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A first test of unattended, acoustic recorders for monitoring Capercaillie *Tetrao urogallus* lekking activity

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ABSTRACT

Capsule: Automated acoustic recording can be used as a valuable survey technique for Capercaillie *Tetrao urogallus* leks, improving the quality and quantity of field data for this endangered bird species. However, more development work and testing against traditional methods are needed to establish optimal working practices.

Aims: This study aims to determine whether Capercaillie vocalizations can be recognized in lek recordings, whether this can be automated using readily available software, and whether the number of calls resulting varies with location, weather conditions, date and time of day.

Methods: Unattended recording devices and semi-automated call classification software were used to record and analyse the display calls of Capercaillie at three known lek sites in Scotland over a two-week period.

Results: Capercaillie calls were successfully and rapidly identified within a data set that included the vocalizations of other bird species and environmental noise. Calls could be readily recognized to species level using a combination of unsupervised software and manual analysis. The number of calls varied by time and date, by recorder/microphone location at the lek site, and with weather conditions. This information can be used to better target future acoustic monitoring and improve the quality of existing traditional lek surveys.

Conclusion: Bioacoustic methods provide a practical and cost-effective way to determine habitat occupancy and activity levels by a vocally distinctive bird species. Following further testing alongside traditional counting methods, it could offer a significant new approach towards more effective monitoring of local population levels for Capercaillie and other species of conservation concern.

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The Western Capercaillie *Tetrao urogallus* (hereafter Capercaillie) is a bird of high conservation concern in the UK, and elsewhere in Europe, on account of its low population size and historical decline (Storch 2000, Eaton *et al.* 2015). Thought to have become extinct in Scotland in the mid to late eighteenth century, it was successfully reintroduced, but has declined again in the twentieth century. Whilst the reasons for this decline are complex and not fully understood, research has shown that low breeding success associated with climate change, and mortality resulting from adult birds flying into forest fences, have contributed to the decline (Moss 2001, Ewing *et al.* 2012). The Scottish Capercaillie population has been subject to concerted conservation management efforts over the past few decades, which appear to have stabilized the population at a critically low level but not increased it (Wilkinson *et al.* 2018), rendering it susceptible to extinction again in Britain (Moss 2001).

A range of methods have been used for Capercaillie monitoring, including counts of displaying males at leks (Picozzi *et al.* 1992, Summers *et al.* 2010) and genetic capture–recapture techniques (Jacob *et al.* 2010) to assess population status. For national status surveys in Scotland, line transects are conducted in winter (Ewing *et al.* 2012, Wilkinson *et al.* 2018). However, the species currently has a low population density and variable detectability relating to habitat type, sex and temperature (Ewing *et al.* 2012). As a result, the 2015/16 national transect survey only recorded an average of one Capercaillie encounter per 12.3 km of transect. Whilst there are good reasons for applying a winter transect count method for the national survey (Ewing *et al.* 2012, Wilkinson *et al.* 2018), the low encounter rates hinder the ability of this survey method to sensitively track changes in the population at smaller temporal and spatial scales.

Capercaillies have a polygonous mating system with an 'exploded' lek breeding system, where males display over a dispersed area to indicate their breeding condition and quality (Wegge *et al.* 2013). The leks

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occur in forest habitat, centre on a display ground covering an area of approximately 0.30 ha, and have mean numbers of male birds of between 0.5 and 20+ per lek, dependent on the quality and quantity of the surrounding old forest habitat (Hjorth 1970, Picozzi *et al.* 1992, Storch 1995, Angelstam 2004, Summers *et al*. 2004, Laiolo *et al.* 2011). Since 2002, Capercaillies in Scotland have been counted at lek sites each April, with a subset of 69 leks subject to consistent monitoring effort. Between 2004 and 2010, the number of male birds at regularly counted leks declined from 215 to 152 birds, a fall of 29.3% (Ewing *et al.* 2012). This may have been due to an overall population decline, abandonment of traditional lek sites in favour of new sites or a combination of these processes. One of the advantages of acoustic monitoring is the potential for wider spatial and temporal systematic sampling, facilitating the identification of newly occupied lek sites.

The quality of data from traditional lek counts may be affected by differences in detection probabilities between habitats or survey events (e.g. in ambient background noise), or measurement and identification errors. Biases may occur in traditional bird count data, with large inter- and intra-observer errors (Celis-Murillo *et al.* 2009, Simons *et al.* 2009) – sometimes due to existing knowledge about the survey area (Hancock *et al.* 1999). For Capercaillie, the surveyed lek sites are often remote, experienced surveyors are few in number, and the necessary timing and seasonal constraints on field survey methods raise difficulties. As a result, the spatial and temporal coverage of Capercaillie sites is currently limited, leading to low confidence in the results from point counts. In addition, Capercaillies are known to be susceptible to human disturbance (Summers *et al*. 2004, Ewing *et al.* 2012), and regular disturbance due to traditional counts has the potential to negatively affect populations. There is a clear need for improved monitoring techniques, especially at important sites, or locations where management actions have been implemented, to determine site occupancy and finer scale temporal and spatial trends. In this way, significant short-term population changes could be identified more readily to alert conservationists to both acute problems and management intervention success. The use of automated acoustic detection, alongside existing survey methods, could reduce the recognized biases and act as a complementary method to enable more accurate population estimates, but there are always going to be logistical and cost implications undertaking both methods in parallel.

As an alternative or complement to existing techniques, we test here the use of unattended sound recorders (often called 'passive' or 'autonomous' recorders) for monitoring Capercaillie leks. Recording of vocalizations has previously been used to monitor other bird species, such as Great Bitterns *Botaurus stellaris* (Gilbert *et al.* 2002), Corncrakes *Crex crex* (Peake & McGregor 2001) and European Nightjars *Caprimulgus europaeus* (Zwart *et al.* 2014). Unattended sound recording is especially applicable in situations where populations are remote, sensitive to disturbance, or the species is cryptic, as recorders can be deployed in the field for long periods of time with minimal surveyor influence at the monitoring site. Hence, this method is potentially highly applicable for Capercaillie.

The displays of Capercaillie males at lek sites commonly entail a sequence starting with vocalizations from a tree perch, before moving to the ground to commute to the lek centre and later adding visual signals to their continuing display songs (Wegge *et al.* 2013). The typical full Capercaillie display song (Figure 1) consists of a low frequency broadband rattle between 1 and 5 kHz, then a deep pop, followed by a repeated scratchy sound between 2.5 and 6.5 kHz. This sequence is described as 'drum roll – cork pop – whetting' by Liaolo *et al.* (2011).

As part of a monitoring programme, effective recording and recognition of Capercaillie vocalizations within large audio data sets could allow the occupancy of a site to be determined, and an index of relative use to be developed (Briggs *et al.* 2012, Cornec *et al.* 2014). It may also be possible to assess the number of male birds at a lek from sound recordings. Laiolo *et al.* (2011) found that Capercaillie song rate (the number of songs per minute from an individual bird) is significantly associated with the number of displaying males. This is likely to be as a signal of intimidation, as the birds attending the lek stimulate each other by increasing their vocal display. Therefore, song rate, recorded using automated bioacoustic techniques, could be used as a proxy for lek counts undertaken by traditional methods.

This study sets out to determine whether Capercaillie vocalizations can be recognized to species level in recordings, and whether this recognition can be automated and calls counted using readily available software. The results are then used to determine how the number of calls varied according to location, weather conditions, date and time of day.

Methods

Four Wildlife Acoustics (www.wildlifeacoustics.com), SM2 acoustic recorders were placed at known Capercaillie lek sites near Aviemore, Scotland (57.19°N 3.82°W) in April 2016. Each recorder was programmed to record in stereo, with one Wildlife Acoustics SMX-II

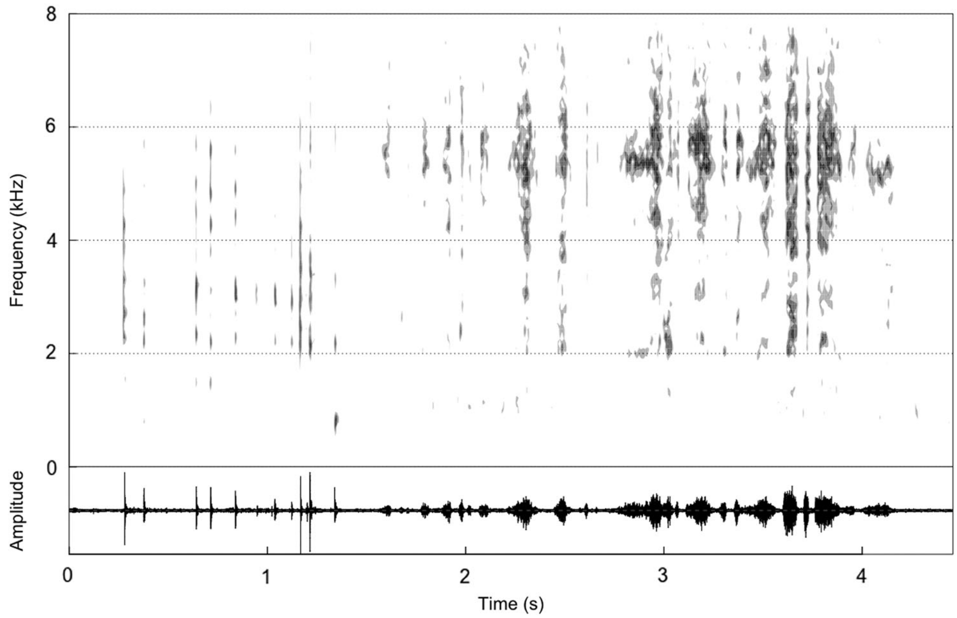

Figure 1. Typical spectrogram of an example Capercaillie call showing frequency spectrum in upper window and amplitude in lower window.

omnidirectional microphone (left channel, 0) mounted on the recording unit and another (right channel, 1) at the end of a 50 m extension cable. The recorder and cabled microphones were both attached to trees at approximately 1.5 m off the ground, and oriented horizontally in opposite directions N–S or E–W. The microphone and recorder were both placed in the vicinity of the lek centre as indicated by a surveyor familiar with the sites and the normal lek count hide locations. A global positioning system device was used to record coordinates of all recorder and microphone locations. The four recording devices were placed at three lek sites, each separated by a distance of kilometres. At one lek site, two recorders (9333 and 9898) were placed together, with the four microphones mounted on the recorders and associated cables forming the corners of an approximate 50 × 50 m^2. The reason for doing this was the fact that previous count surveys and checks for field signs had been unable to accurately define the location of the lek at the site.

The recorders were programmed to record between 04:00 and 10:00 hours every day, starting at 04:00 on 23 April 2016 and ending at 10:00 on 6 May 2016. Recording was limited to these times based on standard lek count practice and surveyor advice (Haysom 2013, S. West, pers. comm.), whilst saving the limited battery life and data storage capacity. Sunrise time at the start of the survey period was at 05:46 hours, getting earlier to 05:14 hours at the end of the survey. During each survey day, the recorders created a series of 10-minute duration full-spectrum data files in Waveform Audio File (.wav) format, recording at a sampling rate of 24 000 Hz and 16 bits per sample. Recording was constant during the set times, without triggers being set. No high or low pass filters were used, and a gain setting of +48 dB was applied. The SMX-II microphones used have a typical sensitivity of −40 to −43 dBV/pa and frequency response of 20–20 000 Hz (Ehnes & Foote 2015, Turgeon *et al.* 2017).

The survey provided a data set covering 14 days (84 hours) at each of the four recorders, with the data from each recorder comprising 505 stereo files (total 2020). The final day of recording (04:00–10:00, 6 May) was used to produce a set of training data for developing an automated call recognizer in the software. The remaining 13 days were retained for analysis purposes.

Data were analysed using Kaleidoscope Pro 4.0.0 software (Wildlife Acoustics 2016), using its ‘cluster analysis’ method. This process searches for repeated phrases in the recordings (e.g. the song of a particular bird species) and groups these into a number of clusters based on their similarity. It provides a numerical score to quantify the ‘distance’ of each individual vocalization phrase from the centre of the cluster (low scores being better matches with this average). According to the software protocol, a preliminary analysis was conducted on the training data to scan and cluster recordings. The clustering process identified individual ‘phrase segments’ within the training data, each of these being a mono recording (from either the right or left channel), >2 and <7 seconds in duration (the typical song length of Capercaillie), comprising a sequence of 'syllables' occurring close enough together in time such that the defined 'maximum inter-syllable gap' of 1 second is not exceeded. All the phrase segments from the training data were individually reviewed and manually identified as either Capercaillie calls or other sounds, by viewing the sonogram and listening to playback. In addition, the performance of the clustering process was assessed by comparing clustered data to a stratified sample of the original recordings. Each phrase segment selected by clustering could include vocalizations by more than one bird species, if these were singing simultaneously within the frequency band, but they were assigned as Capercaillie if calls from this species were included. From this manual review, the cluster with the highest proportion of Capercaillie phrases from the training data was identified, and this cluster was then used as a recognizer to identify matching Capercaillie phrases within the 13-day sequence of analysis data, using the same analysis parameters as used for the training data.

To assess the effectiveness of the classification process, all the phrase segments identified in the analysis data as 'Capercaillie' matches were manually checked by viewing the sonogram and listening to playback. This allowed the proportion of false positive matches to be assessed. To identify the proportion of false negatives, a random selection of 500 (4%) 'non-Capercaillie' phrase segments from the analysis data was also manually checked.

For call analysis with Kaleidoscope Pro, the following analysis parameters were used: Daily subdirectories created; Files split to 60 seconds max duration; Split channels; Signal of interest 1500–4000 Hz; Duration 2–6 seconds; Maximum inter-syllable gap 1 seconds; Max distance from cluster centre to include outputs in cluster.csv = 1.0; Fast Fourier Transforms window = 5.33 ms; Max states = 12; Max distance to cluster centre for building clusters = 0.5; Max clusters = 500.

As environmental context for the acoustic data, weather data for the Met Office MIDAS station at Aviemore was accessed through BADC (badc.nerc.ac.uk/cgi-bin/midas_stations/station_details.cgi.py?id=113&db=midas_stations) and DATA.GOV.UK (using the Aviemore weather station codes DCNN 0585 and RAIN 817692). Daily rain data for Northern Scotland was also accessed from Hadley UKP (www.metoffice.gov.uk/hadobs/ hadukp/data/download.html). Statistical tests were carried out using R and R Studio software (R Core Team 2013, R Studio Team 2015).

Results

The first stage of analysis used clustering to identify and group similar vocalizations within the single day of training data. This identified 5401 individual phrase segments, produced by a variety of bird species, grouped into ten clusters. The total duration of these phrase segments amounted to 4.88 hours, out of a total recording time of 48 hours (4 recorders × 6 hours × 2 channels). All 5401 training data phrase segments were manually reviewed (taking less than eight hours), with 258 segments (5%) identified as having Capercaillie calls, and 5143 segments without Capercaillie (Table 1). Of the 5401 phrase segments, 80 were assigned to Cluster 09, in which 52 (65%) were manually confirmed to contain Capercaillie calls (the highest proportion of Capercaillie calls of any cluster). The remaining 206 phrase segments that included Capercaillie vocalizations (often overlapping calls from other species) were spread through the remaining clusters. Most of these were in Cluster 08, which had Capercaillie vocalizations in 20.1% of its phrase segments, whilst all remaining clusters had less than 5% of phrase segments being positive for Capercaillie. Hence, clustering of the training data at this initial stage provided a single main Capercaillie cluster which picked out 52 (20%) of 258 Capercaillie phrase segments manually identified from the data set. The check back of clustered data against the original recordings showed that the clustering performed well according to the set parameters. The clustering correctly identified the presence or absence of Capercaillie in the 10-minute .wav files 75% of the time, with false positives (calls incorrectly assigned to Cluster 9) in 8% of cases and false negatives (calls missed or assigned to another cluster) in 17% of cases. This manual review also indicated that there were a number of short Capercaillie sequences or individual spaced calls present that were outside the parameters of the clustering process due to their limited duration (often being less than 1 second).

Using Cluster 09 to identify similar Capercaillie recordings, the remaining 13-day sequence of analysis data was processed to determine whether Capercaillie phrases could be effectively identified within the recorded data set. A total of 13 626 phrase segments were produced from the analysis data (Table 1), of which 907 (6.7%) were assigned as a match to the Cluster 09 Capercaillie data. These were all manually checked and 758 of the 907 (83.6%) were confirmed as Capercaillie, with 149 (16.4%) false positive matches. To identify the proportion of false negatives, a random selection of 500 phrase segments (4%) out of the

Table 1. The error matrix produced from: (a) the clustering process which produced the classifier from the single-day training data set and (b) applying this classifier to the 13-day analysis data set. False negatives are where the species was present but not detected by the software (read along the rows less the diagonal cell). False positives are where the software identified the species to be present when it was not (read down the columns less the diagonal cell).

		Software classifier			
		Capercaillie	Other	Total	False negative (%)
(a) Training data set					
Manual identification	Capercaillie	52	206	258	79.8
	Other	28	5115	5143	0.58
	Total	80	5321	5401	
	False positive (%)	35.0	3.87		
(b) Analysis data set					
Manual identification	Capercaillie	758	1399 (estimate)	2157	64.9
	Other	149	11,320 (estimate)	11,469	1.3
	Total	907	12,719	13,626	
	False positive (%)	16.4	11.0		

remaining 12 719 were manually checked. Of these, 55 phrases (11%) were confirmed as including Capercaillie vocalizations and hence being false negatives. The greatest proportion of these was in Cluster 08, which had 29% false negatives, and Cluster 01, which had 13%. The remaining clusters 02–07 all had a false negative proportion of <10%. Hence, overall there were estimated to be 1399 ($0.11 \times 12\,719$) phrase segments containing Capercaillie calls in the analysis data set which were not discovered. This equates to the supervised clustering successfully identifying 83.6% of Capercaillie vocalizations in Cluster 09, and correctly extracting 35% of all Capercaillie phrase segments. These findings mean that the limited number of false positives in Cluster 09 could be manually screened quickly, with a low rate of false negatives scattered through the other clusters – these often being low 'quality' phrase segments with single calls or poorly recorded, and therefore difficult and time-consuming to identify manually.

The data set of 758 Capercaillie phrase segments identified by the cluster process and manual confirmation was used for further analysis. The spectrograms were first analysed to ascertain the characteristics of the recorded calls. Within the data set, the vocalizations had a mean frequency of 3083 Hz, within a general range of 2000–4000 Hz (Figure 2). Some variation was found between the data from different locations, with means between 2874 Hz at recorder 9558 and 3234 Hz at 9333. A median duration of 4.512 seconds was found for the identified phrase segments, with a minimum of 2 seconds and a maximum of 6.94 seconds (as constrained by the software settings).

The differences in the total number of recorded phrase segments (from all species), and those of Capercaillie, were investigated across different recorder locations and between left and right stereo channels. The numbers of all of these varied widely between recorder locations, with almost no vocal activity recorded at 9333, moderate levels at 9558 and highest activity at 9898 and 9573 (Table 2). As context, the number of males recorded during lek counts at these sites in the same season (but not concurrently with recording) were three birds at 9333/9898, five at 9573 and seven at 9558 (S. West, pers. comm.). A great deal of variation was found between the two stereo channels on each recorder, with all locations recording many more calls on one channel than the other. Review of the Capercaillie call data revealed very few instances ($n = 8$, approximately 1%) where near-simultaneous calls were recorded on both left and right channels, that is from the same bird being recorded simultaneously on both channels. Hence large differences were found between data from microphones located 50 m apart. In addition, recorders 9333 and 9898 were both placed in the vicinity of a single lek site and recorded widely differing numbers of vocalizations. A possible reason for this is discussed below.

The number of calls recorded per day was investigated to determine whether there was any trend across the survey (and lekking) period. The overall levels of Capercaillie vocal activity, pooled across all recorder locations, varied day-to-day between 1 and 191 phrase segments, but were highest at the start (23 April) of the survey and declined (with daily variations) throughout the rest of the period (Figure 3). This is likely to reflect a true decline in lekking activity, as the survey was undertaken at the tail end of the main lekking season. The highest daily total of phrase segments at a single recorder was a maximum of 146 at recorder 9898 – this being more than half of all segments recorded at that location, recorded in a single day.

Prior to the study, an early morning peak in vocal activity was expected, with units set to record between 04:00 and 10:00 hours. This assumption was found to be correct, with our data clearly indicating that the highest levels of call activity were recorded in the 2-

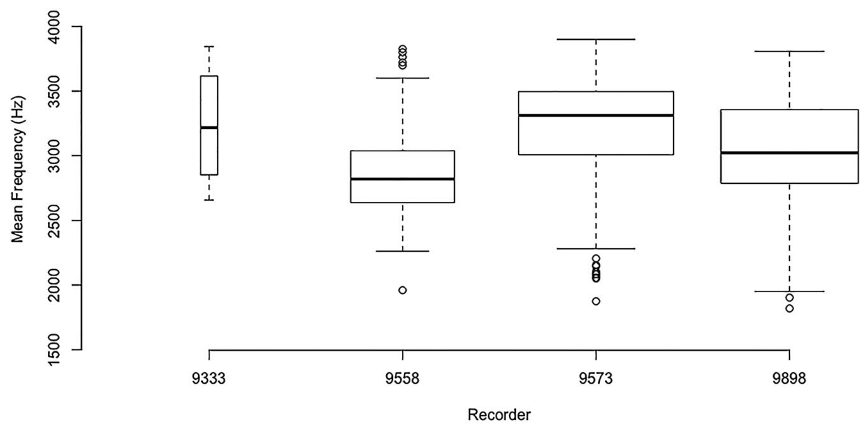

Figure 2. Box plot of mean frequency of Capercaillie phrase segments at each recorder location. The centreline of each box indicates the median value for all phrase segments at each recorder location. Boxes represent the data between lower and upper quartiles, and the whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range. Outliers in each population are represented by dots.

hour period around sunrise (Figure 4), with a median time for all calls of 36 minutes before sunrise. There are significant differences between the recorder locations though (Kruskal–Wallis chi-squared = 289.13, df = 3, $P < 0.01$), with unit 9573 being significantly earlier than the other three locations.

If the morning peak in activity is related to sunrise time (i.e. light levels), then we would expect this to get earlier through the survey period as day length changes. This relationship between peak vocalization time and sunrise appears to be demonstrated in Figure 5, where in addition, the high level of calls around 04:00 hours, the start of the recording session, are indicated.

Relationships between the total number of vocalizations per day with three weather parameters were tested using Spearman's rank correlation (Table 3). A significant negative correlation ($P < 0.05$) was found with windspeed (Figure 6), but there was no significant relationship with temperature or rainfall.

Discussion

Our results confirm that automated passive acoustic recorders can effectively be used to detect and record Capercaillie vocalization activity in the field. This study has also shown that semi-automated call analysis can rapidly identify individual vocalization phrases for a target species, with call classification having an accuracy of over 80% accuracy and correctly extracting 35% of all Capercaillie calls (most of those not extracted being of poor quality) – and only producing 16% false positives. The clustering process applied here is a different approach to the use of pre-constructed species-specific recognizers used in many other studies (Brandes 2008, Bardeli *et al.* 2010, Oppel *et al.* 2014). It is primarily intended to be a human-supervised process which organizes sound data into call-type groups to allow rapid manual review and labelling. With the appropriate manual checks, including identification of false negative and positive classifications, it was very successful in correctly identifying Capercaillie vocalizations in the analysis data set, even when based on a small single set of training data – albeit with a relatively high omission error (64.9%). Although the clustering process used here, based on a limited number of individuals, was suitable for identifying birds at the study sites, it is expected that improved rates of detection, with fewer false positives and negatives, could be achieved in future studies with a larger training data set (Digby *et al.* 2013). In addition, it is worth noting that our method

Table 2. Total numbers of phrase segments at each recorder location.

Recorder		9333	9898	9558	9573
Lek site		A	A	B	C
Lek count (males)		3	3	7	5
All phrase segments	Microphone 1/2 Left/Right	449/75	1445/743	186/1750	5599/3379
	Total	524	2188	1936	8978
Capercaillie phrase segments	Microphone 1/2 Left/Right	4/0	206/59	0/152	272/65
	Total (% of all phrases)	4 (0.76%)	265 (12.11%)	152 (7.85%)	337 (3.75%)
	Mean(range)/day	0.31(0–2)	20.38 (0–146)	11.69 (0–40)	25.92 (0–101)

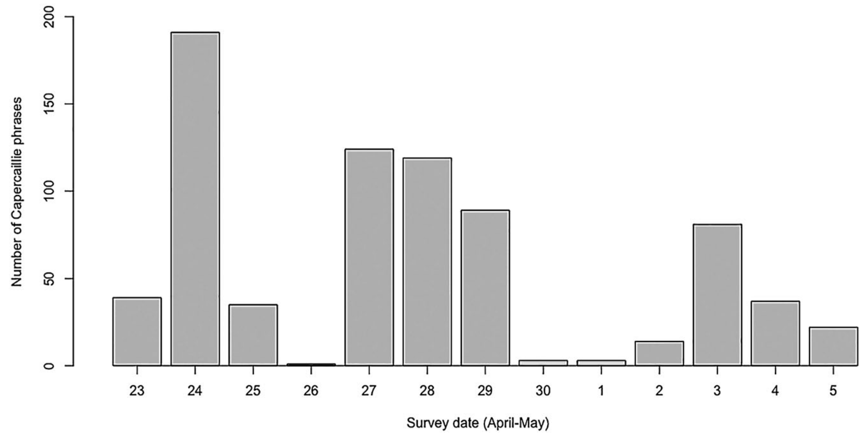

Figure 3. Total number of Capercaillie phrase segments recorded per day, across all detectors.

did not attempt to exhaustively identify every Capercaillie vocalization in the recorded data set. The clustering approach allowed a user-determined set of search parameters to be applied to the data, with vocalizations that matched the settings being selected as phrase segments. As a result, it is accepted that vocalizations not matching these criteria (e.g. short individual calls) would not have been identified, and the Capercaillie phrase segments used in our analysis are a reduced subset of the overall recorded activity. However, the defined criteria used in the clustering ensure that vocalizations of the same type and quality are being compared between different days and detector locations, allowing a coherent analysis of the call data. This rapid analysis method, with low levels of false positives, is particularly suited to ascertaining the presence of Capercaillies at a site, which could be a very useful tool for a species with low densities and fluctuating lek site occupancy.

The numbers of calls recorded varied widely between recorder locations and also between left and right channels on the same recorder. The former could indicate differences in the levels of vocal activity between different lek sites, whilst the latter indicates that Capercaillie calls do not travel well over distance, that is detectability is limited at distances over 50 m. This is similar to detection ranges found in other bioacoustic studies of forest birds (Venier *et al.* 2012, Sedláček et al. 2015). Using the same type of recorders and microphones, Turgeon *et al.* (2017) found bird call detection radii of between 13 and 203 m, dependent on the species, background noise levels and microphone condition. For comparison, the spacing between individual Capercaillies at leks has been recorded as 64–212 m (with interactions between males sometimes occurring at less than 10 m), and calls from this species can generally be heard at a distance up to approximately 200 m by the human ear (Hjorth 1970, Moss & Lockie 1979, Wegge *et al.* 2013). This relationship between detection distances and bird density clearly raises the issue of detectability during surveys, for both human

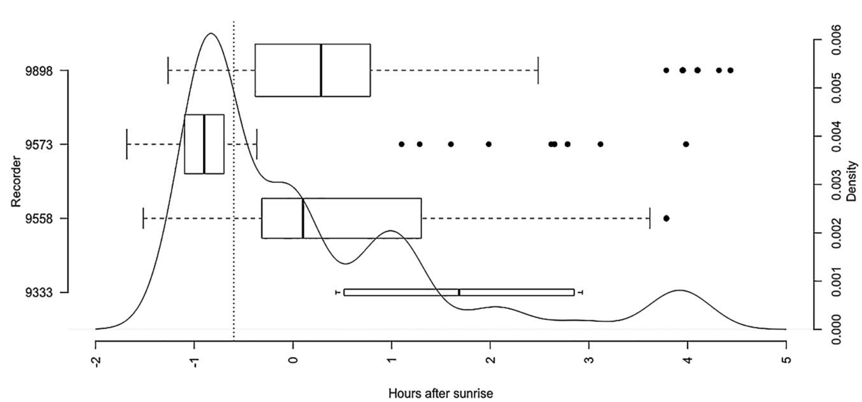

Figure 4. Capercaillie vocalizations in relation to sunrise time. Box plots indicate median times, quartiles and ranges for Capercaillie phrase segments at each recorder location, in relation to sunrise. Box plot width indicates relative sample size. The median time for all Capercaillie phrase segments recorded is indicated by the dotted vertical line at 36 minutes before sunrise. The kernel density of Capercaillie phrase segments over time is shown by the solid line.

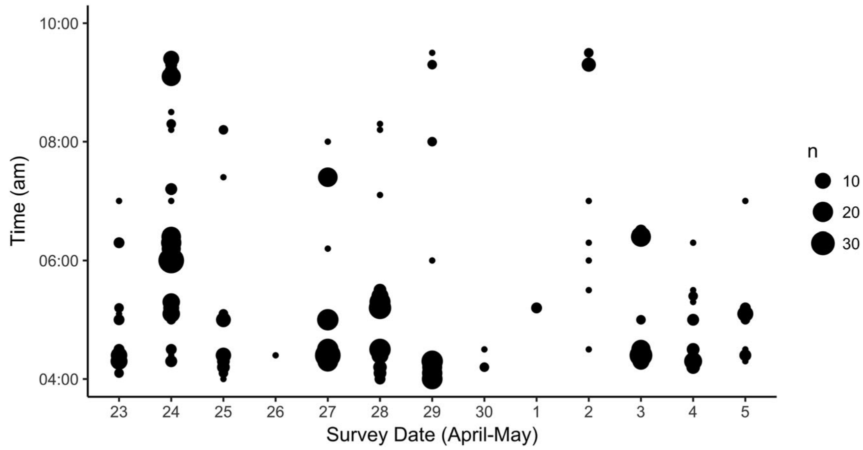

Figure 5. Timing of Capercaillie vocalizations in relation to date, for all recorder locations combined. The size of circles indicates the number of phrase segments recorded within each 10-minute recording period.

Table 3. Spearman''s rank correlation of weather conditions with total number of Capercaillie calls per day.

Variable	S	*P*	rho
Wind	576.64	0.036	−0.584
Temperature	523.22	0.135	−0.437
Rain	532.46	0.111	−0.463

counters and automated recording equipment (Yip *et al.* 2017). This indicates that, for bioacoustics methods, careful thought needs to be given to the number, layout and response of recorders and microphones, as well as the characteristics of the recording environment. In addition, when recording and analysing sound files, the appropriate audio settings, such as gain, sample rate and the use of high and low pass filters should be considered. The development of good practice guidance for this should be prioritized to ensure repeatable results from any future monitoring programme (Eyre *et al.* 2014, Pocock *et al.* 2015), and further research should focus on elucidating the optimum number of microphones, and distance between them, at a lek site.

In this study, the pair of recorders 9333 and 9898 were located either side of a wide electricity pylon way leave through the forest, with the lek site thought possibly to be present within the open way leave habitat between. However, the recorder on the northern side of the way leave (9898) recorded 265 Capercaillie phrases, compared to only four on the south side (9333). This is likely to indicate that the lek site was actually present within the forest to the north of both recorders, and audible sounds were only picked up by the closest set of equipment.

Differences were found in median call timings between locations, with recorder location 9573 recording calls significantly earlier in the day compared to other locations. This could perhaps be due to habitat differences, such as forest structure, aspect or altitude. For example, 9573 was the lowest of all four sites at

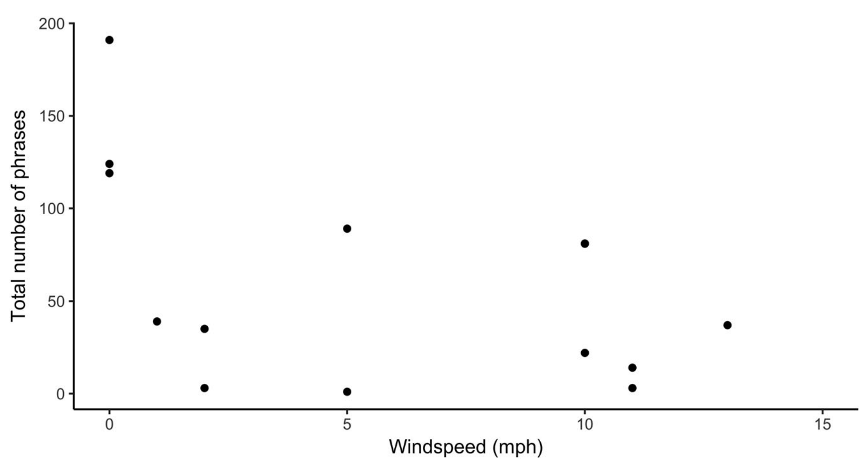

Figure 6. Inverse relationship between number of phrase segments recorded per day and wind speed. Spearman's rank correlation coefficient ($S = 576.64$, $P = 0.036$, rho = −0.584).

255 m above sea level (asl) and in relatively open forest habitat, whilst the rest were at 325–375 m asl, and in denser plantations. Further exploration of how the environment might affect Capercaillie lekking behaviour would be worthwhile (Angelstam 2004, Laiolo *et al.* 2011).

Lek monitoring at the local scale rather than winter transect counts, which are subject to low encounter rates (Ewing *et al.* 2012), should be seen as an important method of monitoring the effects of management and alert practitioners to local population changes. As discussed above, there are significant limitations to traditional manual lek counts, and the automated acoustic approach provides a promising alternative or complement. Within our study, large differences were found between the number of Capercaillie vocalizations recorded at each of the three locations. This may partly be due to the precise location of the recorders in relation to the lekking birds, given the range detectability issue discussed above (which is also likely to affect human observers), but could also be a true reflection of bird numbers and activity levels at each site. We anticipate that the level of call data recorded using our methods should be indicative of population size and lekking activity, but comparison with human observer counts has not been attempted in this study, due to the limited number of leks covered and the lack of synchronous count data. Further work is clearly required in this area, but studies have shown that recorded calling rates are positively relate to lek size in White-bearded Manakin *Manacus manacus* (Cestari *et al.* 2016) and White-bellied Emerald *Amaziliu candida* (Atwood *et al.* 1991), and to nest density at Cory's Shearwater *Calonectris borealis* breeding sites (Oppel *et al.* 2014). These findings indicate that acoustic monitoring may be useful to document relative changes in local bird populations over time. In particular, the day-to-day variation we recorded in call activity at each site over the survey period (Figure 3) must sound a note of caution to reliance on Capercaillie population data from single visit lek counts.

Haysom (2013) recommends that Capercaillie lek surveys in Scotland should take place during the peak period of mid-April to early May, with variation according to spring temperatures. The call activity we recorded was highest at the start of the survey period (23 April) and declined through the survey period. Hence, this indicates that earlier activity might have been missed in this study. Further unattended acoustic research of Capercaillie leks should aim to test whether there is activity prior to mid-April, to understand whether the recommended seasonal parameters of traditional lek surveys need to be adjusted.

The peak of highest levels of call activity, across all recorders, occurred at 36 minutes before sunrise. The standard guidance by Haysom (2013) recommends that leks should ideally be counted from 04:00 to 06:00 hours. However, relatively high levels of call activity were recorded at the start of our daily survey period (04:00–10:00 hours), so for future studies, an earlier survey start is recommended, for example, 2–3 hours before sunrise (02:30–03:30 hours).

The number of recorded vocalizations decreased with increasing wind speed. This could be due to: (i) reduced calling (and possibly lekking) activity in adverse weather conditions, (ii) reduced detectability of calls in high winds or (iii) increased masking by background noise in high winds (Digby *et al.* 2013). There is anecdotal recognition of the effects of environmental parameters – weather and altitude – on call activity from human observers at lek counts. The impacts of this on results could benefit from further investigation to allow the quality of count data to be assessed against weather conditions, with weather factors being modelled into data analysis. It would be more practicable to achieve this with the long data sets possible from automated recording, than those provided by the limited resource of human surveyors (Oppel *et al.* 2014).

In conclusion, this study has shown that Capercaillie can be effectively recorded in the field using automated passive acoustic methods. The equipment necessary to do this is simple and readily available, and enormous progress in signal processing and pattern recognition in recent years has made it possible to incorporate automated methods into the detection of vocalizations (Bardeli *et al.* 2010). As a result, there is a clear opportunity for acoustic monitoring of this species over extended periods, with rapid analysis of the recorded vocalizations. The time and cost savings of this approach over manually reviewing all of the sound data are significant. In this study, a total equivalent of 56 days of recording was completed with only two days of fieldwork and one–two days of call analysis. This is not uncommon; Digby *et al.* (2013) assessed that autonomous recorder methods required less than 3% of the time needed for a comparable traditional field survey.

The continuing vulnerability of the Scottish population of Capercaillie makes regular and consistent monitoring a priority. The use of acoustic techniques could eliminate or minimize observer biases, reduce disturbance caused by surveyors and provide standardized field data that can be permanently archived. It could also help resolve problems associated with surveying in pre-dawn darkness, hard to access survey sites and with the limited availability of expert field observers (Hobson *et al.* 2002, Celis-Murillo *et al.*

2009, Zwart *et al.* 2014). Acoustic recording methods could allow for cost-effective lek occupancy checks of suitable, but previously unmonitored or unoccupied, areas, which would be unfeasible using manual lek surveys. Acoustic data may also be useful in testing when (in terms of weather conditions, season and time of day) manual monitoring would be most effective and could help gauge the accuracy of point counts. As a result, it is a developing tool that could potentially have great application and significance, offering to fill a methodological gap especially for the census of cryptic taxa such as Capercaillie (Dawson & Efford 2009, Bardeli *et al.* 2010, Laiolo 2010, Zwart *et al.* 2014).

The next step in the development of bioacoustics for birds should be in the establishment of recognized survey protocols and statistical approaches to be employed by practitioners such as conservation professionals and ecological consultants (Marques *et al.* 2013), to set out good practice and allow greater comparability between studies of different species and at different locations. This will require testing and work to compare traditional versus acoustic methods – probably developing an improved approach which combines the two into an integrated system. For Capercaillie, the obvious first step is to correlate lek count numbers against the numbers of calls recorded during the same survey event, or better, over a longer survey period surrounding a number of repeated counts at each lek.

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