Title: Sampling environmental acoustic recordings to determine species richness: I.

Authors: Jason Wimmer[a], Michael Towsey[b], Paul Roe[a], Peter Grace[b] and Ian Williamson[a]

Affiliations:

[a]Science and Engineering Faculty, Queensland University of Technology, Brisbane, Australia

[b]Institute for Future Environments, Queensland University of Technology, Brisbane, Australia

Email: (j.wimmer, m.towsey, p.roe,pr.grace, i.williamson)@qut.edu.au

Corresponding Author: Jason Wimmer

Corresponding Author Address: School of Electrical Engineering and Computer Science, QUT Gardens Point, Brisbane, Queensland, 4000, Australia. Ph: +61 7 3138 2240 Fax: +61 7 3138 9390

Abstract:

Acoustic sensors provide an effective means of monitoring biodiversity at large spatial and temporal scales. They can continuously and passively record large volumes of data over extended periods, however these data must be analysed to detect the presence of vocal species. Automated analysis of acoustic data for large numbers of species is complex and can be subject to high levels of false positive and false negative results. Manual analysis by experienced users can produce accurate results, however the time and effort required to process even small volumes of data can make manual analysis prohibitive. Our research examined the use of sampling methods to reduce the cost of analysing large volumes of acoustic sensor data, while retaining high levels of species detection accuracy. Utilising five days of manually analysed acoustic sensor data from four sites, we examined a range of sampling rates and methods including random, stratified and biologically informed. Our findings indicate that randomly selecting 120, one-minute samples from the three hours immediately following dawn provided the most effective sampling method. This method detected, on average 62% of total species after 120 one-minute samples were analysed, compared to 34% of total species from traditional point counts. Our results demonstrate that targeted sampling methods can provide an effective means for analysing large volumes of acoustic sensor data efficiently and accurately.

1. Introduction

Acoustic sensors provide an effective means for monitoring biodiversity at large spatial and temporal scales [1-5]. They can record large volumes of acoustic data continuously and passively over extended periods. However, these recordings must be analysed to detect the presence of vocal species. Acoustic recordings can be analysed automatically using specially designed call-recognition software or manually, by using humans to identify species-specific calls [2,6-8]. Automated analysis of acoustic sensor data for large numbers of species is complex and can be subject to high levels of false positive and false negative results [9,10]. Manual analysis can produce accurate results, however the time and effort required to process recordings can make manual analysis prohibitive [10,11]. Continuous acoustic sensor deployments are restricted practically only by data storage capacity, which continues to increase in size and decrease in price. Therefore, the volume of data that we are now able to collect far outweighs our present ability to process it efficiently and accurately. The result is that many consumers of acoustic sensor data are employing acoustic sensors to monitor biodiversity and subsequently finding that it is difficult to interrogate the data in a meaningful way.

Many studies have identified the issues of efficiently analysing large amounts of acoustic data collected in the field [1,3,8,12-14]. The amount of effort required to analyse acoustic data depends on the objective of the analysis. These objectives fall broadly into two categories:

- Single species surveys: analysing acoustic recordings of the vocalisations of a single species to assess aspects of that species' ecology or behaviour;
- Species richness surveys: analysing acoustic recordings and identifying all taxa to generate a measure of species richness for a study area.

These objectives differ subtely in terms of the analysis methods and effort required to process large data sets. Single species analyses may be undertaken manually (due to the smaller number of potential vocalisations), or automatically using custom developed software or existing tools such as Raven [15]. Automated detectors for species with distinctive vocalisations such as the Koala (*Phascolarctos cinereus*) and Cane Toad (*Bufo marinus*) have been developed and used successfully for a number studies [16-18]. Due to the larger number of species (and therefore range of vocalisations), species richness analyses typically require much greater time and effort. Irrespective of the objective, efficient analysis methods must be developed which can deal with the volumes of data that result from large scale deployments of acoustic sensors.

Automated analysis tools use software development techniques borrowed from speech recognition to detect the vocalisations of individual species in recordings. Perhaps due to the importance of birds as indicator species of environmental health [19], there is a significant body of literature relating to the automated detection of bird vocalisations [7,8,20-29] . Some approaches, focusing on limited numbers of species or single species surveys, have produced promising results by extracting sets of specific features to classify calls [30,31]. Automated analysis techniques are evolving quickly, however, due to the inherent complexity of acoustic environmental data, it will be some time before automated methods are capable of detecting all species likely to be found at a location [8,32,33] .

Manual analysis typically involves listening to recordings and identifying individual species vocalising in the recordings. This can be augmented by the use of tools to visualise the audio in the form of spectrograms, and by providing 'reference calls' which can be used to assist in species identification [6]. Manual analysis can be very accurate if experienced observers are involved, however it is time consuming, expensive and ultimately fails to scale over large spatial and temporal frames [11].

To take advantage of the benefits of acoustic sensing in the near-term, users of this technology require effective methods to analyse large volumes of acoustic data. Sampling is a common and well-established method for estimating species richness for an area [34]. This study investigates whether sampling methods can be used to make reasonable estimates of bird species richness from large volumes of acoustic sensor data. Sampling methods were tested on 480 hours of manually analysed acoustic sensor data. These data were also used to compare a range of sampling methods with the results from traditional avian point count surveys.

2. Materials and Methods

Study site

Traditional avian point count [35] and acoustic sensor surveys were conducted simultaneously in four locations over five days at the 51ha, Queensland University of Technology (QUT) Samford Ecological Research Facility (SERF). SERF is located in the Samford valley in south east Queensland, Australia (Figure 1).

The main vegetation at SERF is open-forest to woodland comprised primarily of *Eucalyptus tereticornis*, *E. crebra* (and sometimes *E. siderophloia*) and *Melaleuca quinquenervia* in moist drainage. There are also small areas of gallery rainforest with *Waterhousea floribunda* predominantly fringing the Samford Creek to the west of the property, and areas of open pasture along the southern border.

The four sampling points were positioned in the north east corner within open woodland, the north west corner in closed forest along a creek line, in the south west corner within *Melaleuca* woodland, and in the south east corner bordering open pasture (Figure 2).

Samford Valley has a sub-tropical climate and experiences approximately 1020mm of rainfall per year. Maximum and minimum mean temperatures are 26 and 13 degree Celsius respectively [36]. During the month of the survey period (October 2010) the site experienced rainfall of 296mm, compared to an average of 116mm. During the actual survey period however (13^{th} October – 17^{th} October), only 1mm of rainfall was recorded. Acoustic sensors were located at the centre of each survey site and configured to record continuously for five consecutive days.

Acoustic Sensors

Acoustic sensors were deployed at four locations within SERF with at least 300m between the centre of each survey site and therefore between any two sensors. Sensors used for this study were custom-developed using commercially available, low cost digital recording equipment. Acoustic data were recorded using Olympus DM-420 digital recorders and external omni-directional electret microphones. Data were stored internally in stereo MP3 format (128 Kbit/s, 22.05 KHz) on high capacity 32GB Secure Digital memory cards. The units were stored in a weatherproof enclosure and powered by four D cell batteries, providing up to 20 days of continuous recording.

Acoustic Sensor Data Analysis

At the completion of the survey, sensor recordings were analysed manually by experienced bird observers to identify each unique species vocalising in each one-minute segment. Species were identified using a custom online acoustic workbench designed to manage the process of acoustic data analysis [6]. The workbench plays audio and displays a spectrogram, which allows the user to visualise and hear audio simultaneously. Bird vocalisations were identified aurally and visually by listening to the recording with headphones and simultaneously observing the corresponding spectrogram. To mark species vocalisations within recordings, the workbench provided the ability to annotate spectrograms. Annotation involved selecting the portion of the spectrogram image that contained the specific vocalisation, using a rectangular marquee tool in the audio player. A tag was then assigned to the selection, which identified the species. The upper and lower frequency bounds, start time and end time, duration and species tag were associated with each selection. Figure 3 shows an example of a spectrogram annotated with a Bush Stone Curlew (*Burhinus grallarius*) vocalisation in the audio player.

To simplify data management and analysis, sensor recordings were split into one-minute segments. Each one-minute segment was played and assessed for species vocalisations, and a single vocalisation from each species in that minute was tagged. To reduce overall effort, once a species was identified in a one-minute segment, all further calls for that species in that minute were disregarded. Therefore, the data derived from the five days of recording at the four sites is comprised of the number of different species calling in each one-minute segment. Species richness measures are species calling per unit time (minute, hour, day). The information obtained from one-minute segments was considered an adequate compromise between the time-consuming task of identifying every call made over the five day period, and the need to have detailed information on the number of species calling at a particular time of the day. The amount of time taken to analyse each one-minute segment was also recorded for each observer.

Following manual analysis of the sensor data, species list reports were generated for the four sites over five days. One-way analysis of variance (ANOVA) was calculated to compare the mean proportion of species detected for each sampling method, and the EstimateS 8.2 package was used to calculate the Chao2 species richness estimate for each site [37,38]. Chao2 is a nonparametric richness estimator, which can estimate total species richness based on occurrence data. These data were used to examine the performance of different sampling methods.

Sampling Methods

Five sampling methods were investigated to determine the method that returned the highest estimate of species richness (compared to the output from manually analysed data sets) for the least amount of manual analysis effort. These sampling methods were:

Full Day – One-minute samples selected randomly from the full 24-hour periods;

Dawn – One-minute samples selected randomly from 3 hours after dawn (05:15 – 08:14);

Dusk – One-minute samples selected randomly from 3 hours before dusk (14:55 – 17:54);

Dawn + Dusk – One-minute samples selected randomly from Dawn + Dusk periods;

Systematic – One minute every half hour on the half hour, from the full 24-hour periods.

The Full Day sampling method included all data from all days for each site. In total, this constituted 7,200 one-minute segments per site. The Dawn sampling method included 900 one-minute segments over the five-day period per site. The Dusk sampling method also included 900 one-minute segments over the five-day period per site. The Dawn and Dusk sampling method included both Dawn and Dusk periods, and hence was comprised of 1,800 one-minute segments over the five-day period.

Many users of acoustic sensors have adopted a systematic sampling method as a means of reducing the data collected overall and hence the manual analysis effort [17]. The systematic sampling method selected one-minute every half-hour, on the hour and half-hour (total of 2 minutes every hour). This constituted 240 one-minute segments over the five-day survey period.

For each sampling method, one-minute samples were randomly selected from the pool of one-minute samples corresponding to the sampling method. For example, applying the Full Day sampling method to Site 1 involved taking *n* random one-minute samples (without replacement) from 7,200 one-minute recordings over five days, and counting the unique species detected in the *n* samples. This sampling was repeated 1,000 times for each sampling method and sampling frequency (value of *n*) at each site.

For each of these sampling strategies the number of species detected per 1,000 samples was examined in relation to sampling effort (number of one minute segments examined). These data were compared with the number of species detected from full manual analysis, and from traditional survey methods.

Traditional Point Count Surveys

Traditional avian point count surveys were conducted at each survey site using the Birds Australia 2ha Atlas Survey methodology [39]. The 2ha Atlas survey is a 20-minute survey carried out over a 2ha site (100m x 200m) where all birds observed within the site are recorded as seen, heard, or seen and heard.

During the survey period, a total of 60 Atlas 20 minute surveys were conducted at dawn, noon and dusk at four sites over five consecutive days from 13^{th} to 17^{th} October 2010. Surveys were carried out by two experienced Birds Australia observers with over 20 years of combined bird watching experience in the South East Queensland area. In total, each survey constituted 40 minutes of effort (two observers x 20 minutes) and each day constituted 120 minutes of effort (two observers x 20 minutes x three surveys). Over the five-day period at each site, the traditional point count surveys constituted 10 person hours of effort.

3. Results

Manual Analysis Results

Across the four sites and five days, a total of 28,800 one-minute segments were manually analysed. Fifty-six per cent (16,019) of total segments contained calls, and from these, 63,089 birdcalls were identified and annotated (~ 2.2 call types per minute). Over the five-day survey period, 99 unique species were identified across all four sites. The total species detected through manual analysis of acoustic data at each site ranged from 77 to 83 species (Figure 4). Chao2 species richness estimates indicated that most detectable species were being identified at each site, with estimates ranging from 77 (Site 3) to 101 (Site 1) (Figure 4).

The mean number of species recorded per site per day across the five-day period ranged from 57 to 59, however there was some variation recorded between days, particularly at Site 1 (Figure 5). Figure 6 shows the mean number of species detected in recordings at different times of the day. The dawn period had the greatest number of species, with a lull around midday and a less-pronounced peak towards dusk. A smaller number of species were detected through the night period. On average, more than 80% of total species from each site were detected during the three hour Dawn period over five days. This compares with an average of 64% of all species at a site calling in the three hour Dusk period.

Although there was some day-to-day variation in the number of species detected, an average of 78% of total species were detected in the first day across all sites. In addition, for all four sites, at least 75% of all species detected at a site were detected by 7am on the first day. There was very little variation in species composition across the four sites, with 93% of species found at all sites. This was expected because the sites were within approximately 300m of each other and in similar habitat.

Five species were detected only once over the five day period at all sites; Pale-vented Bush-hen (*Amaurornis moluccana*), Glossy Black Cockatoo (*Calyptorhynchus lathami*), Forest Kingfisher (*Todiramphus macleayii*), Collared Sparrowhawk (*Accipiter cirrhocephalus*) and Azure Kingfisher (*Alcedo azurea*). Having vocalised in one out of 28,800 one-minute segments, these species had a very low probability of detection. In contrast, the most frequently detected species was Rufous whistler (*Pachycephala rufiventris*), which was detected in 6941 one-minute segments over the five-day period at all sites.

Sampling Results

The total number of species detected in the corresponding times for each sampling method was calculated from the manually analysed acoustic data. This represents the maximum number of species that can be detected from the periods corresponding to each of the sampling methods (Table 1).

The minimum number of one-minute segments required (theoretically) to detect all species for each sampling method at each site was calculated using a greedy optimisation algorithm [40] (Table 1). This algorithm first calculated and selected the one-minute segment from each site with the highest number of unique species. These species were then removed from analysis and the number of unique species per minute recalculated. The next one-minute segment with the highest number of unique species was then selected and the species removed from the analysis, and so on, until all species were recorded.

The greedy algorithm data (Table 1) provide the theoretical minimum number of samples required to achieve the maximum number of species that were detected through full manual analysis for each of the sampling methods. This is theoretical because it assumes prior knowledge of the data set, from full analysis of the data. For example, for the Dawn + 3 hours sampling method for Site 1 (column 1, row 3 of Table 1), 66 species (80% of total species detected at Site 1) were detected through full manual analysis, and a minimum of 28 one-minute samples are required to detect all 66 species. This represents the optimum result obtainable from sampling of the Site 1 data in the Dawn + 3 hours period. These data are included for comparison with actual sampling results.

Figure 7 shows the percentage of total species that were detected (averaged for the four sites) in relation to the number of one-minute samples examined. The relative difference in number of species detected by each sampling strategy changed in relation to sample size. This is because different numbers of species were detected calling at different times. Different sampling methods also reached asymptote at different times because they had different limits to the number of samples available. For example, fixed interval sampling only drew on 240 x one minute samples (2 samples per hour x 24 hours x 5 days per site), whereas Dawn sampling drew on 900 samples (180 minutes per day x 5 days per site). Dawn plus Dusk sampling had 1,800 minutes of sampling available (360 min per day x 5 days per site). Only sampling from the Full Day method did not reach its asymptote in Figure 7 (24 hours x 60 minutes per hour x 5 days = 7,200 samples).

These asymptotes matched the percentage of species calling in the periods of the day corresponding to the sampling method. An average of 82% of species were detected at Dawn, compared with 87% from the combined Dawn and Dusk sampling period (Table 1) (i.e. an additional 5% of total species were detected by combining the Dawn and Dusk periods). Systematic sampling comprised between 58 and 71% of species across all sites (mean = 63%), and the Dusk sampling period comprised 64% of species (Figure 7).

Sampling from the Dawn period detected the highest mean proportion of species until 1,080 samples were selected, at which point the Dawn and Dusk period took over with an average of 83% of species. Detecting the remaining 4% of species present in the Dawn and Dusk period required a further 600 samples (one-third of the total number of one-minute samples in the Dawn and Dusk period).

Comparison with Traditional Point Counts

To evaluate the relative effectiveness of acoustic sensor data sampling, results were compared with observations from traditional avian point count surveys, which were carried out simultaneously over the same period as the acoustic sensor survey.

The effort involved in conducting traditional point count surveys was not equivalent to the effort involved in analysing acoustic data. For traditional point count surveys, every minute of observation effort yields one minute of observations. For acoustic data analysis however, on average, it took approximately two minutes of effort to manually analyse one-minute of acoustic data (2:1 ratio). This is because there is a tendency for observers to replay recordings to distinguish individual species, and because of the time taken to annotate vocalisations. Hence, one minute of analysed observations from acoustic sensor data is equivalent to two minutes of traditional point count survey observations.

For traditional point counts, each site had 120 person-minutes of effort per day (three 20-minute surveys x two surveyors), and 600 person-minutes of effort in total over the duration of the 5 day survey period. Based on the 2:1 ratio of analysis effort to acoustic data, the equivalent manual data analysis effort is therefore 60 one-minute samples per day (half of 120 person-minutes of traditional point count effort), and 300 minutes over the duration of the survey (half of 600 person-minutes of traditional point count effort).

The mean proportion of total species detected for each sampling method was compared using a one-way ANOVA with Sites as replicates. Post hoc comparisons using the Tukey HSD test ($p < .05$) indicated that up to 120 audio samples (equivalent to 240 minutes of point count effort) from the Dawn and Dawn + Dusk sampling methods on average returned a higher number of species than all other sampling methods (Figure 8). Beyond 120 samples, the Full Day, Dawn, Dawn + Dusk and Systematic sampling methods returned a significantly higher number of species than the Dusk and Point Count (PC) methods.

The systematic sampling method (1 minute every half hour) constituted 48 one-minute segments per day and 240 samples over the five-day period. At 180 samples (equivalent to 360 minutes of traditional point count effort), the systematic method returned on average 58% of species (Figure 8) and reached asymptote at 240 samples for 63% of species (Figure 7).

4. Discussion

Acoustic sensors are being used increasingly to augment traditional field survey methods. They can increase the spatial and temporal scales of observations [8,41]. However, analysis of acoustic sensor data is complex and time consuming [10,11]. Methods for the analysis of acoustic sensor data will continue to mature and improve, but there is currently a significant gap in analysis capability. Manual analysis, which is expensive and time consuming, contrasts with fully automated analysis, which though cheaper, cannot currently cater for large numbers of species and lacks verifiable high detection rates.

Our results demonstrate that reasonable estimates of avian species richness can be obtained through targeted sampling and manual analysis of acoustic sensor data. Specifically, randomly selecting 120 one-minute segments around the dawn period can detect up to 62% of total species, compared to 34% of species from the equivalent amount of traditional point count effort. Similarly, systematic sampling (i.e. recording 1 minute every half hour) can detect over 50% of species from 120 recordings while reducing the volume of data collected.

All sampling methods investigated detected a higher number of species on average than traditional point count methods, when compared using the equivalent amount of analysis/point count effort. This supports other research comparing traditional survey methods and acoustic sensors [1-3,5,10], however there are issues relating to the detection range of acoustic sensors which should be considered. When conducting traditional point count surveys, observers disregard species seen or heard outside the survey area, whereas with acoustic sensor analysis, all species heard (regardless of potential distance from the sensor) are included.

Ignoring the travel time to and from sites (which were deemed to be approximately equivalent for both point count and acoustic sensor methods), the ratio of two traditional point count minutes to one acoustic data analysis minute is possibly higher than necessary. This ratio was initially observed when each species was annotated once per minute over the duration of the survey period (five days). For species richness studies, one annotation per species over the duration of the survey period would be sufficient to establish presence. This would therefore reduce the time taken to analyse data considerably. In addition, improvements in the graphical user interface design of the annotation system could reduce repetitive tasks, assist in identification of species and automate manual documentation tasks.

These results are promising, but they fall considerably short of the maximum number of species detectable from full manual acoustic data analysis. Theoretically, all species at each site could be detected in less than 50 samples (Table 1). This represents the optimum result obtainable with the highest return for effort. Even at 720 samples, the best-performing random sampling method (Dawn) detected a maximum of 80% of species. In practice, analysing beyond 240 minutes is prohibitively expensive and impractical in most cases.

To take full advantage of the capability of acoustic sensors, automated methods are required that can assist in reducing manual analysis by selecting samples most likely to contain vocalisations. This also means finding more cryptic species, which call very infrequently or not at all during targeted periods, such as dawn. Here automated analysis does not attempt to identify individual species; rather it attempts to identify segments of recordings with potential calls, or removes from analysis, segments which contain ‘noise’, such as rain or wind. Segments containing potential calls can then be analysed by a human to identify individual species. Considering approximately 18% of species were detected only 10 times or less across the five-day period, the probability of detecting a significant proportion of species by random sampling alone is very low (0.0014). By using automated methods to target periods that contain potentially unique species vocalisations, and removing extraneous noise, we can significantly reduce the amount of manual analysis required to process large volumes of data.

Ultimately, analysis of large volumes of acoustic sensor data is a trade-off between analysis cost and detection accuracy. At one extreme, manual analysis of acoustic data is costly with high levels of detection accuracy. At the other, automated analysis *can* be less costly, but with less certainty in the confidence of detection accuracy. Methods that combine the strengths of both approaches may help to make acoustic sensing for monitoring biodiversity feasible at larger spatial and temporal scales.

Acknowledgements

This research was conducted with the support of the QUT Institute of Sustainable Resources and the QUT Samford Ecological Research Facility. Thanks to Tom Tarrant, Julie Sarna and Rebecca Ryan for assistance conducting point count surveys and analysing acoustic sensor data. Special thanks to Dr William Ellis for his insightful comments and suggestions.

References

1. Haselmayer J, Quinn JS (2000) A Comparison of Point Counts and Sound Recording as Bird Survey Methods in Amazonian Southeast Peru. The Condor 102: 887-893
2. Celis-Murillo A, Deppe J, Allen M (2009) Using soundscape recordings to estimate bird species abundance, richness, and composition. Journal of Field Ornithology 80: 64-78
3. Acevedo MA, Villanueva-Rivera LJ (2006) Using Automated Digital Recording Systems as Effective Tools for the Monitoring of Birds and Amphibians. Wildlife Society Bulletin 34: 211-214
4. Thompson M, Schwager S, Payne K (2009) Heard but not seen: an acoustic survey of the African forest elephant population at Kakum Conservation Area, Ghana. African Journal of Ecology 48: 224-231
5. Penman T, Lemckert F, Mahony M (2005) A cost-benefit analysis of automated call recorders. Applied Herpetology 2: 389-400
6. Wimmer J, Towsey M, Planitz B, Williamson I, Roe P (2012) Analysing environmental acoustic data through collaboration and automation. Future Generation Computer Systems.http://dx.doi.org.ezp01.library.qut.edu.au/10.1016/j.future.2012.03.004.
7. Acevedo MA, Corrada-Bravo CJ, Corrada-Bravo H, Villanueva-Rivera LJ, Aide TM (2009) Automated classification of bird and amphibian calls using machine learning: A comparison of methods. Ecological Informatics 4: 206-214.doi: 10.1016/j.ecoinf.2009.06.005.
8. Brandes ST (2008) Automated sound recording and analysis techniques for bird surveys and conservation. Bird Conservation International 18: S163-S173.doi:10.1017/S0959270908000415.
9. Towsey M, Planitz B, Nantes A, Wimmer J, Roe P (2012) A Toolbox for Animal Call Recognition. Bioacoustics 21(2): 107-125
10. Swiston KA, Mennill DJ (2009) Comparison of manual and automated methods for identifying target sounds in audio recordings of Pileated, Pale-billed, and putative Ivory-billed woodpeckers. Journal of Field Ornithology 80: 42-50.doi:10.1111/j.1557-9263.2009.00204.x.
11. Rempel RS, Hobson KA, Holborn G, Wilgenburg SLv, Elliott J (2005) Bioacoustic Monitoring of Forest Songbirds: Interpreter Variability and Effects of Configuration and Digital Processing Methods in the Laboratory. Journal of Field Ornithology 76: 1-11
12. Corn PS, Muths E, Iko WM (2000) A Comparison in Colorado of Three Methods to Monitor Breeding Amphibians. Northwestern Naturalist 81: 22-30
13. Mason R, Roe P, Towsey M, Zhang J, Gibson J, et al. (2008) Towards an Acoustic Environmental Observatory. Fourth IEEE International Conference on eScience: IEEE Computer Society. pp. 135-142.
14. Collins SL, Bettencourt LM, Hagberg A, Brown RF, Moore DI, et al. (2006) New opportunities in ecological sensing using wireless sensor networks. Frontiers in Ecology and the Environment 4: 402-407.doi:10.1890/1540-9295(2006)4[402:NOIESU]2.0.CO;2.

15. Charif R, Ponirakis D, Krein T (2006) Raven Lite 1.0 User's Guide. Ithaca, NY: Cornell Laboratory of Ornithology.
16. Ellis W, Bercovitch F, FitzGibbon S, Roe P, Wimmer J, et al. (2011) Koala bellows and their association with the spatial dynamics of free-ranging koalas. Behavioral Ecology.doi:10.1093/beheco/arq216.
17. Ellis WA, Fitzgibbon SI, Roe P, Bercovitch FB, Wilson R (2010) Unraveling the mystery of koala vocalisations: acoustic sensor network and GPS technology reveals males bellow to serenade females. Integrative and Comparative Biology 50: E49-E49
18. Grigg G, Taylor A, McCallum H, Fletcher L. Monitoring the impact of cane toads (Bufo marinus) on Northern Territory frogs–a progress report. Pages 47 - 54 in Science of Cane Toad Invasion and Control. Proceedings of the Invasive Animals CRC/CSIRO/Qld NRM&W Cane Toad Workshop, Brisbane, June 2006, edited by K. L. Molloy and W. R. Henderson. Canberra: Invasive Animals Cooperative Research Centre. ; 2006.
19. Carignan V, Villard M (2002) Selecting indicator species to monitor ecological integrity: a review. Environmental Monitoring and Assessment 78: 45-61
20. Cai J, Ee D, Binh P, Roe P, Jinglan Z. Sensor Network for the Monitoring of Ecosystem: Bird Species Recognition. Intelligent Sensors, Sensor Networks and Information, 2007. ISSNIP 2007. 3rd International Conference on; 2007 3-6 Dec. 2007. pp. 293-298.
21. Juang C, Chen T (2007) Birdsong recognition using prediction-based recurrent neural fuzzy networks. Neurocomputing 71: 121-130
22. Chen Z, Maher R (2006) Semi-automatic classification of bird vocalizations using spectral peak tracks. The Journal of the Acoustical Society of America 120: 2974
23. Kwan C, Mei G, Zhao X, Ren Z, Xu R, et al. Bird classification algorithms: theory and experimental results. IEEE International Conference on Acoustics, Speech, and Signal Processing, 2004. Proceedings. (ICASSP '04). 2004 17-21 May 2004. pp. V-289-292 vol.285.
24. McIlraith AL, Card HC (1997) Birdsong recognition using backpropagation and multivariate statistics. IEEE Transactions on Signal Processing 45: 2740-2748
25. Somervuo P, Harma A, Fagerlund S (2006) Parametric Representations of Bird Sounds for Automatic Species Recognition. IEEE Transactions on Audio, Speech, and Language Processing 14: 2252-2263
26. Anderson S, Dave A, Margoliash D (1996) Template-based automatic recognition of birdsong syllables from continuous recordings. The Journal of the Acoustical Society of America 100: 1209-1219
27. Kasten EP, McKinley PK, Gage SH. Automated Ensemble Extraction and Analysis of Acoustic Data Streams. 27th International Conference on Distributed Computing Systems Workshops, 2007. ICDCSW '07. ; 2007 22-29 June 2007. pp. 66-66.
28. Bardeli R, Wolff D, Kurth F, Koch M, Tauchert KH, et al. (2010) Detecting bird sounds in a complex acoustic environment and application to bioacoustic monitoring. Pattern Recognition Letters 31: 1524-1534.10.1016/j.patrec.2009.09.014.
29. Sueur J, Pavoine S, Hamerlynck O, Duvail S (2008) Rapid Acoustic Survey for Biodiversity Appraisal. PLoS ONE 3: e4065.10.1371/journal.pone.0004065.
30. Schrama T, Poot M, Robb M, Slabbekoorn H. Automated monitoring of avian flight calls during nocturnal migration. In: Frommolt K, Bardeli R, Clausen M, editors. Proceedings of the International Expert meeting on IT-based detection of bioacoustical patterns; 2008 December 2007; Isle of Vilme, Germany. pp. 132 - 134.
31. Farnsworth A, Gauthreaux JSA, Blaricom Dv (2004) A comparison of nocturnal call counts of migrating birds and reflectivity measurements on Doppler radar. Journal of Avian Biology 35: 365-369.10.1111/j.0908-8857.2004.03180.x.
32. Mundinger P (1982) Microgeographic and macrogeographic variation in acquired vocalizations in birds, p. 147–208 in D.E. Kroodsma and E.H. Miller, eds. . Acoustic communication in birds. New York: Academic Press.

33. Baker MC, Logue DM (2003) Population Differentiation in a Complex Bird Sound: A Comparison of Three Bioacoustical Analysis Procedures. Ethology 109: 223-242.10.1046/j.1439-0310.2003.00866.x.
34. Krebs CJ (1999) Ecological methodology. Menlo Park, CA: Addison-Welsey Educational 620 p.
35. Bibby CJ, Burgess ND, Hill DA, Mustoe SH (2000) Bird census techniques. London: Academic Press.
36. Australian Government Bureau of Meterology (2012) Climate Statistics for Samford CSIRO.
37. Chao A (1987) Estimating the Population Size for Capture-Recapture Data with Unequal Catchability. Biometrics 43: 783-791
38. Colwell RK (2009) EstimateS: Statistical estimation of species richness and shared species from samples. Version 8.2. User's Guide and application published at: http://purl.oclc.org/estimates.:
39. Birds Australia (2010) Atlas starter kit, Birds Austalia and NRM bird-monitoring project. 222.
40. Cormen TH, Leiserson CE, Rivest RL, Stein C (2009) Introduction to Algorithms, Third Edition. Massachusetts: MIT Press.
41. Parker TA, III (1991) On the Use of Tape Recorders in Avifaunal Surveys. The Auk 108: 443-444

Figures

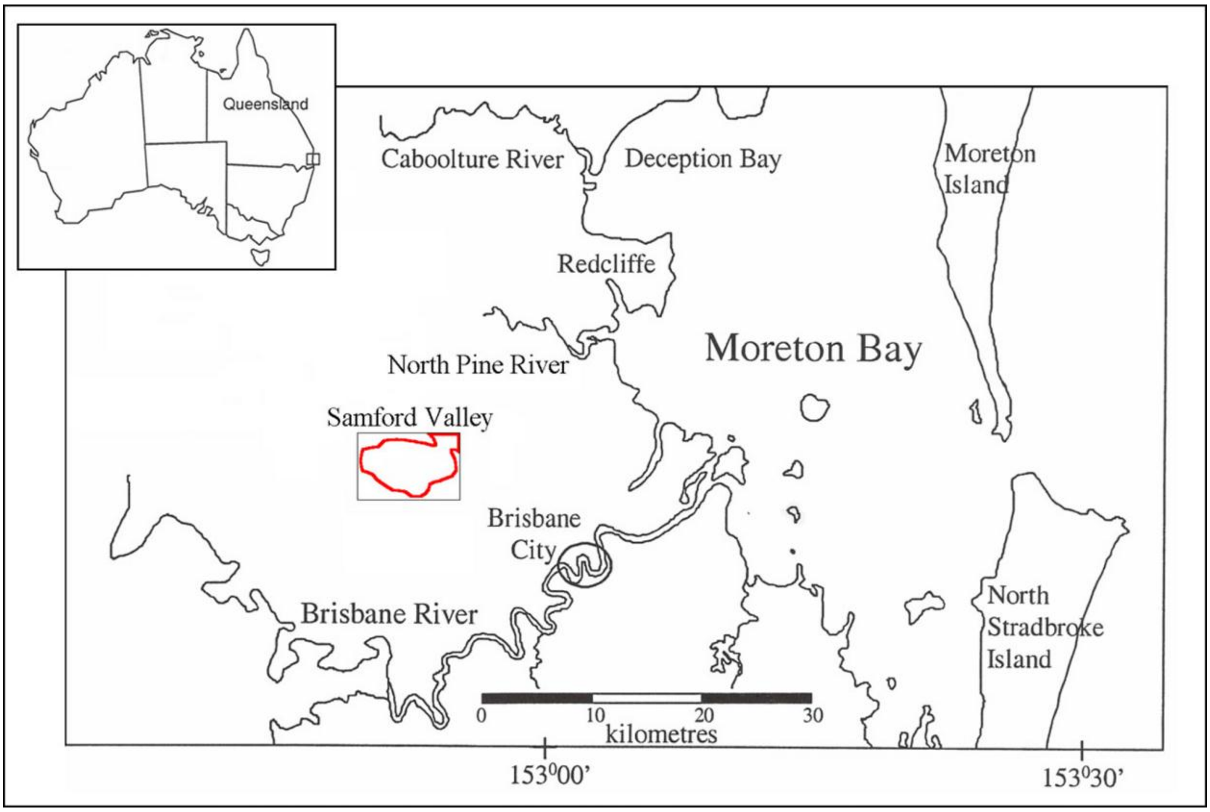

Figure 1. Samford Valley in southeast Queensland, Australia.

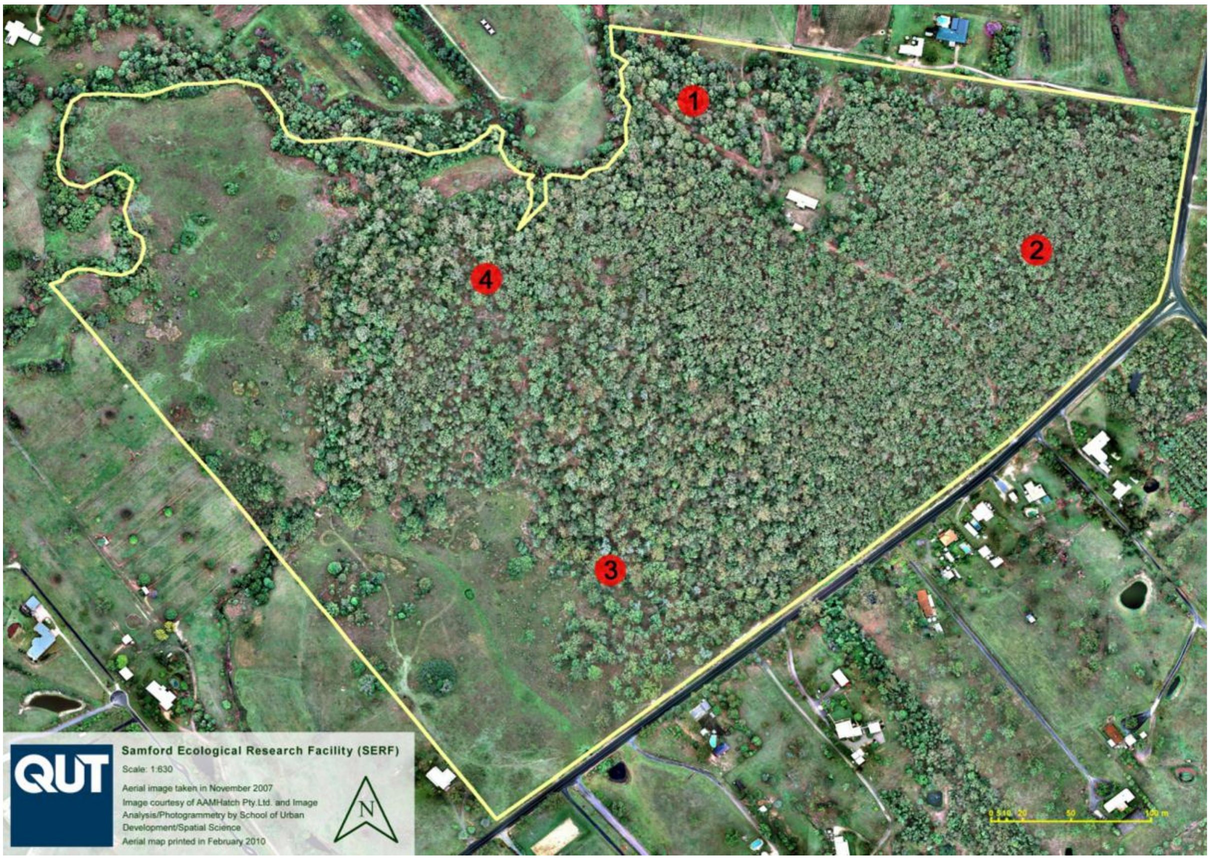

Figure 2. Samford Ecological Research Facility (SERF) with survey site positions.

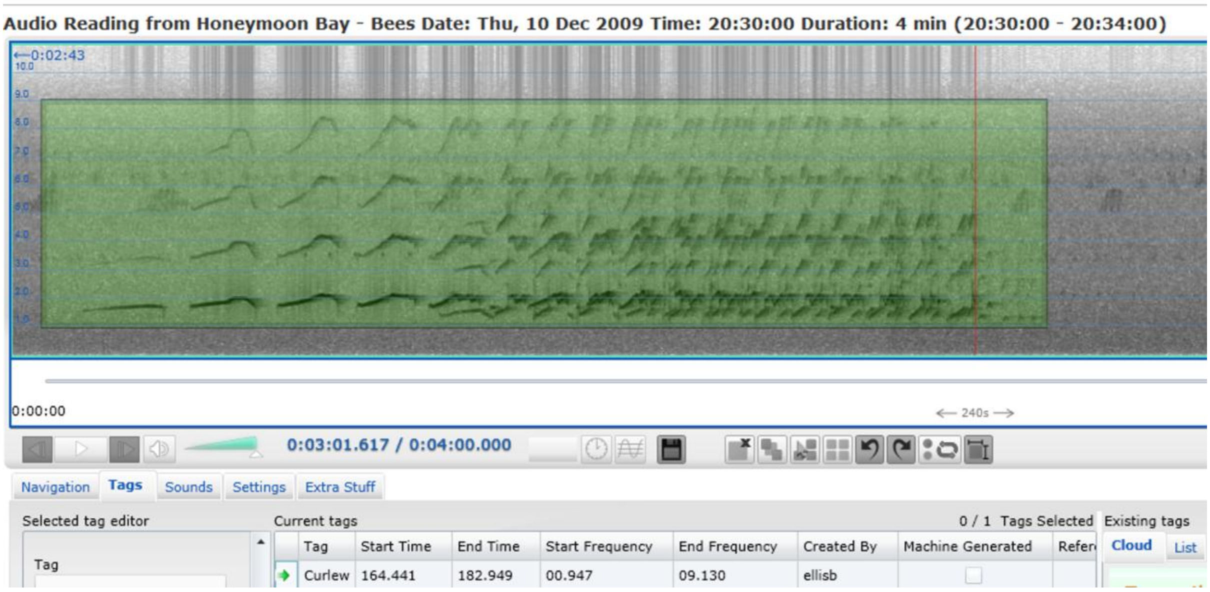

Figure 3. Spectrogram with annotated (green box) Bush Stone Curlew (*Burhinus grallarius)* call

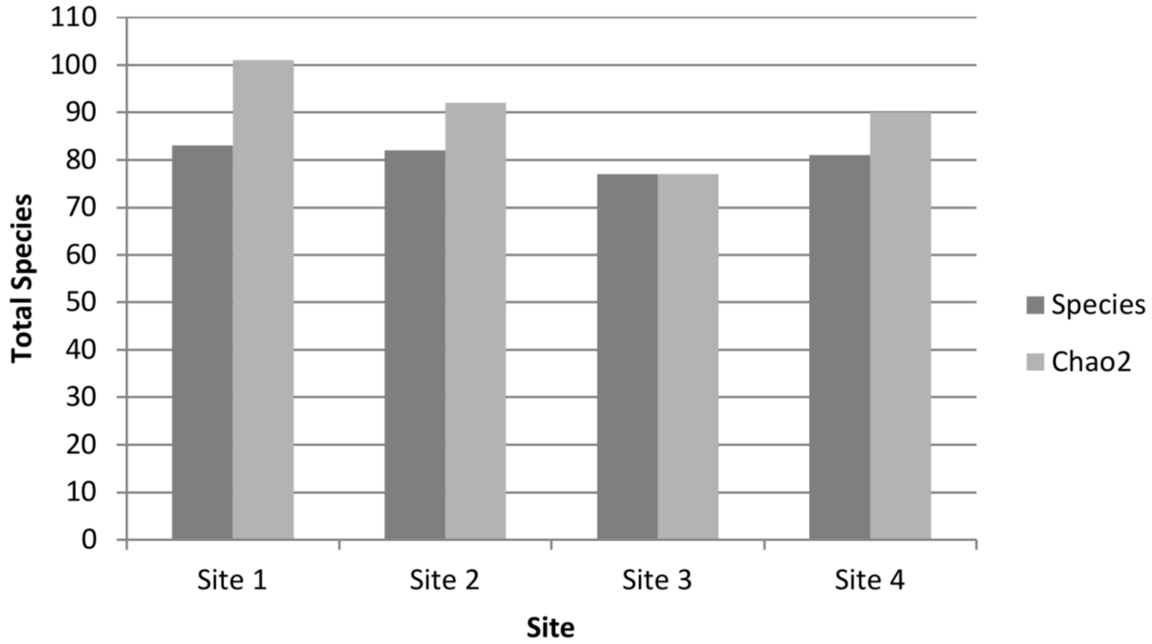

Figure 4. Total number of unique bird species detected and Chao2 species richness estimates for each site over the five-day survey period.

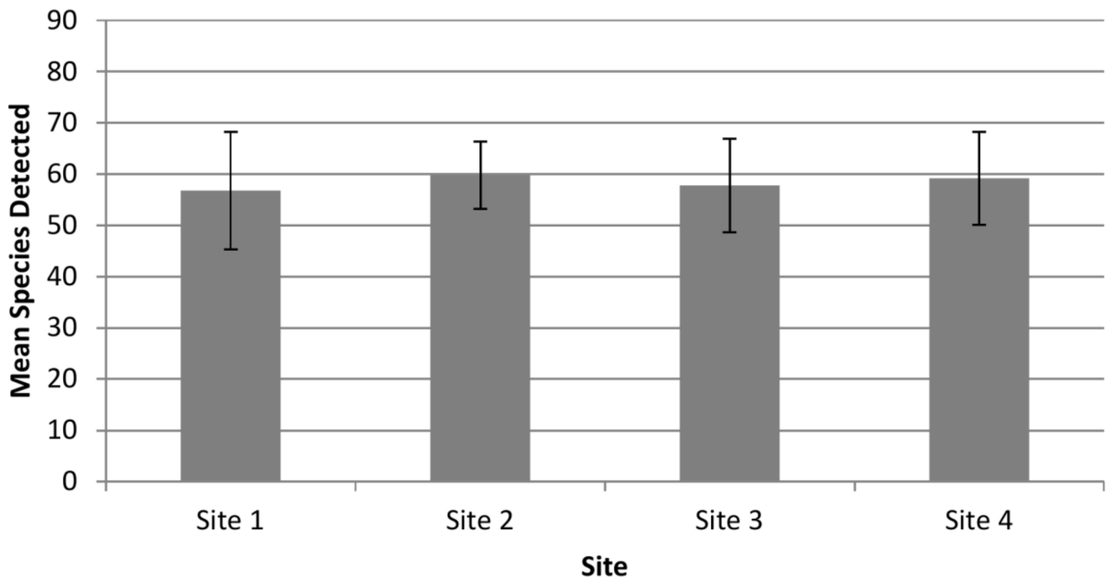

Figure 5. Mean number of bird species detected daily (± 95% CI) at each site.

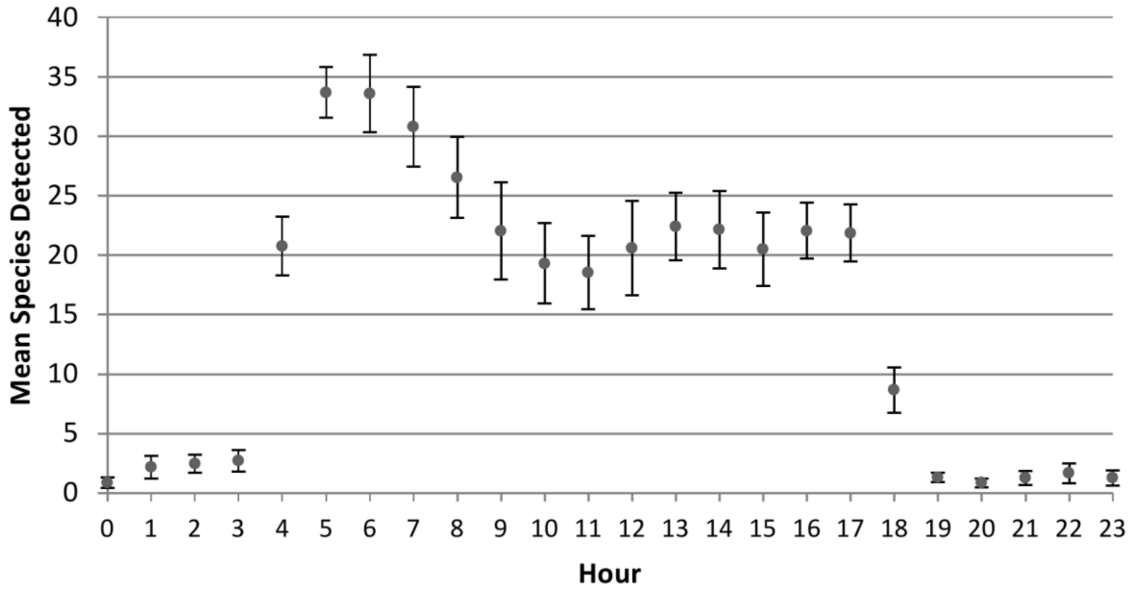

Figure 6. Mean number of species detected per hour across all sites (± 95% CI).

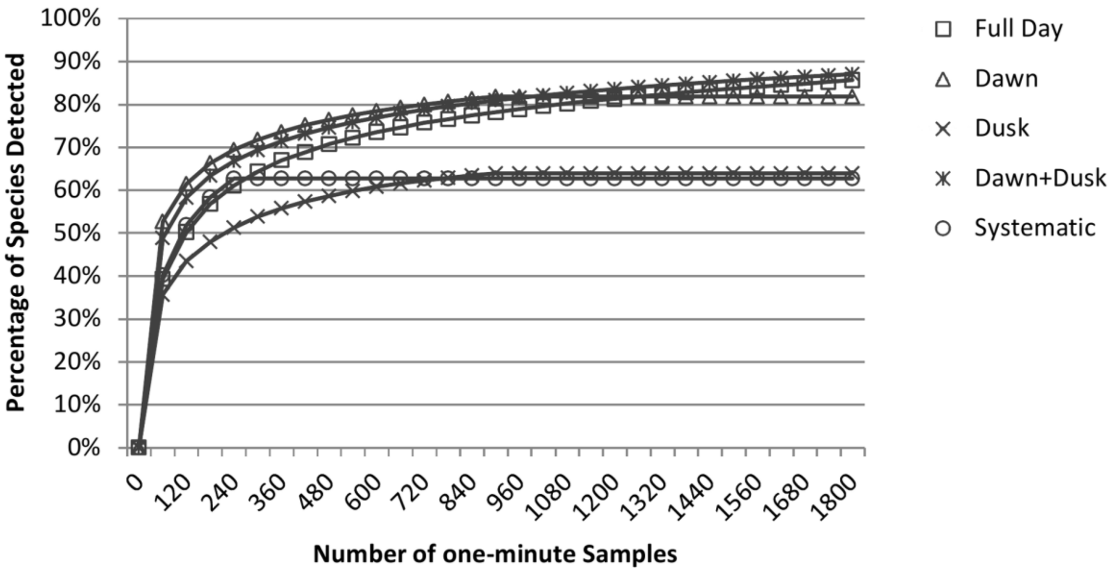

Figure 7. Mean percentage of total species detected for each sampling method (Data combined over sites).

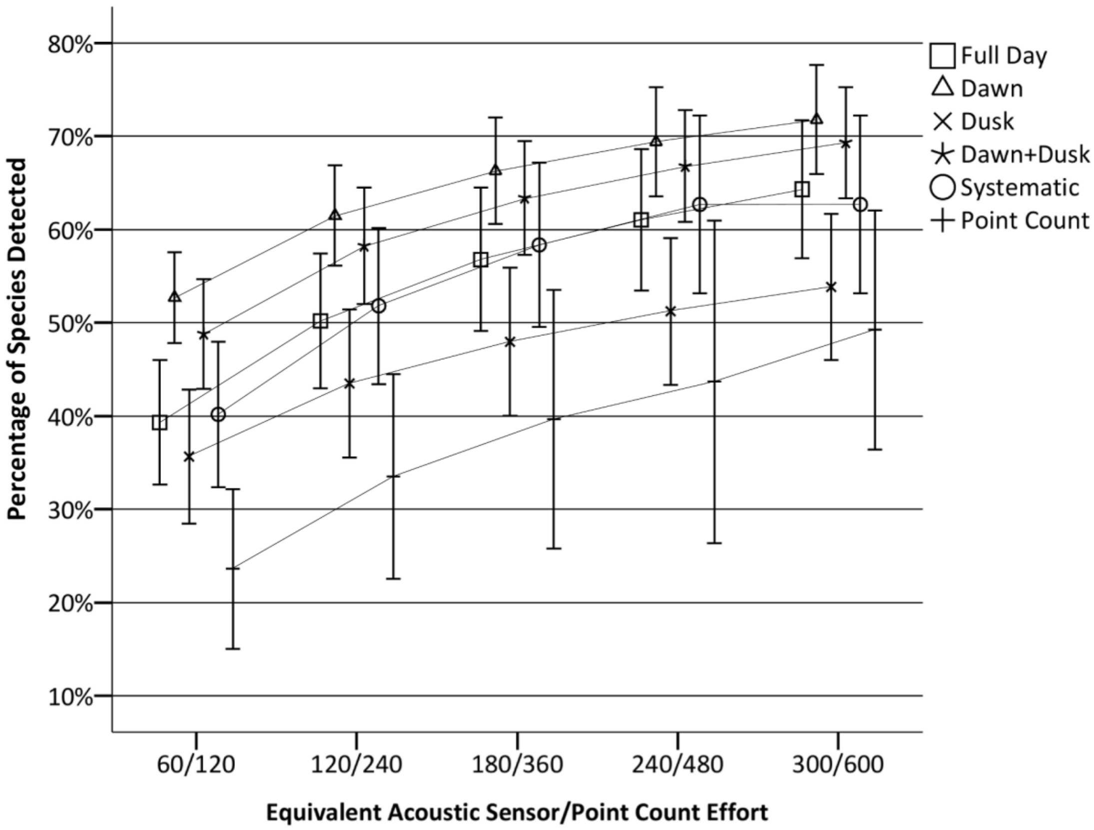

Figure 8. Mean percentage of total species detected by each sampling method, compared to equivalent traditional point count survey across all sites.

Tables

Table 1. The number and percentage of species detected from full manual analysis, along with the minimum number of samples required to detect the total species (greedy algorithm). Results are presented for each site and the mean of all sites.

Sampling Method	Site 1	Site 2	Site 3	Site 4	Mean
Full Day	83 [100%] (43)	82 [100%] (39)	77 [100%] (30)	81 [100%] (38)	81 [100%] (38)
Dawn + 3 hours	66 [80%] (28)	68 [83%] (26)	65 [84%] (27)	65 [80%] (29)	66 [82%] (28)
Dusk – 3 hours	51 [61%] (26)	50 [61%] (26)	54 [70%] (25)	51 [63%] (26)	52 [64%] (26)
Dawn+Dusk	73 [88%] (33)	72 [88%] (30)	69 [90%] (28)	67 [83%] (29)	70 [87%] (30)
Systematic	48 [58%] (48)	50 [61%] (48)	55 [71%] (48)	50 [62%] (48)	51 [63%] (48)