Title: Acoustic localisation of wildlife with low-cost equipment: lower sensitivity, but no loss of precision

Running Head: Comparison of synchronised acoustic recorders

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Abstract

Context. Synchronised acoustic recorders can be used as a non-invasive tool to detect and localise sounds of interest including vocal wildlife and anthropogenic sounds. Due to the high cost of commercial synchronised recorders, acoustic localisation has typically been restricted to small or well-funded surveys. Recently, low-cost acoustic recorders have been developed, but their efficacy has yet to be compared to higher specification recorders.

Aims. This study aimed to compare the efficacy of a newly developed low-cost recorder, the CARACAL, with an established, high-end recorder, the Wildlife Acoustics Song Meter (SM).

Methods. We deployed four recorders of each type in a paired set-up across five nights in Wisconsin, USA. We manually identified domestic dog (*Canis familiaris*), grey wolf (*Canis lupus*), coyote (*Canis latrans*), and barred owl (*Strix varia*) calls on the recordings then compared the ability of each recorder type to detect and localise the vocalising animals.

Key results. The CARACALs were less sensitive detecting only 47.5% of wolf, 55% of coyote, 65% of barred owl, and 82.5% of dog vocalisations that were detected on the paired SMs. However, when the same vocalisations were detected on both recorders, localisation was comparable with no significant difference in the precision or maximum detection ranges.

Conclusions. Low-cost recording equipment can be used effectively for acoustic localisation of both wild and domestic animals. However, the lower sensitivity of the CARACALs means that a denser network of these recorders would be needed to achieve the same efficacy as the SMs. Deploying a greater number of cheaper recorders increases the labour time in the field and the amount of data to process and store. Thus, there is trade-off between cost and time to be considered.

Implications. The ability to use low-cost recorders for acoustic localisation provides new avenues for tracking, managing and researching a wide range of wildlife species. At present, we suggest that CARACALs are more suited to monitoring species that have small home ranges and high amplitude vocalisations, and when a large time investment for *in situ* equipment checks and data processing is feasible.

Additional keywords: animal movement, bioacoustics, *Canis latrans*, *Canis lupus*, multilateration, passive acoustic monitoring, *Strix varia,* wildlife management.

Short summary

Synchronised acoustic recorders can be used as a non-invasive tool to detect and localise sounds of interest including vocal wildlife. This study compared the efficacy of a commercial, high-end acoustic recorder with a newly-developed low-cost recorder finding that while the commercial recorder was more sensitive, the acoustic localisation capabilities of the two were comparable. The ability to use low-cost recorders for acoustic localisation provides new avenues for tracking, managing and researching a wide range of wildlife species.

Introduction

Monitoring spatial and temporal distributions of wild animals is important for detecting population changes and informing management decisions (Jones 2011). Tracking individual animal movements uncovers a wide variety of behavioural and ecological processes such as interspecific interactions, habitat selection, foraging ecology, migration patterns, and responses to human disturbances (Kays *et al.* 2015). Understanding which habitats animals prefer to use and move through, and knowing where animals are in real-time, can also help with resolving human-wildlife conflicts (e.g. Cooke 2008, Katzner & Arlettaz 2020, Melzheimer et al. 2020).

Many methods exist to monitor the spatial distribution and movements of wild animals (Kays *et al*. 2015). Often, animals are fitted with location-emitting devices such as VHF and GPS trackers that provide location data at set time intervals (Kays *et al.* 2015). Although these devices provide valuable movement data, their deployment is time-consuming, costly, and only provides data for a few tagged individuals (Hebblewhite and Haydon 2010). Furthermore, attaching these devices requires capturing and handling of animals, which can cause physical and psychological stress, potentially disrupting normal behaviour and compromising animal welfare (Powell and Proulx 2003; Dennis and Shah 2012). These devices can even reveal animal locations to people wishing to view, disturb, capture, harm, or kill tagged animals for non-research purposes (Cooke *et al.* 2017). Thus, researchers have sought less invasive methods to survey and track wild animals; one being the use of passive acoustic monitoring (PAM) (Blumstein et al. 2011, Sugai et al. 2019).

During PAM surveys, autonomous acoustic recorders are deployed in the field for elected periods of time to record sounds, typically animal vocalisations, without interacting with or disturbing wildlife (Browning *et al*. 2017). This method was originally developed in marine ecosystems to monitor the presence and abundance of a wide range of species, but has increasingly been used to monitor terrestrial ecosystems (Sugai *et al.* 2019). Recently, PAM has been used for a wide range of purposes including documenting biodiversity (Sugai & Llusia 2019), estimating species occupancy (e.g. primates: Kalan et al. 2015), detecting species declines (e.g. vaquitas (*Phocoena sinus*) in the Gulf of California: Jaramillo-Legorreta et al. 2017), studying animal behaviours (e.g. post-translocation behaviour of hihi (*Notiomystis cincta*): Metcalf et al. 2019) and even monitoring entire ecosystems (e.g. Linke et al. 2018).

While PAM provides a non-invasive method to record wildlife, detecting an animal vocalisation cannot reveal its exact location. To overcome this problem, PAM systems have been adapted for acoustic localisation, whereby the precise location of the sound source can be calculated from the time difference of arrival of the sound at three or more different recorder locations (Mennill *et al.* 2012; Wilson *et al.* 2014; Kershenbaum *et al.* 2019). Acoustic localisation is a rapidly growing technique and has been successfully used to locate simulated animal vocalisations (Mennill et al. 2012; Papin et al. 2018), as well as wild species including cetaceans (Gillespie et al. 2008), grey wolves (Canis lupus: Kershenbaum et al. 2019), yellow-bellied marmots (Marmota flaviventris: Ali et al. 2009) and several bird species (e.g. Mennill & Vehrencamp 2008, Collier et al. 2010, Gayk & Mennill 2020). In addition to monitoring wildlife, acoustic localisation can be used for conservation and management purposes such as locating poachers via gunshot sounds and illegal logging activity via chainsaw noise (Andrei et al. 2015; Wijers et al. 2019).

The range of functions and applications of PAM means there is strong interest in making the technique available to as many researchers and practitioners as possible, which has driven the development of smaller, lighter, and cheaper acoustic recorders such as the AudioMoth (Hill *et al*. 2018), Solo (Whytock and Christie 2016) and AURITA (Beason *et al.* 2019) units (Browning *et al.* 2017). However, due to measuring small time differences, acoustic localisation requires recorders to be physically connected to each other, or more practically, to be equipped with additional hardware (e.g. GPS receivers) to provide precisely synchronised clocks. Without this precise level of synchronisation, the time on the recorders would suffer from what is known as ‘clock drift’ whereby even clocks started at exactly the same moment will run at a different rate and eventually be out of sync from one another. The errors associated with this clock drift would lead the times of arrival of the sounds at the different recorders to be inaccurate relative to each other, thus providing incorrect localisations. The current low-cost recorders such as AudioMoths do not possess GPS synchronisation so are unsuitable for localisation projects.

As such, studies have been limited to using commercial recorders such as the Wildlife Acoustics Song Meters (SMs), as used in Mennill et al. (2012) and Kershenbaum et al. (2019) as these are, to the best of our knowledge, the only commercially-available acoustic recorders offering GPS synchronisation. The high cost of these SM recorders restricts their use to small, or well-funded studies that can afford the upfront costs in excess of US $2,500 to purchase the minimum number of three recorders necessary for localisation (Wildlife Acoustics 2021). However, researchers from the University of Oxford recently developed a new low-cost acoustic recorder, the CARACAL (Conservation at Range through Audio Classification And Localization), which has GPS synchronisation and costs approximately US $600 for three recorders (Wijers *et al.* 2019). These CARACAL recorders have so far been used in one study in Zimbabwe where they were shown to successfully detect and localise gunshots with an average accuracy of 33.2 ± 15.3 m, as well as localise three species of wildlife - Cape buffalo (*Syncerus caffer*), chacma baboo (*Papio ursinus*), and spotted hyena (*Crocuta crocuta*) – at distances greater than 1 km (Wijers *et al.* 2019).

In this study, we compared the use of high-end Wildlife Acoustics SM recorders and newer, low-cost CARACAL recorders to detect and localise wildlife in Wisconsin, USA. We present the results for four highly vocal species: grey wolves, coyotes (*Canis latrans*), domestic dogs (*Canis familiaris*) and barred owls (*Strix varia*). The performance of the two recorder types was compared with respect to overall detection ability of the four focal species, and whether the detections could be used for acoustic localisation. When vocalisations were detected on three or more recorders and were successfully localised, we compared the precision of localisation and the detection range for each recorder type. Here we present the results of this comparison, highlighting the relative merits and detection sensitivities of each to help future survey co-ordinators decide which recorder type is better suited to their needs and constraints.

Materials and methods

Study area

The study was conducted in Juneau County in Central Wisconsin, USA (Figure 1). The topography of the area was generally flat with an approximate elevation of 285m throughout the study area and comprised of extensive wetlands interspersed with sandy, upland forests dominated by aspen (*Populus spp.*), oak (*Quercus spp.*), and jack pine (*Pinus banksiana*). Human presence in the area was characterised by cranberry farms and low-density human settlements where domestic dogs were present. We focused on recording these domestic dogs as well as two vocal wild canid species – grey wolves and coyotes. At the time of the study there were an estimated 37 wolf packs totalling a population of 137-143 individuals in the central forest region of Wisconsin (Wiedenhoeft *et al.* 2020). Our study area overlapped with the core territory of one known wolf pack (Mather East: estimated seven individuals), and was likely in audible range of at least two other packs, Mather West: est. five individuals and Meadow Valley: est. six individuals (Wiedenhoeft *et al.* 2020). The number of individual coyotes and dogs in the area was unknown. There are several other vocal wildlife species in the area including many species of bird, red foxes (*Vulpes vulpes*), and white-tailed deer (*Odocoileus virginianus*), none of which were expected to interfere with our detection of the target species. Some ambient, anthropogenic noise was expected in the recordings due to the presence of vehicles (cars, ATVs, trains and planes), although the presence of all was low at this time of year with many roads being inaccessible due to snow.

Data Collection

As part of a larger study investigating interspecific vocal interactions between canid species, we deployed several GPS-synchronised Wildlife Acoustics SM3 and SM4 recorders (Wildlife Acoustics Inc., Concord, MA, USA) over an area of approximately 65 km^2. General locations for deployment were chosen after conducting transect surveys to identify areas with signs (tracks and scat) of wolves and coyotes with precise locations based on ease of access and relatively open habitat where sound propagation and GPS signal would be high.

To compare the two recorder types, four CARACALs were paired with SMs over an area of approximately 5 km^2 (latitude and longitude of central location: 44.11058, -90.25704) for five consecutive nights in December 2019. At each recorder site there was only one recorder of each type and each CARACAL, except for one that was moved to an SM location registering higher canid activity for the last two nights, remained with the same SM recorder for all five nights (Figure 1). Thus, at any one night there were four sites being monitored concurrently, but with five sites in total. For the first three nights, the average spacing between all recorders was 3.28 km, which reduced to 2.72 km for the last two nights after one of the CARACALs was relocated from location 4 to location 5 (Figure 1).

The SM recorders were programmed to operate with two omnidirectional microphones at 16,000 Hz sample rate, 16-bit resolution, in Waveform Audio File (WAV) format, and with two channels operating at different gain levels: -35 dB and -45 dB, to allow for variability in ambient noise levels. The CARACALs have four microphones and were factory programmed to record at 44,100 Hz sample rate and 16-bit resolution. It is not possible to alter the gain of the CARACALs. The resulting audio from the CARACALs was post-processed to increase the signal to noise ratio by detecting phase coherence between the channels using the Matlab v2020a ‘xcorr’ function and then averaging across the phase-corrected channels. Given the very different architectures of the two systems, a direct comparison of audio gain is not possible. For example, the SMs use an adjustable gain pre-amplifier, whereas the CARACALs have an array of four fixed gain digital microphones, and we averaged the four channels to reduce uncorrelated noise and body SNR – something not possible with the SMs. However, the frequency responses of the microphones are similar up to about 8 kHz.

Recorders were checked every morning to download data from the previous night, swap SD cards and change batteries.

Data Processing

Although several automated algorithms have been developed for detecting acoustic signals (e.g. Lostanlen et al. 2019, Brooker et al. 2020, Shiu et al. 2020), we have previously found it more reliable to identify canid vocalisations manually (Kershenba*um et al.* 2019). We used Raven Pro 1.6 (Cornell Lab of Ornithology, Ithaca, NY, USA) to view recordings as spectrograms (limited between 0 and 2 kHz) and visually scan each recording for the vocalisations of our focal species. To speed up data processing, we only considered recordings taken between 1700 and 0600 (approximately dusk until dawn) when wolves and coyotes are more likely to be active and vocalising (Harrington and Mech 1982; Okoniewski and Chambers 1984; Nowak *et al.* 2007; Suter *et al.* 2017).

Given the commercial availability and high performance of the SM recorders, we considered SMs as the gold standard and only identified animal vocalisations on the SMs. The SMs have two microphones, thus producing two channels in the generated spectrograms in Raven Pro. We marked animal vocalisations on whichever channel showed the strongest signal, which was dependent on ambient noise levels relative to the gain of the microphone for each channel. We marked all canid vocalisations as either wolf, coyote, or dog. Whilst processing the files we observed clear detections of barred owls across multiple recorders, so we marked these and incorporated barred owls into our analyses too. Each of these species produces multiple different vocalisations, although most of our recordings were characterised by solo and chorus howls for wolves and coyotes (wolves typically vocalising at a lower frequency than coyotes), extended periods of barking for dogs, and either short hoots or the distinctive 8-9 notes of the barred owl call often referred to with the phrase “who cooks for you, who cooks for you-all” (see Figure 2 for examples). Each recording and identification was reviewed by two coders. Sounds that could not be confidently assigned to either wolf, coyote, dog or barred owl by the second coder were checked by a group of five coders. If a consensus was not reached by the five coders, the identity of the species was marked as an unknown canid (e.g. where it was not possible to distinguish dog and coyote barks) or unknown sound.

Recorder Comparisons

As the gold standard, we used the SM detections to identify ‘bouts’. We defined bouts as any period of vocalisation from one of the focal species that was separated from the next vocalisation of the same species by 45 sec for wolves, 58 sec for coyotes, 49 sec for dogs, and 73 sec for barred owls. The time differences were determined for each species separately by examining the histogram of inter-vocalisation intervals for conspecific calls, using the method described in Sibly et al. (1990).

We first measured the *detection ability* of the CARACALs, which we define as the percentage of bouts detected by the SMs that were also detected by the CARACALs. To be considered a successful detection, the CARACAL could detect any part of a bout that was detected on the SM, as only a small sample of a bout is needed for multilateration if the same sound is recorded on three or more recorders. As wolf bouts were the least abundant in our data with just 40 bouts detected, we considered all wolf bouts and randomly selected a subset of 40 bouts each for dogs, coyotes and barred owls from the SM detections. We then viewed the corresponding timeframe in the 40 paired CARACAL recordings and noted whether the CARACALs had detected at least part of the same bout for the species in question. We noted this as a binary yes or no response regardless of how much or little of the bout was detected (see Figure 3 for examples).

We then compared the abilities of each recorder type to localise the detected vocalisations i.e. to estimate the likely position of the vocalising animal. First, we took the bouts that were detected across all of the SMs and generated multitrack audio files whereby the recordings taken during the same time period from multiple active recorders were included in the same file as different tracks, with each track containing the recording from a different location. Where bouts recorded on different recorders overlapped in time and were therefore likely the same vocalisation, these were included as one multitrack file; hence we generated fewer multitrack files than the total number of bouts. Multitrack files were then generated for the CARACALs that mirrored those of the SMs. We used the multitrack files to mark a salient point of each unique vocalisation within the bouts that could be identified as the same point on at least three different tracks, and measured the time differences between these points being detected at the different recorders. From here on, we refer to the salient points that were marked on three or more tracks as *events*. We independently marked the SM and CARACAL multitrack files without reference to each other meaning the number of *events* marked are not comparable between devices. We then performed multilateration by optimisation, using the Matlab script provided in Kershenbaum et al. (2019), to localise the *events*.

Following acoustic localisation, we compared the precision and maximum detection range of successfully localised points between the SMs and CARACALs. To calculate the *localisation precision* we first established which localised *events* could reasonably be associated with a single sound source. To do this we grouped all vocalisations that occurred within 120 sec of each other, and that were localised to within 35 m of each other (these thresholds having been determined using the method described in Sibly et al. 1990), and classed these as a ‘single animal event’ (SAE) (Figure 1). We then examined the spatial spread of the unique localised points associated with each SAE; the median distance between points being our measure of *localisation precision.* To test for differences in precision of localisation between the SMs and CARACALs we performed a Mann Whitney rank sum test. We performed this test separately for each of the focal species, as well as for all species localisations combined. We also calculated the distance between each localised event and the furthest recorder on which it was recorded and called this the ‘maximum detection range’. To test for differences in the maximum detection range of the SMs and CARACALs, we performed another Mann Whitney rank sum test for each focal species and all species combined. Analyses were conducted in Matlab v2020a using the ‘ranksum’ function. Effects were considered significantly different where $p<0.05$.

Results

All recorders were active between 1700 and 0600 on each of the five nights, generating 65 hours of recordings for the both the SMs and CARACALs. Over the five nights we recorded a total of 40, 88, 227 and 312 bouts of vocalisations for wolves, coyotes, dogs, and barred owls, respectively (Table 1).

Detection Ability

After visually examining the spectrograms of all 40 wolf bouts and a random subsample of 40 bouts for each other focal species, we found that the *detection ability* of the CARACALS was less than that of the SMs: more bouts were detected by the SMs than the CARACALs for all four species (Table 1). Specifically, we found that 47.5% of the wolf bouts, 55% of the coyote bouts, 65% of the barred owl bouts, and 82.5% of the dog bouts that were detected on the SMs were also detected on the CARACALs (Table 1).

Localisation

We generated a total of 242 multitrack files from the SM detections, 117 of which were dog bouts, 69 coyotes bouts, 28 barred owl bouts, and 28 wolf bouts (Table 2). From visually inspecting these multitrack files, we found that none of the wolf bouts were detected across three or more recorders, which is the minimum number required to achieve localisation. Subsequently, wolves were removed from further analysis. When analysing the dog, coyote and barred owl vocalisations that appeared on both the SMs and CARACALs, we were able to localise 13, 8 and 7 bouts for dogs, coyotes, and barred owls, respectively on the SM devices. Looking at the same times in the CARACAL multitrack files, we could localise vocalisations from 9, 7 and 5 bouts for dogs, coyotes and barred owls, respectively (Table 2). Thus, we found that localisation was comparable between the two recorders with localisation performed on 28 of the multitrack files for the SMs and 21 for the CARACALs, and almost all identified events in these files were successfully localised (Table 2; Figure 1). The *localisation precision* was not significantly different between the SMs and CARACALs, neither for each species considered separately, nor for all detections pooled (Table 3; Figure 4). The *maximum detection range* was no different between the SMs and the CARACALs for the three focal species that could be localised (Figure 4).

Discussion

We tested and compared the performance of two passive acoustic recorder types at detecting and localising three canid species (domestic dogs, wolves and coyotes) and one owl species (barred owls) across five nights in a forest habitat in Central Wisconsin. We found that both CARACALs and SMs provide passive acoustic monitoring and acoustic localisation capabilities for these species (although we could not localise wolves in the five nights of this study, we have previously used SMs successfully for this purpose e.g. Kershenbaum *et al.* 2019). However, the SMs were more sensitive detecting more bouts of animal vocalisations than the paired CARACALs.

The greater sensitivity of the SMs was demonstrated by our observation that the CARACALs did not detect all of the same bouts of animal vocalisations that were detected on the SMs. The *detection ability* was lower for wolves and coyotes than barred owls and dogs. Differences in *detection ability* could reflect a difference in the detection range between the two recorder types. The recorders were placed near to a farm with domestic dogs; hence this species, for which the highest *detection ability* was demonstrated, was more likely to be closest to the recorders. In contrast, wolves and coyotes often use long-distance communication calls that can be heard from several kilometres away (Joslin 1967; Ha*nsen et al.* 2015), even over 10 km for wolves (Harrington & Mech 1979). Although the CARACALs were previously reported to detect three mammals in Zimbabwe at distances greater than 1 km, the terrain was relatively open and flat (Wijers *et al.* 2019) meaning sound attenuation was likely lower during the study in Zimbabwe than in the forests of Central Wisconsin. Thus, it is possible that the wolf and coyote detections missed by the CARACALs in this study were those originating from further away.

Although we measured the *maximum detection range*, directly comparing the absolute maximum values for the two recorders is problematic in this study. Many localisations fell outside the convex hull formed by the detectors (as visible in Figure 1), at which point the localisation accuracy and, therefore, the accuracy of the distances measured, decreases (Mennill *et al*. 2012; Kershenbaum *et al*. 2019; Wijers *et al.* 2019). Thus, although we found no significant difference between the *maximum detection ranges*, this should not be considered a definitive finding. The greater sensitivity of the SMs could still translate to a longer maximum detection range than the CARACALs. It is, therefore, worth considering whether the focal species of a study employs short or long-distance communication, the amplitude of the species' vocalisations, and the typical home range size of the species when deciding on the appropriate recording equipment. In addition, researchers should consider the topography and habitat type and how this will affect sound attenuation in order to decide on the spatial distribution of recorders.

As the CARACALs detected fewer bouts overall, there were fewer bouts that appeared on three or more recorders, thus fewer individual vocal events that could be localised. However, when vocalisations were detected on both recorders, the localisation success rates were comparable. Importantly, there was no significant difference in the precision (spread) of the localisations between the two recorder types, indicating that the estimation of time differences did not suffer as a result of using the lower-cost CARACALs. This suggests that the CARACALs are a cost-effective recorder for locating vocal species in the wild. In this study, we did not measure the accuracy (absolute localisation error) of the detections, for example with artificial sound sources, although this has been performed previously with SM devices (Kershenbaum *et al*. 2019), and with the CARACALs (Wijers *et al.* 2019). Therefore, we have no reason to doubt the accuracy of the detection.

Although the SMs allowed the gain to be set manually, the CARACALs do not have variable gain settings. However, our experience in this and in previous studies has been that higher gain does not always improve detection, as environmental noise such as wind then becomes a masking effect.

Due to the lower sensitivity of the CARACALs, researchers might need to deploy more recorders to cover the same area with comparable efficacy to fewer SMs. The difference in price between the SMs (average cost of $849 for an SM4 recorder; Wildlife Acoustics 2021) and CARACALs (approx. $200; Wijers et al. 2019) is considerable and unlikely to be negated solely by the need to purchase more CARACALs. However, the initial cheaper start-up costs of purchasing CARACALs could eventually be offset by the greater labour time in deploying and checking a greater number of recorders, and, therefore, more data that needs to be stored and processed to achieve the same monitoring capacity as fewer SMs.

In our five-night study, we found that manually processing the data was extremely time-consuming; the effort of which only increases as the number of deployed recorders increases. Thus, we suggest that future studies consider whether funds are better allocated to reusable equipment or staffing costs before selecting their recorder. However, current and new developments in automated detection (e.g. Lostanlen et al. 2019, Brooker et al. 2020, Shiu et al. 2020), could help reduce, or completely eliminate, the need for human observers to find and mark vocalisations on spectrograms. The ability to use more low-cost recorders like CARACALs without the need for intense human effort in processing data could, therefore, be feasible with advances in AI and automatic detection software.

Further consideration should be made for the environmental conditions of the survey duration. We only tested the two recorder types in one habitat and weather clime, but found that both performed well even at temperatures as low as –8° C. Further tests of performance in other weather conditions and habitats are required to establish the limits on the efficiency of either recorder, particularly as the temperature could affect the battery life. Similarly, one option for extending the battery life of recorders is to use solar-powered batteries, but the feasibility of this would depend on the weather conditions, as well as habitat type (e.g. canopy type). We did not test the effective lifetime of batteries in the recorders during our brief field season, as we changed them every other day to maximise recordings, but the number of batteries required, especially if this differs between the SMs and CARACALs under different temperatures, would also have a clear effect on the cost of deploying either recorder. Furthermore, the habitat type (e.g. topography and forest cover) could heavily influence the efficacy and sensitivity of each recorder. We compared the SMs and CARACALs over a flat landscape with areas of open wetlands hence sound attenuation would be lower here than if deploying these recorders in a heavily forested or urban environment. Researchers should, therefore, consider that the habitat type will affect the required spatial distribution of recorders and the cost of deployment if the density of recorders needed is higher.

Overall, those wishing to use acoustic recorders for acoustic localisation should calculate the initial capital costs (recorders, SD cards, batteries, storage) and ongoing costs (staffing, fieldwork, data processing) of their planned survey and determine how frequently recorders need checking before deciding which recorder type is best for their budget and time. For example, if recorders need checking daily then a deployment of fewer SMs might be more appropriate, but for a survey checking recorders monthly, perhaps a denser network of cheaper CARACALs would be feasible, given that provisions are made for intense data processing and storage capabilities.

In conclusion, both CARACALs and SMs can be appropriate options for detecting and localising a range of species, both domestic and wild, depending on the aims of the study, the focal species and the environmental conditions. While CARACALs are cheaper, the lower sensitivity might make them better suited for use where the sound amplitude is high at the deployment range i.e. for studying species that have a large audible distance to home range ratio. At present, SMs appear the better choice for researchers interested in species with longer call transmission ranges or large home ranges, such as wolves, due to the greater probability of detecting these species on multiple recorders despite having only a few recorders spaced out through the study area. However, advances in automatic detection software might make it more feasible to saturate a study area with a large number of cheaper recorders, such as CARACALs. The ability to use low-cost equipment means that acoustic localisation could become more commonly employed for spatial monitoring of wildlife and potential illegal activities, thus helping to inform management and conservation decisions. Nevertheless, consideration of the focal species, financial budgets, and available automatic detection systems at the time of the survey are required when deciding which recorder to deploy.

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Data Availability Statement

The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of Interest

AM is lead developer of the CARACAL system. MW is a member of the CARACAL development team.

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Tables

Table 1. Total number of bouts marked on the SM recordings, as well as the number and percentage of bouts recorded on the SMs that were also visible on the

CARACALs for each focal species, as determined by visual examination of all 40 wolf bouts and a random subsample of 40 bouts for each of the other three focal species.

Species	Total number of bouts	Number of subsampled bouts recorded on CARACALs	*Detection ability* (%)
Wolf	40	19	47.5
Coyote	88	22	55
Dog	227	33	82.5
Barred owl	312	26	65

Table 2. Number of multitrack bouts generated and the number of these multitrack bouts that we could perform localisation on (i.e. where unique vocalisations appeared on three or more tracks - *events*), along with the total number of these events within the multitrack bouts, the number of those events that were successfully localised using multilateration, and the number of single animal events (SAEs) for each of the different species. SAEs were categorised as events from the same species occurring within 120 sec of each other and being localised to within 35 m of each other.

	Recorder type								
	SM					CARACAL			
Species	Total multitrack bouts	Localised multitrack bouts	Total events	Localised events	# of SAEs	Localised multitrack bouts	Total events	Localised events	# of SAEs
All	242	28	385	379	20	21	195	195	16
Wolf	28	0	0	0	0	0	0	0	0
Coyote	69	8	24	24	4	7	42	42	5
Dog	117	13	325	319	13	9	137	137	9
Barred owl	28	7	36	36	3	5	16	16	2

Table 3. Spread of localised events in metres within each single animal event (SAE: *events* deemed to be likely to originate from the same source), for each of the different species. p-value is for the Mann-Whitney rank sum test, with the null hypothesis that the spreads are drawn from the same distribution. Results were considered statistically significant where p<0.05.

	Recorder type						
	SM			CARACAL			
Species	Median	SE	N	Median	SE	N	p
All	19.3	2.83	20	21.6	2.62	16	0.911
Coyote	28.1	5.72	4	20.0	3.03	5	0.413
Dog	21.6	3.88	13	23.2	3.56	9	1.000
Barred owl	15.5	0.23	3	26.2	16.23	2	1.000

Figure captions

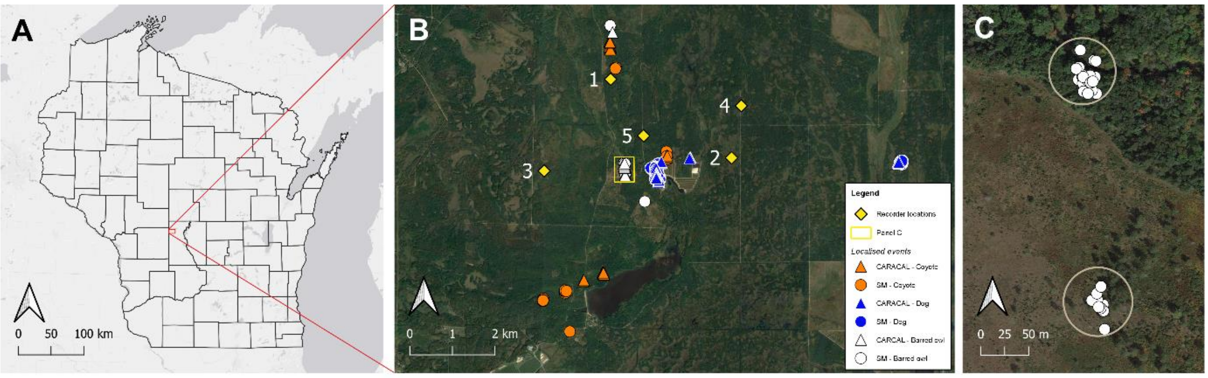

Figure 1. Location of the study site within Wisconsin, USA (A) showing the deployment of recorders (yellow diamonds) and localisations of different species (B): coyotes (orange); dogs (blue); barred owls (white). SM localisations are shown as circles, CARACALs as triangles. Panel C depicts an example of clustering of barred owl vocal events (white circles) that were recorded within 120 sec and 35 m (grey rings) of each other and which were, therefore, classed as Single Animal Events (SAE). Maps produced in QGIS using Google Satellite and ESRI World Light Gray imagery.

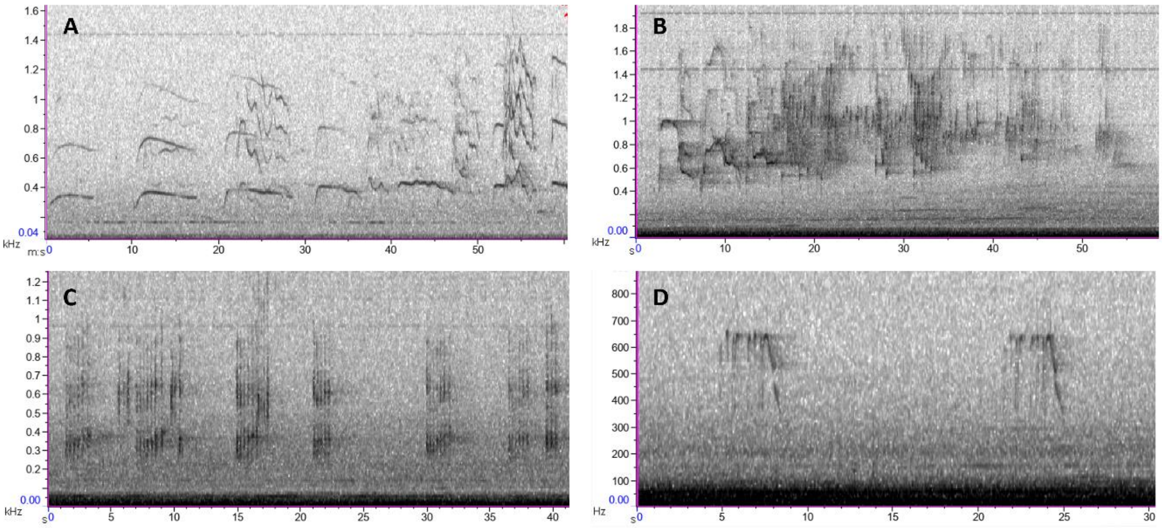

Figure 2. Spectrogram examples of the common vocalisations of each study species: wolves (A); coyotes (B), dogs (C), and barred owls (D). Spectrograms produced in Raven Pro 1.6 (Cornell Lab of Ornithology, Ithaca, NY, USA).

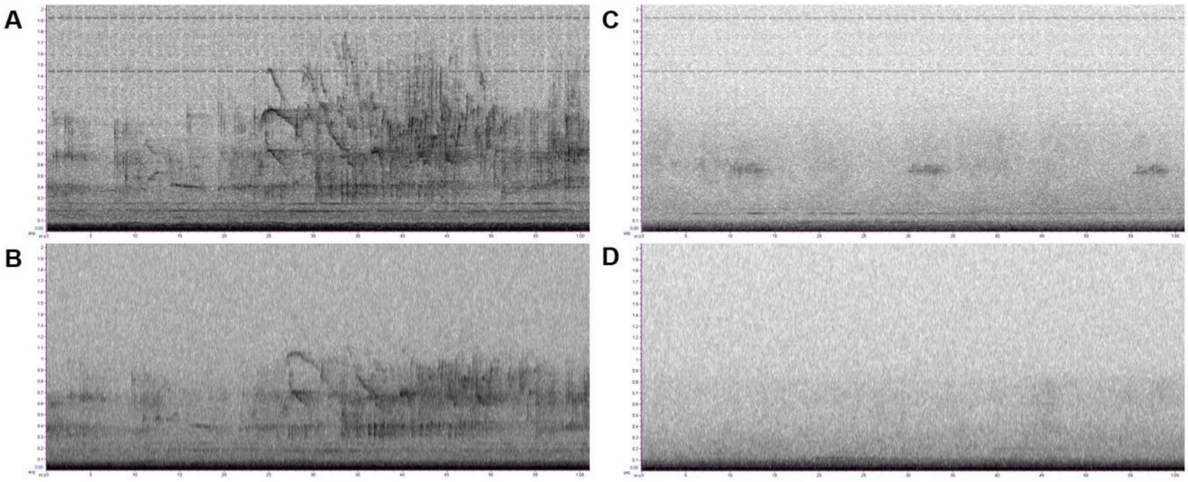

Figure 3. Examples of the *detection ability* comparison between the SMs and CARACALs. Left: coyote bout that was detected by both the SM (A) and the CARACAL (B), even though the whole of the bout was not as clear on the CARACAL. Right: barred owl bout that was detected by the SM (C) but not the CARACAL (D). Spectrograms produced in Raven Pro 1.6 (Cornell Lab of Ornithology, Ithaca, NY, USA).

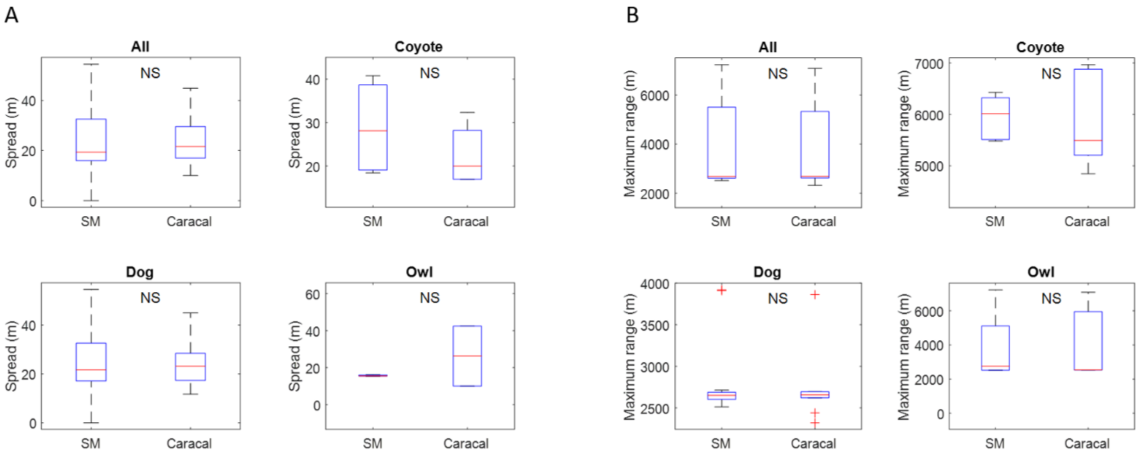

Figure 4. A) Box plot showing the spread of localised points in metres (for *events* deemed likely to originate from the same location – single animal events, SAEs), for each of the different species. Significance is for the Mann-Whitney rank sum test, with the null hypothesis that the spreads are drawn from the same distribution. B) Maximum detection ranges (m) – the distance between localised *events* and the furthest detector they were recorded on – for each species separately and combined. Significance is denoted as 'NS' for Not Significant following results of the Mann-Whitney rank sum test, whereby the null hypothesis was that the spreads are drawn from the same distribution.