustic data, which amounted to approximately 8 terabytes. Using the Kaleidoscope Pro classifier, a total of 58,303 signals were detected in the contact and coo clusters during the survey season between June 15–August 15, with 53,568

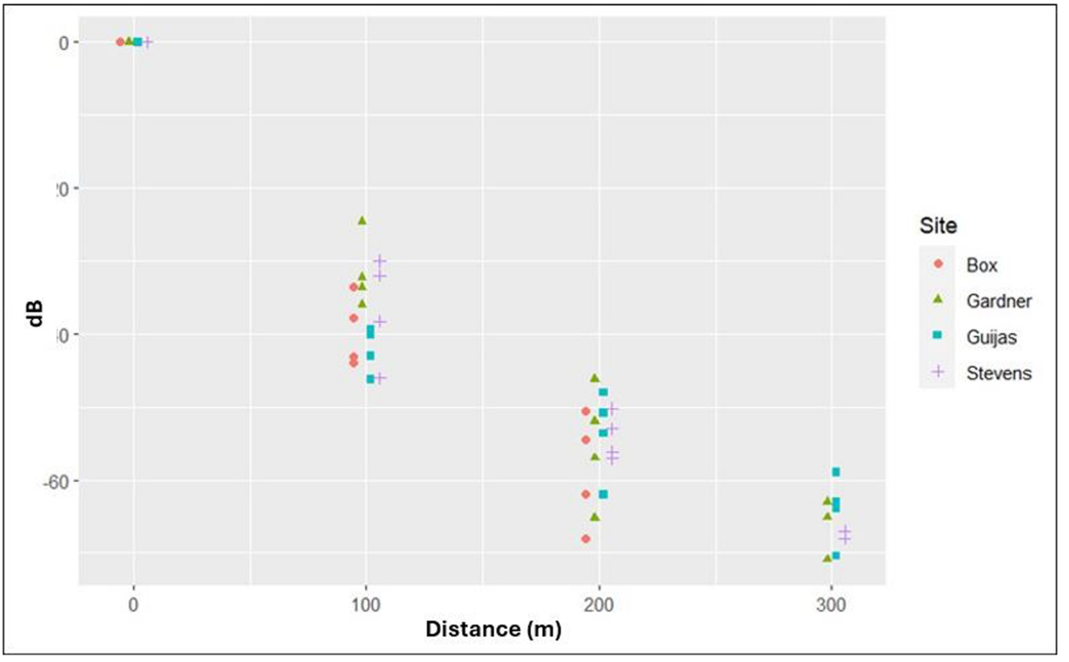

FIGURE 2 Changes in sound pressure level (relativized to 70 dB at 1 m) of recorded yellow-billed cuckoo (*Coccyzus americanus*) contact calls played back at 100-m interval distances at each autonomous recording unit within each of 4 occupied sites in southeastern Arizona, USA, in 2018. No ARUs at any site recorded playback calls beyond 300 m.

TABLE 2 Results from Kaleidoscope Pro classifier for 2 yellow-billed cuckoo (*Coccyzus americanus*) call types at 4 sites in southeastern Arizona, USA in 2018, including the total number of detections in each call's cluster, and the true positive detections from each classifier as determined through manual review.

	Classifier detections			True positive detections		
Site	Coo	Contact	Total	Coo	Contact	Total
Stevens Canyon	371	1,806	2,177	286	9	295
Las Guijas Wash	2,528	37,766	40,294	1,084	1,194	2,278
Gardner Canyon	1,230	6,794	8,024	963	305	1,268
Box Canyon	606	7,202	7,808	119	108	227
Overall	4,735	53,568	58,303	2,452	1,616	4,068

detected signals classified into the contact call cluster, and 4,735 signals classified into the coo call cluster (Table 2). Manual review of all detections in the contact and coo clusters took approximately 40 hours and resulted in 4,061 true positive calls detected (1,609 contact and 2,452 coo).

Classifier performance assessment

The true positive rate was 51.78% for coo calls and 3.02% for contact calls, with a combined overall true positive rate for both the coo and contact clusters of 6.98%. The majority of false positives in the contact call

TABLE 3 Performance metrics of a Kaleidoscope Pro classifier for 2 yellow-billed cuckoo (*Coccyzus americanus)* call types across 4 sites in Arizona, USA in 2018.

	Coo performance			Contact performance			Overall Performance		
Site	Precision	Recall	F-score	Precision	Recall	F-score	Precision	Recall	F-score
Stevens Canyon	0.77	0.54	0.63	0.00	0.01	0.01	0.14	0.14	0.14
Las Guijas Wash	0.43	0.67	0.52	0.03	0.03	0.03	0.06	0.09	0.07
Gardner Canyon	0.78	0.61	0.68	0.04	0.05	0.05	0.16	0.20	0.18
Box Canyon	0.20	0.19	0.19	0.01	0.02	0.02	0.03	0.03	0.03
Overall	0.52	0.51	0.52	0.03	0.03	0.03	0.07	0.09	0.08

cluster were from yellow-breasted chats (*Icteria virens*), cactus wrens (*Campylorhynchus brunneicapillus*), and Mexican jays (*Aphelocoma wollweberi*), while the majority of false positives in the coo call cluster were from greater roadrunners (*Geococcyx californianus*) and several species of dove and nightjars, as well as cattle and anthropogenic sources.

Manual review of the benchmark dataset resulted in 544 contact calls and 638 coo calls. Of these, the classifier detected 69 contact calls and 325 coo calls, resulting in a false negative rate of 86.58% for contact calls and 49.06% for coo calls. The contact call cluster resulted in a precision score of 0.03 and a recall score of 0.03, with an F-score ($\beta = 1$) of 0.03, whereas the coo call cluster resulted in a precision score of 0.52 and a recall score of 0.51, with an F-score ($\beta = 1$) of 0.52 (Table 3). With both clusters combined, the classifier resulted in an overall precision score of 0.07 and recall score of 0.09, with an F-score ($\beta = 1$) of 0.08.

Temporal call patterns

Across our 4 occupied sites, the total number of true positive calls detected ranged from 225–2,270 per site and the number of days on which calls were detected ranged from 17–61 days per site between June 15 and August 15. We detected only 2 true positive calls, both on a single day, at our fifth site (Hunter Canyon), which was consistent with protocol survey results of an unoccupied status, and we therefore removed this site from further analysis. Coo calls accounted for 60% of all detected true positive calls. However, contact calls were detected on more days overall (62) than coo calls (55).

For both call types, calls were most commonly detected between 0500 and 0700, consistent with previous observations by Hamilton and Hamilton (1965), with a downward trend in subsequent morning hours (Figure 3). Overall, rates of contact calls peaked in the first half of July and slowly declined through August. Coo calls were largely driven by relatively few prolonged bouts of cooing and peaked once in late July and again in August.

Evidence of breeding was documented within 100 m of 3 individual ARUs, each at different sites. We also documented an additional 3 breeding locations within 250 m of ARUs, and one breeding location approximately 600 m from the nearest ARU. While the total number of calls detected varied among ARUs located near breeding territories, we observed spikes in coo calls detected during the estimated days of nest initiation and completion in all of these ARUs, particularly those <100 m from nests. At 2 sites, contact calls were consistently detected during the entire nesting period, with a slight decrease in daily detections during the middle of the estimated breeding period. At another site, no contact calls were detected during the estimated incubation period of a nest <100 m away from an ARU but contact calls were detected on adjacent ARUs during this time.

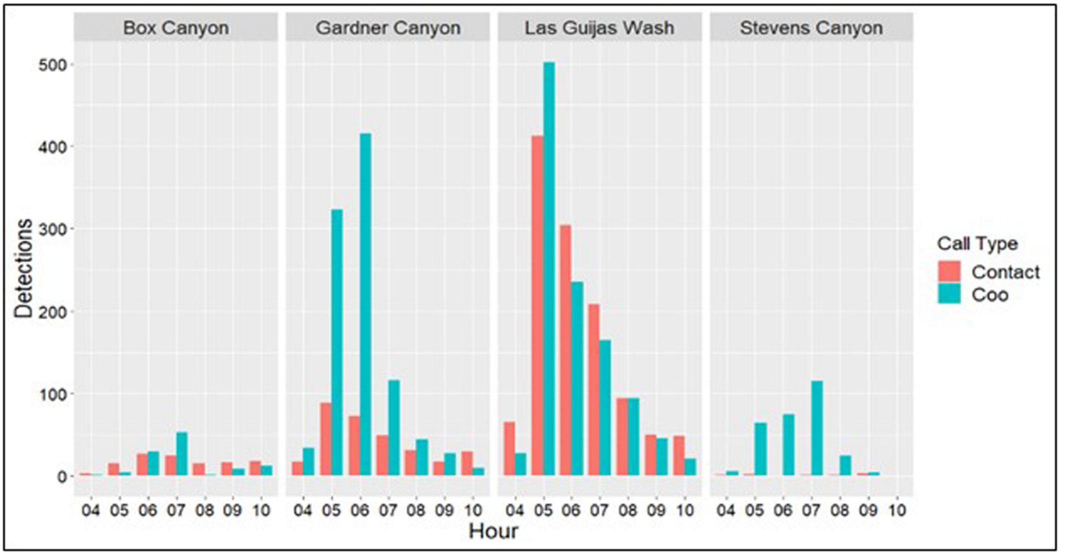

FIGURE 3 Total yellow-billed cuckoo (*Coccyzus americanus*) contact and coo calls detected each hour across 4 occupied sites in southeastern Arizona, USA, in 2018.

		Continuous recording			5-min intervals			First 15 min/hour		
Segment	Protocol Surveys	7 Hours	3 Hours	2 Hours	2 Hours (3.5 hrs/day)	3 Hours (1.5 hrs/day)	2 Hours (1 hrs/day)	7 Hours (1.75 hrs/day)	3 Hours (0.75 hrs/day)	2 Hours (0.5 hrs/day)
Gardner 1	O	O	O	O	O	O	O	O	O	O
Gardner 2	O	O	O	O	O	O	O	O	O	O
Gardner 3	O	O	O	O	O	O	O	O	O	O
Gardner 4	O	O	O	O	O	O	O	O	O	O
Las Guijas 1	O	O	O	O	O	O	O	O	O	O
Las Guijas 2	O	O	O	O	O	O	O	O	O	O
Las Guijas 3	O	O	O	O	O	O	O	O	O	O
Las Guijas 4	O	O	O	O	O	O	O	O	O	O
Box 1	O	O	O	O	O	O	O	O	O	O
Box 2	O	O	O	O	O	O	O	O	O	O
Box 3	O	O	O	O	O	O	O	O	O	-
Box 4	O	O	O	O	O	O	O	O	-	-
Stevens 1	-	O	O	O	O	O	-	O	-	-
Stevens 2	-	O	O	O	O	-	-	O	-	-
Stevens 3	-	O	O	O	O	O	-	O	O	-
Stevens 4	O	O	O	O	O	O	O	O	O	-

O	Occupied
-	Unoccupied

FIGURE 4 Occupancy table comparing results of yellow-billed cuckoo (*Coccyzus americanus*) protocol surveys against results of 9 unique recording schedules in each of 4 segments at 4 study sites with confirmed breeding activity in southeastern Arizona, USA, from June 15–August 15, 2018. Cells with green O represent an occupied segment, and cells with yellow - represent an unoccupied segment.

Estimating occupancy and optimizing deployment parameters

Protocol surveys resulted in 13 of 16 segments considered occupied while ARU data estimated 10 to 16 occupied segments depending upon recording schedule (Figure 4). The only 2 recording schedules which failed to identify the same segments occupied as the protocol surveys were those that used data recorded during 15 minutes of each hour during either 2 or 3 hours in the morning, a total of 30 and 45 minutes/day, respectively. The schedule that drew data from every other 5 minutes for the 2 hours between 0500 and 0700 (one hour of total acoustic data) resulted in the same segments being estimated as occupied as protocol surveys. However, using continuous recording from 0500–0700 or the first 15 minutes of each hour between 0400–1100 (1.75 hours of total acoustic data) resulted in all segments being estimated as occupied.

DISCUSSION

We found that acoustic data paired with classifiers reliably estimated positive yellow-billed cuckoo occupancy at all 4 sites that were also estimated to be occupied according to human observer protocol surveys. Given that behaviorally cryptic species pose unique challenges for conservation and monitoring (Martin et al. 2022), our results provide an important framework for expanding survey efforts for cuckoos. Although detection totals varied between these sites, all segments within each of these sites retained their positive occupancy estimation even under reduced recording schedules. At our fifth site, cuckoos were detected using both survey methods early in the season with no subsequent detections, and both methods estimated the site as unoccupied. Our results demonstrated the ability of ARUs to efficiently identify cuckoo habitat comparable to protocol surveys and provides insights into cuckoo vocal activity that will benefit future acoustic monitoring programs.

All of our ARUs detected contact call playbacks at distances to 200 m, and 56% of our ARUs detected contact call playbacks at 300 m. We only measured detection distance of call playback at a specific volume, however, and therefore these results do not reflect the detection distance of actual cuckoo calls. Range of ARUs has been shown to depend on many factors, including local conditions at deployment sites, and the characteristics of the focal species' calls (Darras et al. 2016, Kreh et al. 2023, Winiarska et al. 2024). For example, Kreh et al. (2023) found that gobbling from wild turkeys (*Meleagris gallopava*) was detected at distances up to 300 m, but detection distance was negatively affected by topographic features. Tegeler et al. (2012) and Winiarska et al. (2024) both identified maximum detection distances of less than 200 m for several small- to medium-sized birds, although Winiarska et al. (2024) noted the common cuckoo (*Cuculus canorus*) was detected at a distance up to 500 m. In our study, geomorphology was likely important at one site, Box Canyon, where few calls were detected compared to other sites, despite visual confirmation of 3 active nests within the site. The overall false negative rate at this site was lower than the rate among all sites, and therefore low detection rates were not due to site-specific low recall scores. Instead, ARUs at this site had the shortest average detection range, likely due to the particularly steep and winding terrain relative to other sites. This highlights the importance of evaluating local factors affecting ARU detection space when designing acoustic monitoring programs and analyzing results.

Our classifier detected coo calls more efficiently than contact calls, with higher recall and precision scores. As the analysis of our benchmark data set demonstrated, low recall for the contact calls meant an estimated 87% of contact calls were missed by the classifier. This is consistent with other studies using Kaleidoscope Pro to study cryptic species such as 88.6% and 77.9% false negative rates for different call types of king rails (*Rallus elegans*; Schroeder and McRae 2020) but much higher than some studies using other emerging software platforms such as BirdNet (6% and 24% false negative for different call types of Eurasian bitterns [*Botaurus stellaris*]; Manzano-Rubio et al. 2022) or convolutional neural networks (25% false negative for common nighthawk [*Chordeiles minor*], Knight et al. 2017). We also observed particularly low precision in the contact call cluster, which results in a greater proportion of false positive detections requiring time-consuming manual review (Knight et al. 2017).

Poor performance in the contact call classifier may be attributed to the natural variation in the structure of the contact call—including alarm and kowlp variations—resulting in a more loosely defined statistical algorithm used to form the contact call cluster, which increased rates of both false positives and false negatives. Stronger classifier performance of the coo call may be due to the simpler call structure as well as the lower and narrower frequency range as compared to the contact call. Given that classifier development is a supervised process with many user-defined parameters at each step, further experimentation based on our results would likely lead to improvements in performance and efficiency.

Approximately 50% more true positive coo calls were detected than contact calls by our classifier, but contact calls were detected over more overall days than coo calls in all sites except 1. Therefore, monitoring for contact calls may provide superior temporal resolution of daily cuckoo occurrence despite the low rate of recall. However, without the inclusion of coo calls at our Stevens Canyon site, where few true positive contact calls were detected, occupancy would have been underestimated even though we had confirmed breeding at that site. At ARUs deployed near known nests, we also observed high rates of coo calls before and after the estimated nesting cycle, with generally reduced rates of all call types during the estimated incubation period. This suggests that a dual-peak of coo call activity separated by 1–3 weeks may be an important indicator of cuckoo nesting and is consistent with the hypotheses that 1) females use coo calls to solicit copulation during the egg laying stage (Hughes 2015), and 2) that females may initiate new nests soon after young have hatched (Halterman 2009). These results highlight the importance of developing classifiers that account for the variety of calls produced by the focal species and to consider their biological context in interpreting results.

Recording schedules for ARU monitoring programs vary between studies, and ultimately depend on specific project goals and available resources (Blumstein et al. 2011, Shonfield and Bayne 2017, Gibb et al. 2019, Manzano-Rubio et al. 2022). In most studies, sampling occurs during specific diel periods corresponding to high acoustic activity, such as dawn or dusk, to maximize the probability of detection while minimizing data storage requirements (Schroeder and McRae 2020, Sugai et al. 2020). Consistent with these previous studies, we identified a peak of vocal activity between 0500–0700, which guided our data subsampling. Under several subampled recording schedules, our classifier provided sufficient true positive detections to accurately estimate occupancy using temporal and spatial criteria adopted from the Halterman et al. (2015) survey protocol. This included using 2 continuous hours of daily recording around sunrise or using as little as 15 minutes per hour over 7 hours of daily recording. Such recording schedules improve efficiency through reduced time investment in manually reviewing classifier results as well as in field maintenance due to extended battery life and reduced data storage needs.

Our study demonstrates that even a poor-performing classifier may be sufficient for obtaining biologically relevant information for cuckoos. Moreover, we have shown that cuckoos may be effectively monitored with common recording schedules used for other species, making them a suitable candidate for multispecies acoustic monitoring programs. This may be particularly beneficial given that cuckoos inhabit riparian areas where many other species of conservation concern often co-occur.

MANAGEMENT IMPLICATIONS

Human observer surveys according to Halterman et al. (2015) protocols currently remain the standard for conducting western yellow-billed cuckoo surveys. However, our results supported the use of acoustic monitoring to identify cuckoo habitat. For acoustic monitoring programs, we recommend 1) recording schedules with a minimum of 2 hours of daily recording, either continuously between 0500–0700 or 15 minutes of each hour throughout the morning, 2) spacing of ARUs at 500 m intervals unless local environmental conditions are likely to obstruct more distant sounds, and 3) the use of classifiers for both coo and contact calls. We also suggest that further experimentation in classifier development may increase performance and lead to improved acoustic monitoring protocols. We conclude that despite their cryptic behavior and challenges in classifier performance, cuckoos are well-suited for acoustic monitoring programs. Given the rapid increase in the application of acoustic monitoring for wildlife biology and management (Shonfield and Bayne 2017), we encourage the adoption of such programs for cuckoos to expand survey capacity and inform management decisions.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

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DATA AVAILABILITY STATEMENT

Data used for this study are available by request via USGS Data Release.

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