Original Article

Using Extended-Duration Audio Recordings to Survey Avian Species

AMY K. TEGELER,[1,2] *Department of Biology, Humboldt State University, Arcata, CA 95521, USA*
MICHAEL L. MORRISON, *Department of Wildlife and Fisheries Sciences, Texas A&M University, College Station, TX 77843, USA*
JOSEPH M. SZEWCZAK, *Department of Biology, Humboldt State University, Arcata, CA 95521, USA*

ABSTRACT Point-count surveys are widely used to infer avian presence and estimate species richness. Advancements in bioacoustic technology enable automated surveys that can supplement human-based point-count surveys with expanded temporal and spatial coverage. We surveyed birds in 13 Sierra Nevada and Cascade Range (CA, USA) montane meadows from May to August 2006 using 8 point-count surveys and automated audio recorders (ARU) to compare species richness between the 2 methods and evaluate the use of ARUs as a monitoring tool. We analyzed species richness using 30 minutes of ARU data per point and 2 point-count surveys. Automated audio-recorder data revealed 14 species per meadow (56 species total) while point counts detected 16 species per meadow (67 species total). Automated audio recorders provided >1,100 additional hours of data with personnel effort similar to 2 point-count surveys. An asymptote in species richness was reached for every meadow using ARU data and 8 of 13 meadows using 2 point-count surveys. We detected 81 species during all 8 point-count surveys. We used SonoBird (DNDesign, Arcata, CA) software to search for 24 species detected by point-count surveys but not in the manually sampled subset of audio files. We detected 22 additional species, bringing the total audio-file species detections to 85, 4 more than detected by 8 point-count surveys. We conclude that audio recordings and analysis provide an alternative to avian point-count surveys or as a supplement to increase their accuracy, particularly over larger temporal and spatial scales, or for species with low detectability.

KEY WORDS accumulation curve, autonomous recording unit, bioacoustics, montane meadow, point count, Sierra Nevada, SonoBird, species richness.

Point-count surveys are widely used to aid in detecting avian presence and estimating species richness. Species richness provides important information about the composition of avian communities. Species richness is used as an indicator of habitat quality in urban environments (Cam et al. 2000), after natural habitat disturbances (Greenberg and Lanham 2001), and in relation to habitat patch size (Helzer and Jelinski 1999). Land managers also use species richness to make land management decisions about grazing and prescribed fire (Pillsbury et al. 2011) and tree harvesting (Thiollay 1992). Recently, species richness has become an important means of researching the effects of climate change on avian species (Lemoine and Böhning-Gaese 2003). However, inconsistent data from survey to survey can hinder accurate population estimates. Field observers have variable visual and auditory abilities (Cyr 1981, Kepler and Scott 1981, Bart 1985). Even within a field season, an observer's ability to detect and identify individual bird species changes due to his or her experience, and changes in his or her physical and mental state (Sauer et al. 1994, Kendall et al. 1996). In addition, the presence of observers performing the point counts can attract or deter some avian species and cause biases in detectability (Bye et al. 2001). Temporal bias is also frequently present in point-count data because the number of skilled observers available limits the number of locations that can be sampled simultaneously (Anderson et al. 1981, Best 1981).

Advancements in bioacoustic recording and processing technology now make automated audio recording surveys a practical alternative or supplement to standard survey methods. Audio recorders (ARU) reduce several types of bias associated with point-count surveys (Hobson et al. 2002). Data collection does not depend on observer skill level, which practically eliminates observer bias. Audio recorders also facilitate simultaneous monitoring at multiple sites, thus eliminating temporal bias. Both of these qualities facilitate consistent data from survey to survey and so improve detecting species presence and estimating species richness. Audio recorders can also collect data in locations with restricted access (i.e., military bases, wildlife preserves). Audio recording provides permanent records of the survey period that can be played repeatedly and, if necessary, independently verified by third parties, increasing confidence in species identified (Hobson et al. 2002). Audio recording can also assist with personnel scheduling and assignment because processing of recordings can continue, or be entirely

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[1]*E-mail: amy.tegeler@gmail.com*
[2]*Present address: Powdermill Avian Research Center, Carnegie Museum of Natural History, 1847 Route 381, Rector, PA 15677, USA.*

completed, after the breeding or active recording season. Automated signal-detection software can augment this process and leverage human resources. Audio recorders also have the potential to free up time and personnel resources to focus on surveying for species undetectable by audio, accomplish other project goals (Haselmayer and Quinn 2000), or expand landscape coverage.

Although ARUs have shown promising results (Haselmayer and Quinn 2000, Hobson et al. 2002, Celis-Murillo et al. 2009), the full potential of ARUs to detect avian species and support routine avian monitoring has yet to be realized. Previous studies have shown that short-duration audio recordings have the potential to estimate avian species presence and probable absence (Haselmayer and Quinn 2000, Hobson et al. 2002, Celis-Murillo et al. 2009). For example, short-duration audio recordings were preferred to point counts when species richness was high, although point counts were more effective at detecting rarely heard species (Haselmayer and Quinn 2000, Hutto and Stutzman 2009). Low rates of acoustic detection for a species may occur either because it sings infrequently or because it is uncommon (Haselmayer and Quinn 2000). Multiple site visits are often necessary to detect those species with human observers (Queheillalt et al. 2002). Advancements in audio recording technology now enable recording units to operate continuously for entire field seasons and, therefore, sample more intensively than with human observers and short-duration recordings. Extended-duration recordings have the potential to increase the chance of assessing presence or absence of uncommon and rarely heard species, which require greater survey effort to detect than more common species (Green and Young 1993).

The adoption and acceptance of audio recording as a method for avian surveys requires further evaluation of different recording systems in different ecosystems, and testing the effectiveness of acoustic software to detect species from extended-duration audio files. Furthermore, no studies have evaluated the effectiveness of extended-duration audio recording to estimate species richness or compared the efficiency of long-duration recordings versus point counts for estimating richness. We first evaluated the use of ARUs to determine avian species richness compared to standard point-count surveys when each method monitored for the same duration. We then determined the additional sampling effort needed to reach an asymptote in species richness from audio-recorder data. We also used the semi-automated acoustic search algorithm of SonoBird™ (DNDesign, Arcata, CA) software to detect species from our audio recordings.

STUDY AREA

We conducted our study in wet montane meadows from the north-central Sierra Nevada to the southern Cascade Range including portions of Plumas, Sierra, Alpine, and Siskiyou counties (CA, USA) a linear distance of about 370 km. Willow (*Salix* spp.) and alder (*Alnus* spp.) dominated riparian shrub communities in these montane meadows. The meadows were surrounded by lodgepole pine (*Pinus contorta*), ponderosa pine (*P. ponderosa*), and quaking aspen (*Populus tremuloides*) forests. Riparian shrubs in the meadows often followed streams but were also scattered throughout the meadow, interspersed with open herbaceous areas of grasses and sedges (*Carex* spp.; Bombay et al. 2003, King and King 2003). All meadows were on California Department of Fish and Game or U.S. Forest Service land.

We selected 13 meadows as study sites under the criteria that they maintained a significant amount of water from spring through early summer (bordering lakes not included). We selected meadows of varying sizes (12–209 ha) because avian species richness has been shown to change due to habitat patch size (Davis 2004). We identified easily accessible meadows fulfilling the criteria by using aerial photographs and Geographic Information Systems software, followed by field observations. The U.S. Forest Service conducted willow flycatcher (*Empidonax traillii*) research in many of these meadows, so we combined efforts with that study.

METHODS

Point-Count Surveys

We placed point-count stations systematically throughout each meadow, 250–400 m apart (112 total points). In small meadows where only 2–5 points could fit within the study area, the first point-count station location was selected by determining all possible locations where the most points could fit into the meadow. We stratified points by the vegetation cover types: riparian deciduous shrub, herbaceous, forest patches within the meadow, and meadow edge. We located point-count locations in the field using Global Positioning Systems and they were marked with polyvinyl chloride pipe and flagging.

Twelve field technicians with previous point-count experience conducted the point-count surveys. We additionally trained and tested all field technicians to identify birds by sight and sound in montane meadows for $\geq$2 weeks before they conducted point counts, reducing observer error with species identification and distance estimation. We recorded unlimited-radius point-count observations for 15 minutes at each station. Technicians tallied all individuals of every species identified during the 15-minute period. The distance at which each individual was detected was recorded as $<$50 m, 50–100 m, or $>$100 m. We also documented whether each individual was detected visually, audibly, or both. We conducted surveys at each point-count station every 7–10 days from 6 June to 3 August 2006, resulting in each point being sampled 8 times during the breeding season. We visited points 8 times to increase the probability of detecting rare species. To make observer effects equal across sites, we randomized observers by having a different field-crew member conduct each point-count survey in each meadow. We conducted point counts from first light until 1000 hours on days without strong winds ($>$30 km per hour [kph]) or heavy precipitation. We sampled every meadow before resampling any meadow during the next round of surveys.

Automated Audio-Recorder Surveys

We sampled 48 point-count locations with an automated ARU. We randomly selected the order of points sampled within each meadow and sampled multiple meadows simultaneously to reduce temporal bias. The number of locations in each meadow was proportional to meadow size. We left recorders at point-count locations for approximately 7 days, then moved them to other, not-yet-sampled, point-count locations for the next 7 days. The automated recording units recorded continuously at each point-count location from 0500 hours to 1000 hours. We collected audio-recorder data from 8 June to 3 August 2006. At least one point-count survey was conducted concurrently with most audio recordings.

We designed our audio recording units to optimize bird detection while maintaining cost-effectiveness. We stored data on DMC xclef HD-500 digital mp3 players (Digital Mind Corp., Carlsbad, CA). The DMC mp3 players had 100 GB of storage, sufficient to store approximately 700 hours of data. We collected mono audio data at 320 kb per second with a sampling frequency of 44.1 kHz. We recorded at this audio quality setting to enable species identification using sonograms to supplement and confirm aural identification. We recorded audio data using PA3 mini microphones (MG Electronics, Hauppauge, NY). The microphones included a built-in preamplifier with line-level output that facilitated recording by the DMC units. The microphones detected frequencies 20–16,000 Hz and had a signal-to-noise ratio of >58 dB. We fitted microphones into a custom 4-horn arrangement that increased gain omni-directionally in the ground plane of the meadows (Tegeler-Amones 2008). The geometry of the horns provided some low-frequency noise rejection to optimize the recording sensitivity to higher frequency songbird vocalizations. The audio recording units were powered by 2 12-V, 12 Amp-hour batteries (24 Amp-hr total capacity) maintained with a 20-W solar panel connected by a charge controller. We housed the power and recording equipment in a waterproof National Electrical Manufacturers Association 3R enclosure (12 in. H × 10 in. W × 6 in. D [30.5 cm × 25.4 cm × 15.2 cm]). The audio recording units successfully collected data in weather below freezing, above 90° F (32° C), and also during heavy wind, rain, sleet, and snow.

Testing Recording Distance of Automated Audio Recorders

We tested the recording sensitivity of 5 ARUs while at point-count locations in study meadows using prerecorded vocalizations. We broadcast territorial vocalizations of willow flycatcher, Lincoln's sparrow (*Melospiza lincolnii*), and Wilson's warbler (*Wilsonia pusilla*) at a sound level equivalent to natural singing volume as judged by 2 experienced birders. We selected Lincoln's sparrow and Wilson's warbler because they were frequently encountered in the meadows, and willow flycatcher because it was a species of concern for California Fish and Game and the U.S. Forest Service. We broadcast the vocalizations starting 50 m from a recording unit and repeated the process, moving further from the ARU in 10-m increments, and then determined when none of the species could be detected from the audio recordings. We conducted trials in willow clumps and open areas in the study meadows. Vegetation density at chest height was recorded along a transect between the ARU and person playing the broadcast. We classified vegetation by percent cover as sparse (0–30%), moderate (31–60%), or dense (61–100%) to determine whether vegetation density affected the distance at which bird species could be identified from the audio recordings. The process was also repeated at 0° and 45° from a microphone horn to assess any difference in directionality of detection sensitivity. All project methods were approved by the Animal Care and Use Committee (no. 05/06.B.97.A).

To establish the distance limitations of audio recordings to identify species, we ran an analysis of variance (ANOVA; Zar 1999) to test whether the maximum distance at which each species could be detected differed between species. We then ran a Type III Factorial ANOVA (Zar 1999) to see whether distances differed between varying vegetation densities and orientations. For the analysis, the distance at which a species could be detected was the dependent variable, vegetation density and orientation were fixed factors, and point location was a random factor. All analyses in the study were run using SPSS™ 13.0 for Mac OS X (IBM Corp., Somers, NY) unless otherwise noted.

Comparison of Automated Audio Recorders and Point-Count Surveys

We directly compared species richness estimates between point-count and audio-recorder surveys. We randomly selected 4 15-minute segments of audio-recorder data from each day between first light and 1000 hours and identified all species detected in the recordings. Two field technicians that conducted the point-count surveys and also had previous experience working with avian species in Sierra Nevada montane meadows (3 yr and 5 yr, respectively) identified species from ARUs manually with audible recognition, and from sonograms generated using SonoBird acoustic analysis software that readily enabled comparison of unknown audio recordings with reference recordings of known species. The technicians replayed the audio files as many times as needed to identify all the species and were able to get verification from third parties when needed. The audio files were randomly assigned to each technician to avoid observer bias between meadows.

Because point-count surveys were conducted every 7–10 days and recorders remained at point-count stations for 7 consecutive days, 2 point-count surveys were conducted on approximately the same dates as recorders were collecting data at each point. To avoid temporal bias, we only included data from the 2 point-count surveys conducted while the ARU collected data in this analysis. We randomly chose 2 15-minute recording segments to compare to the 2 15-minute point-count surveys. Whenever possible, we selected 2 audio recording segments from different days; however, recorder data and point-count data were not always from the same day. There were typically <3 days between the

day of the point count and the day of the recorder data. We calculated the total number of species detected at each point location for each method.

We used a Type III factorial ANOVA (Zar 1999) to compare the total number of species detected between point-count surveys and automated audio recording units. Meadow was a random factor and point-count location was the sampling unit. The 2 treatments—point-count survey and ARU—were a fixed factor, and the dependent variable was the number of species detected at each point by each treatment. We only included meadows that had reached $\geq$95% of an asymptote using species accumulation curves for each method in the analysis (see next section). Because ARUs only collect audio data, we then reran the analysis including species detected audibly from the point-count surveys while excluding species only detected visually.

Species Accumulation Curves

We determined the duration ARUs needed to collect data for each meadow to reach an asymptote in species richness using species accumulation curves. We used a custom software program developed by one of us (J. M. Szewczak) to generate accumulation curves based on methods described by Moreno and Halffter (2000). Data from 15-minute recording segments were added systematically by point location to the analysis until reaching an asymptote in species richness. We generated accumulation curves using 2 different models, an exponential model (Soberon and Llorente 1993) and a Clench model (Soberon and Llorente 1993). We used the models to account for uncertainties in the observational data and to calculate quantitative estimates of species richness and anticipated total species. The exponential model assumes that the number of species detected decreases linearly as sampling effort increases (Moreno and Halffter 2000) and is preferred for populations of well-known species or when the study area is relatively small and could, theoretically, reach an asymptote over a finite period of time (Soberon and Llorente 1993). The Clench model assumes that the probability of adding species increases over time, but decreases as more species are recorded (Moreno and Halffter 2000). Soberon and Llorente (1993) suggested the Clench model be applied to larger areas than when the exponential model would be used, or for taxa where the probability of adding new species would increase as time in the field increases, until an upper limit is reached. The results from the exponential model and Clench model can be considered the lower and upper limit, respectively, of sampling effort needed for estimating species richness (Moreno and Halffter 2000). We smoothed each curve by using the regression of 1,000 randomizations of the 15-minute audio segments. We also created species accumulation curves using the exponential model for the point-count data to determine what percent of an asymptote in species richness was reached for each meadow for a comparison with the audio-recorder data.

Effects of Study Design

We also tested whether there was systematic bias in sampling dates that affected the duration ARUs needed to collect data to reach an asymptote in species richness. Because each meadow had a different number of locations where ARUs collected data, we ran a linear regression (Zar 1999) to determine whether number of recording locations within a meadow affected the recording duration required for each meadow to reach an asymptote in species richness. We also moved ARUs throughout the field season so not all locations were sampled simultaneously. We used a linear regression to assess whether there was a relationship between species richness and the dates on which each recording unit started collecting data in each meadow (Zar 1999). We also ran a 1-way ANOVA to see whether there was a difference in dates on which recorders were collecting data between meadows (Zar 1999).

Automated Species Detection Using SonoBird Software

We tested whether species not detected in the subsampled recordings used in the audio-recorder and point-count survey comparison analysis were present in the complete audio data set by using SonoBird software. We provided SonoBird with representative vocalizations from each species and it automatically scanned all files from the meadows to find similar candidate signals that matched the examples. SonoBird then presented the candidate signals ordered by quality of match (measured by correlation coefficient) that we could then scroll through and confirm or reject species presence. We wanted to determine species presence, so we only scrolled through files until we found the first detection for each target species. We selected representative vocalizations for several individuals of the selected species from Szewczak's bird vocalization library of high-quality (high signal-to-noise ratio), distortion-free recordings.

RESULTS

We sampled 48 point-count locations with automated audio recording units. The number of points per meadow was proportional to meadows size ($\bar{x} = 3.4$, SD = 2.31). Even though we placed automated audio recording units at each location for 7 days, because of equipment failure, not all units recorded for the full 7 days. The average duration recorded at each location was 4.8 days (SD = 2.07). The number of days recording units collected data in each meadow ranged from 3 days to 35 days ($\bar{x} = 16.3$ days, SD = 12.71).

Testing Recording Distance of Automated Audio Recorders

The distance at which willow flycatcher, Wilson's warbler, and Lincoln's sparrow could no longer be identified from the audio recordings was unaffected by vegetation density or orientation to the microphone horns. The average distance at which we detected Lincoln's sparrow was 117 m (SD = 46.00), willow flycatcher was 116 m (SD = 45.75), and Wilson's warbler was 115 m (SD = 48.22); these distances were not significantly different ($F_{2,36} = 0.003$, $P = 0.997$). Distances were not different between species; therefore, we combined species for the rest of the analysis. The mean distance at which the species could be identified was not affected by vegetation densities ($F_{2,36} = 2.546$, $P = 0.089$). In sparse vegetation, the average distance at which we could detect the species was 136 m

(SD = 62.12). Although not statistically significant, the average distance at which we could detect species in moderate vegetation dropped to 109 m (SD = 23.44), and in dense vegetation 104 m (SD = 38.83). Whether the broadcast vocalization was played into a horn or between 2 horns did not affect the distance at which the species could be detected ($F_{1,36} = 0.065$, $P = 0.800$). The average distance at which we could detect the species when broadcast into a horn was 118 m (SD = 49.04) and when broadcast between 2 horns was 114 m (SD = 43.15). Most detections of the 3 species were <100 m from the point-count station (Wilson's warbler = 90%, Lincoln's sparrow = 80%, willow flycatcher = 56%), so we included point-count survey data from all distances in our methods comparison.

Comparison of Automated Audio Recorders and Point-Count Surveys

We included 8 study meadows in our analysis because they had reached ≥95% of an asymptote in species richness using both audio-recorder and point-count methods. When we compared species richness using recordings of equal duration to 2 point-count surveys, ARUs detected slightly fewer species per meadow ($\bar{x} = 14.2$, SD = 3.27) than standard point counts ($\bar{x} = 15.8$, SD = 2.30) when all detections were included ($F_{1,52} = 7.321$, $P = 0.023$). However, there was no difference in estimates of species per meadow between audio recordings ($\bar{x} = 14.2$, SD = 3.27) and point counts ($\bar{x} = 14.5$, SD = 2.06) when comparing data only from species detected audibly ($F_{1,52} = 0.718$, $P = 0.416$). Species detected only visually by point counts are in Table 1.

When we combined data from all meadows, point counts detected 67 species while ARUs detected 56 when sampling effort was equivalent to 2 point-count surveys. We detected 6 species with ARUs that were not detected by point counts, and 10 species during point counts that were not detected by recorders, 4 of which were only detected visually. Most species detected by only one method were detected at fewer than 5 point locations, indicating they were relatively rare or difficult to detect (Table 1).

Species Accumulation Curves

An asymptote in species richness was reached using audio-recorder data for each study meadow using the exponential model (Table 2). When we analyzed the number of additional 15-minute audio-recording segments required for each meadow to reach an asymptote in species richness (0.25–3.25 hr of recordings per meadow), recorders detected 7 additional species, 5 of which had been detected by point counts. We reached 69–100% of an asymptote in species richness using point-count data from 2 surveys for each study meadow with the exponential model (Table 2). The total recording time required in each meadow to reach an asymptote using audio-recorder data ranged from 1 hour to 4.5 hours (Table 2). The recording time at each point location within a meadow required for the meadow to reach an asymptote ranged from 0.25 hour to 2.25 hours (Table 2). We reached 78–86% of an asymptote in species richness for audio-recorder data using the Clench model and 62–87% for 2 point-count surveys (Table 2); however, there were 1,100 hours of audio data that were not included in this analysis.

Effects of Study Design

Our study design did not affect the recording duration needed to reach an asymptote in species richness. There was only a slight indication that the number of recording locations within a meadow was related to the amount of time each recorder had to collect data for the meadow to reach the asymptote ($R^2 = 0.220$, $F_{1,46} = 3.382$, $P = 0.091$). We were also able to eliminate temporal bias between study meadows. At the meadow scale, species richness was not affected by the date on which individual recording units were collecting data ($R^2 = 0.004$, $F_{1,46} = 0.049$, $P = 0.829$), and there was no difference in dates on which recording units were placed in the meadows ($F_{13,34} = 0.637$, $P = 0.806$).

Automated Species Detection Using SonoBird Software

We used SonoBird to search the audio files for all species detected during the 8 point-count surveys, but not during manual listening and inspection of the audio data in previous analysis. Eighty-one species were detected during all 8 point-count surveys, 24 of which were not detected manually in the audio files. SonoBird detected 22 of the 24 species bringing the total number of species detected using ARUs to 85, 4 more than the 8 point-count surveys. We did not have audio detections for 2 species detected by point counts, sandhill crane (*Grus canadensis*) or American dipper (*Cinclus mexicanus*), so we were unable to confirm their presence or absence in the audio files. However, point-count surveys detected neither of these species during the time period we recorded in the meadows where they were detected. Four of the 22 species were detected at points where they were not detected during point counts. After the initial detection, we did not continue searching for additional detections of the species at that point and we did not pursue species detection at alternate points. Each of the species identified in the audio files were detected fewer than 5 times during point-count surveys.

DISCUSSION

Our results indicate that recording units offer a viable supplement and potential alternative to standard point-count surveys to conduct large-scale avian species richness surveys. Audio recorders could monitor all of the regions simultaneously, and provided >1,200 hours of data, ≥1,000 hours more than the typical point-count survey with equivalent personnel effort as 2 point-count surveys.

In contrast to standard observer survey methods, automated ARUs can monitor continuously and, therefore, sample more intensively than human observers. Our automated ARUs collected data for 7 consecutive days, although currently available equipment can acquire data for 24 hours a day for a month or more depending upon installed memory and power capacity. More comprehensive surveys increase the confidence of detecting rare and difficult to detect species (Haselmayer and Quinn 2000). The combined data from all 8 point-count surveys detected 81 species, compared to 67 from only 2 point-count surveys. We detected 85 species

Table 1. Species detected by point-count survey and audio recorders in Sierra Nevada and Cascade Range (CA, USA) montane meadows from May to August 2006.

Species	Scientific name	2 Point-count surveys (*n*)[a]	Manual recorder (*n*)	8 Point-count surveys[b] (*n*)	Automatic recorder[c] (*n*)
American crow	*Corvus brachyrhynchos*	2	1		
American dipper	*Cinclus mexicanus*	1			
American robin	*Turdus migratorius*	38	34		
Bald eagle	*Haliaeetus leucocephalus*		1		
Band-tailed pigeon	*Patagioenas fasciata*	1	1		
Barn swallow	*Hirundo rustica*			2	1
Belted kingfisher	*Megaceryle alcyon*	3	2		
Black-headed cowbird	*Molothrus ater*	18	8		
Black-headed grosbeak	*Pheucticus melanocephalus*	3			1
Brewer's blackbird	*Euphagus cyanocephalus*	19	6		
Brewer's sparrow	*Spizella breweri*	3	3		
Brown creeper	*Certhia americana*	12	5		
Bushtit	*Psaltriparus minimus*			1	1
California quail	*Callipepla californica*		2		
Calliope hummingbird	*Stellula calliope*	11	10		
Canada goose	*Branta canadensis*			7	1
Cassin's finch	*Carpodacus cassinii*	10	7		
Cassin's vireo	*Vireo cassinii*	8	5		
Cedar waxwing	*Bombycilla cedrorum*	4	2		
Chipping sparrow	*Spizella passerina*	8	4		
Clark's nutcracker	*Nucifraga columbiana*	8	2		
Common merganser[d]	*Mergus merganser*	1			1
Common nighthawk	*Chordeiles minor*			1	1
Common raven	*Corvus corax*			3	1
Cooper's hawk[d]	*Accipiter cooperii*	1			1
Dark-eyed junco	*Junco hyemalis*	23	19		
Downy woodpecker	*Picoides pubescens*	2	1		
Dusky flycatcher	*Empidonax oberholseri*	28	32		
European starling	*Sturnus vulgaris*			1	1
Evening grosbeak	*Coccothraustes vespertinus*	8	8		
Fox sparrow	*Passerella iliaca*	4	5		
Golden-crowned kinglet	*Regulus satrapa*	1	1		
Green-tailed towhee	*Pipilo chlorurus*	2			1
Hairy woodpecker	*Picoides villosus*	8	9		
Hammond's flycatcher	*Empidonax hammondii*		4		
Hermit thrush	*Catharus guttatus*	1			1
Hermit warbler	*Dendroica occidentalis*	1	1		
House wren	*Troglodytes aedon*			3	1
Killdeer	*Charadrius vociferous*		2		
Lazuli bunting	*Passerina amoena*	2	4		
Lesser goldfinch	*Carduelis psaltria*	4	6		
Lincoln's sparrow	*Melospiza lincolnii*	19	20		
MacGillivray's warbler	*Oporornis tolmiei*	14	17		
Mallard	*Anas platyrhynchos*	6	1		
Mountain bluebird	*Sialia currucoides*			1	1
Mountain chickadee	*Poecile gambeli*	32	33		
Mountain quail	*Oreortyx pictus*	14	14		
Nashville warbler	*Vermivora ruficapilla*	2	1		
Northern flicker	*Colaptes auratus*	25	25		
Olive-sided flycatcher	*Contopus cooperi*	15	19		
Orange-crowned warbler	*Vermivora celata*	7	3		
Osprey	*Pandion haliaetus*			1	1
Pacific-slope flycatcher	*Empidonax difficilis*	4	2		
Pine grosbeak	*Pinicola enucleator*			1	1
Pine siskin	*Carduelis pinus*	6	2		
Purple finch	*Carpodacus purpureus*	2	2		
Pygmy nuthatch	*Sitta pygmaea*			1	1
Red-breasted nuthatch	*Sitta canadensis*	12	7		
Red-breasted sapsucker	*Sphyrapicus ruber*	6	3		
Red-tailed hawk	*Buteo jamaicensis*	2	1		
Red-winged blackbird	*Agelaius phoeniceus*	23	20		
Rufous hummingbird[d]	*Selasphorus rufus*	1			1
Sandhill crane	*Grus canadensis*			2	
Savannah sparrow	*Passerculus sandwichensis*	3	5		
Song sparrow	*Melospiza melodia*	45	46		
Sora	*Porzana carolina*			2	1
Spotted sandpiper	*Actitis macularius*	12	10		
Spotted towhee	*Pipilo maculatus*	3	1		

Table 1. (*continued*)

Species	Scientific name	2 Point-count surveys (n)[a]	Manual recorder (n)	8 Point-count surveys[b] (n)	Automatic recorder[c] (n)
Steller's jay	*Cyanocitta stelleri*	18	22		
Swainson's thrush	*Catharus ustulatus*	15	13		
Townsend's solitaire	*Myadestes townsendi*	1	1		
Tree swallow	*Tachycineta bicolor*	18	11		
Violet-green swallow[d]	*Tachycineta thalassina*	2			1
Virginia rail	*Rallus limicola*			1	1
Warbling vireo	*Vireo gilvus*	33	39		
Western tanager	*Piranga ludoviciana*	8	6		
Western wood-peewee	*Contopus sordidulus*	38	4		
White-breasted nuthatch	*Sitta carolinensis*	5			1
White-crowned sparrow	*Zonotrichia leucophrys*	21	22		
White-headed woodpecker	*Picoides albolarvatus*	4			1
Willow flycatcher	*Empidonax traillii*	23	24		
Wilson's snipe	*Gallinago delicata*	19	18		
Wilson's warbler	*Wilsonia pusilla*	13	9		
Winter wren	*Troglodytes troglodytes*		1		
Yellow warbler	*Dendroica petechia*	43	45		
Yellow-breasted chat	*Icteria virens*		1		
Yellow-rumped warbler	*Dendroica coronata*	8	3		

[a] n signifies the total number of point locations where each species was detected.
[b] Species detected by 8 point-count surveys are only included if they were not detected during 2 point-count surveys or manual audio-recorder sampling.
[c] Automated software was used to find the initial detection of species not detected manually, so n will not be >1.
[d] Species detected only visually during point-count surveys.

using the ARUs with the same number of site visits as 2 point-count surveys. Although our data suggested an asymptote at approximately 70 species, those were probably just the most common and easy to detect species. With 2 point-count surveys, we reached 95% of an asymptote in species richness in 8 of the 13 meadows. We reached 100% of an asymptote in species richness in all meadows using the audio-recorder data. Extended-duration recording provides an opportunity to collect sufficient data to detect many additional rare and difficult to detect species, and to more confidently conclude absence if not detected.

The advent of automated species search and identification software will further facilitate and enhance the practicality and application of automated recording surveys, such as XBAT™ (Cornell Laboratory of Ornithology, Ithaca, NY), Song Scope™ (Wildlife Acoustics, Concord, MA), and other programs under development (e.g., SonoBird). We successfully used SonoBird to search and identify species

Table 2. Comparison of estimated asymptote, percent asymptote reached, number of species observed, and total sampling time for audio recorders (ARU) and point counts (Pt. ct.) in Sierra Nevada and Cascade Range (CA, USA) montane meadows from May to August 2006.

	Exponential model				Clench model				No. species detected (N)			Time/meadow (hr)[b]	
	Estimated asymptote (N)[a]		% Asymptote reached		Estimated asymptote (N)		% Asymptote reached						
Meadow	ARU[c]	Pt. ct.[d]	ARU	Pt. ct.	ARU	Pt. ct.	ARU	Pt. ct.	ARU	Pt. ct.	Points/meadow	ARU	Pt. ct.
Bigelow	21	23	100.0	99.7	27	32	77.6	72.3	21	17	3	1.75	1.5
Curtis	19	21	101.7	81.5	23	34	83.9	62.2	19	15	1	1.00	0.5
East Coral	29	31	101.1	96.6	37	42	78.8	68.8	29	29	3	2.00	1.5
Forestdale	36	36	101.0	68.8	46	56	79.1	63.8	36	32	2	4.25	1.0
Little Truckee	22	23	101.4	94.4	26	35	84.2	65.9	22	20	4	2.00	2.0
LT West	25	26	100.1	97.6	32	35	79.2	74.4	25	23	3	2.00	1.5
McCloud	34	33	100.4	89.5	43	51	78.6	65.1	34	28	4	4.50	2.0
North Meadow	28	29	100.9	91.6	35	47	79.3	62.0	28	23	3	2.25	1.5
Perazzo	29	29	100.5	100.9	37	42	78.3	69.8	29	31	6	1.75	3.0
Red Lake	37	36	100.5	97.0	46	45	80.1	80.8	37	35	3	3.50	1.5
Red Lake Peak	25	25	100.6	94.4	32	34	78.4	73.6	25	27	4	1.50	2.0
SE Coral	20	23	101.9	86.7	23	26	85.9	87.0	20	19	2	1.25	1.0
West Coral	30	31	101.2	100.4	37	45	80.8	68.3	30	36	10	2.50	3.0
All meadows	61	83	103.4	106.8	67	98	93.4	90.2	63	67	48	30.50	20.75

[a] N signifies no. of species.
[b] Hour of data included in this analysis for each method.
[c] Audio-recorder data include the 15-min segments needed to reach an asymptote in species richness.
[d] Point-count data from 2 point-count surveys conducted while audio recorders collected data at each point.

from our audio files. SonoBird reduced the time necessary to find species in our 1,200 hours of audio files compared to manual identification. Manually searching through audio files took 15–30 minutes for every 15-minute file. With SonoBird we searched >1,100 hours of audio data in <100 hours. However, we likely did not identify all species from the files because we limited our search to selected focal species. With the current state of software development, a combination of interactive manual identification and automated search software provides the most efficient method for estimating species richness from audio recordings. In our study, an effective method of determining species richness from extended-duration recordings was manual identification of individuals until reaching an asymptote in species richness, after which it became more efficient to use automated software to search for species with probable presence or those of particular interest. Our results indicate that the longer our audio units recorded data, the more rarely heard species were detected, providing more accurate species richness data than short-term point-count surveys.

However, automated audio recording surveys do have limitations. Recorded audio data cannot readily estimate species abundances because current systems have only limited ability to estimate distances and number of individuals (but see Celis-Murillo et al. 2009). Recordings also cannot estimate the proportion of individuals present in the sampling area that are not producing acoustic cues. Equipment can also fail, so despite capacity for extended-duration recording, ARUs should be monitored periodically to ensure they are operational. However, periodic site visits by field personnel can provide opportunities to collect data that could be used as covariates in species richness estimation. Such site assessment could be addressed in a study plan as part of the routine visitation to maintain recording equipment.

Audio recorders also have the potential to collect other types of data. For example, it is possible to glean some demographic information from particular call types, such as whisper songs, alarm calls, and scolding (Anderson et al. 2008). They also have the potential to collect data 24 hours a day, providing information about nocturnal avian species that are not typically included in point-count surveys. Additionally, audio-recorder surveys are becoming a standard method of collecting bat species richness data (Parsons 2001, Parsons and Jones 2000). Some ARUs can now record bird species during the day and bat species in the evening, streamlining efforts needed to collect multispecies data. Biologists have also begun using ARUs to study other species, such as marine mammals (Deeck et al. 1999, Campbell et al. 2002, Oswald et al. 2003), amphibians (Meek 2010), and insects (Bertram et al. 2004).

Audio recorders also provide an alternative or a supplement to standard species-specific surveys. For example, in our study ARUs detected willow flycatchers, a California state endangered species, in all the meadows where they were detected during standard U.S. Forest Service surveys. But with the greater sampling effort available using ARUs, we detected a willow flycatcher in a meadow where none were detected during the standard U.S. Forest Service surveys, providing another example of how extended-duration audio recordings can effectively detect rare species (Tegeler-Amones 2008). Recording units like the ones used in our study supplemented U.S. Forest Service great gray owl (*Strix nebulosa*) survey data (Rognan et al. 2009) and demonstrated vocal recognition of individuals. Audio recorders have also been used to simultaneously record bird vocalization, ambient noise, and noise generated from road construction activities at varying distances from the road right-of-way (Lackey et al. 2011).

MANAGEMENT IMPLICATIONS

Audio-recorder surveys provide a viable alternative and supplement to point-count surveys to estimate species richness and can optimize survey effort, scheduling, and project cost. Audio recorders can be more cost-effective than human-based surveys for long-term studies because they reduce field time required for personnel to collect data. Our recording units cost approximately US$800 each, but cost will vary depending on desired data storage capacity and equipment specifications. Additional funds to process and analyze audio data can be minimized because one or a few experts can process the audio recordings as time allows, possibly utilizing experts already employed. Audio recorders provide researchers with the opportunity to design a study around the number of recording units they can purchase and maintain and the amount of data they can feasibly store. Audio data provide a permanent audio record of the survey time period; therefore, the data can be analyzed as funds become available.

Audio recorders can be deployed over large geographic areas and record simultaneously for extended duration, so they result in more intensive surveys. However, different sampling regimes, such as sampling in different landscape or cover types, or differences in desired levels of accuracy, precision, and power in species richness estimates, will require alternate numbers of recording stations and duration of recording. Typically, increasing the number of point-count stations is a more efficient method for detecting new species than increasing the number of visits (Smith et al. 1995). Large meadows with many point-count stations may require shorter monitoring times, whereas small meadows with few point-count stations may require longer monitoring times to reach the desired level of precision and accuracy in species richness estimates. Most of our study meadows contained 1–4 recording stations, so more research with a wider range of number of recording stations is necessary to determine whether audio recording surveys follow the same trend. The recording units detected species at distances similar to our unlimited-distance point counts, so we compared unlimited distance methods for both. However, more research discerning the actual sampling radius of both methods is needed. Our recording units recorded for 7 consecutive days. Further research could determine the recording duration needed to collect data across the breeding season.

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