Carbon Rewild

PROJECT REPORT: BIOACOUSTIC MONITORING IN WOODLANDS

IN PARTNERSHIP WITH

Future Woodlands Scotland

EXECUTIVE SUMMARY

The ongoing loss of global biodiversity has lent an unprecedented urgency to our efforts in wildlife monitoring and conservation. To aid these endeavours, this grant report presents the findings of a study focused on the use of bioacoustic monitoring (or passive acoustic monitoring, PAM) as a tool to survey, study, and continually monitor biodiversity, specifically bird and bat communities, within Scottish woodland environments.

Bioacoustic monitoring represents an innovative approach to studying and understanding marine and terrestrial species groups. It employs automated recording units (ARUs) to capture the acoustic signatures of wildlife, including vocalisations and other sound-producing behaviours (e.g. the drumming of a woodpecker on a tree). This technology can operate continuously over extended periods, yielding comprehensive audio data sets that can be used to study species' activity, behaviour and populations.

The principal objective of this study was to test the suitability of bioacoustics to carry out simple and accessible biodiversity monitoring surveys that can be deployed in multiple locations within a site by experts and non-experts alike. This involved testing the recording hardware, deployment methods, and analysis techniques. This real world testing generated plenty of data on bird and bat species assemblages in different woodland environments and adequately demonstrated its effectiveness as an accessible surveying technique.

Between June 2022 - May 2023, we surveyed 12 Scottish woodland sites, in various regions of Scotland. The woodland sites chosen for this study represented a diverse array of habitats, differentiated by their maturity and tree species composition. Each woodland site was monitored for a one month period, and multiple bioacoustic recording devices were deployed at each site. These automated units were programmed to perform continuous monitoring over a month-long period, recording at intervals 24 hours per day. Typically, audio data can be analysed manually by experts, or through software or automated machine learning (ML) algorithms. During this project, we utilised a combination of classification algorithms and statistical modelling, followed by human verification for certain species.

This approach allows for the identification of species, assessment of individual behaviours, estimation of population densities, and tracking of temporal and spatial changes in biodiversity. We identified a total 83 species across the 12 woodland sites, including all woodland indicator species that would have been present at the respective locations when the survey was conducted.

We also analysed datasets from surveys that took place in March/April to measure the activity of the Chiffchaff, a migratory bird species, to evaluate the use of passive acoustic monitoring devices as a tool to measure the changes of migratory behaviour. Bioacoustic methods produce a standardised, long-duration dataset, which can be revisited for further verification and quality assurance. The methodology can be repeated to measure biodiversity change in landscapes, although further study is needed to establish the connection between activity (frequency and regularity of identifications) and abundance.

This project also allowed for the verification and validation of the non-measurement aspects of the technology such as: all-weather testing, memory reliability, battery management, data handling, courier logistics, site deployment, health and safety, data security, packaging and shipping. All of which are important behind-the-scenes contributors to enabling bioacoustics to be scaled as an accessible, reliable and cost-effective technology. Furthermore, work was performed to ensure that the measurements are standardised and repeatable, thereby ensuring that successive measurements will be comparable.

Approximately 70% of the surveys involved either the deployment or retrieval of recording devices by non-expert users and volunteers. Feedback from the users who set up the devices themselves was positive, and all users agreed that the devices were easy-to-use and the final survey report was clear. The logistics of shipping the devices to and from the users was continually refined during the project period. Furthermore, it was demonstrated that it was cost effective for deployments with multiple devices at several sites across Scotland to be deployed by a small team. Further expanding the potential of this technology to be deployed at scale across Scotland.

The survey process has been designed to be repeatable, so that future surveys can be replicated. This includes recording hardware and species classification analysis. Data can be stored in the very long term, and so even if the classification software updates, the process can be repeated for precise comparison.

This project has successfully shown that bioacoustic monitoring can be used as an accessible and cost effective tool to measure species assemblages in woodland environments, as well as conduct studies on individual species' behaviour and activity. Bioacoustic monitoring offers a non-invasive, scalable, and repeatable tool for ecological research and conservation planning. We hope to continue to evaluate the usage of bioacoustic monitoring in woodland environments, as an alternative or complementary to other survey techniques.

PROJECT HIGHLIGHTS

5 BAT SPECIES IDENTIFIED

78 BIRD SPECIES IDENTIFIED

12 WOODLAND LOCATIONS SURVEYED

188,000+ BIRD CALLS FROM IDENTIFIED SPECIES

200,000+ MINUTES OF AUDIO

Click here to watch our 2 minute video on Scottish birdsong!

Most frequently identified birds

Multiple species of conservation concern identified, including:

Woodcock

Tree Pipit

Mistle Thrush

ACKNOWLEDGEMENTS

We would like to express our deepest gratitude to all who have contributed to the successful completion of this bioacoustic monitoring study.

First and foremost, we wish to thank our grant providers, Future Woodlands Scotland, without whose financial support this study would not have been possible. Our gratitude extends to the organisations and staff members of the various woodland sites we surveyed across Scotland: The Woodland Trust, Highlands Rewilding, Wildlands Ltd., Forest Carbon, Strathfillan Community Development Trust, Cormonachan Woodlands, Bute Forest. Their cooperation, support, and invaluable local knowledge greatly enhanced the quality and efficiency of our fieldwork and surveys.

Together, we have contributed to an innovative, collaborative effort to advance the understanding of woodland biodiversity and to promote the use of bioacoustic monitoring as a powerful tool for ecological research and conservation planning.

INTRODUCTION

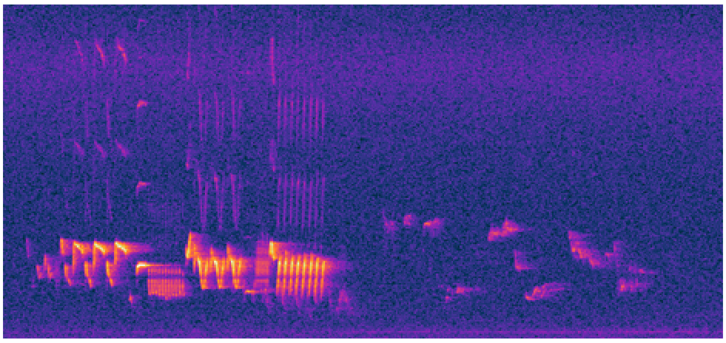
Due to the ongoing decline of global biodiversity [1], understanding and conserving biodiversity in the face of unprecedented environmental changes has emerged as one of the most critical challenges we face.

Acoustic monitoring, a method that involves recording and analysing the sounds produced by wildlife, has a long history in conservation and ecological studies. For decades, researchers and conservationists have measured the vocal behaviours of animals - their calls, songs, or echolocation clicks - as an auditory fingerprint to identify species, estimate population sizes, track animal movements, and study behavioural patterns.

The foundation of bioacoustic monitoring was laid with the early recognition that animals produce distinctive sounds for communication and navigation. As early as the 1700s [2], ornithologists, in particular, have long noted that bird songs and calls can be used to identify different species, even when the birds themselves are not visible. Early bioacoustic studies were primarily observational, with scientists manually documenting the sounds they heard in the field.

20th century advancements in recording technology accelerated the study of animal sounds; the tape recorder enabled researchers to capture and store animal sounds for later analysis, and the spectrograph provided a visual representation of sound, known as a spectrogram.

An example of a spectogram from a woodland recording of a wren (in Little Druim Wood). By converting audio into spectograms, they can be analysed for species identification.



Recently, with advancements in technology and data analysis, the potential of acoustic monitoring has grown exponentially. Modern recording devices (or ARUs, automated recording units) can operate autonomously for extended periods, and sophisticated machine learning algorithms can process large acoustic datasets, converting audio into spectrograms before extracting key acoustic features to automate species classification and behavioural analysis. These advancements have set the stage for bioacoustic monitoring to become an established tool for conservation and landscape monitoring.

Acoustic monitoring can be completed in the field with use of a handheld recording device. Whereas, automated or passive acoustic monitoring equipment can be programmed to remotely capture long-term data from a fixed location over a long time period.

The benefits of using passive acoustic recording are well documented in scientific research [3], including woodland environments [4,5]. Benefits include the production of standardised datasets, minimising observer bias, and the possibility of performing quality assurance checks thanks to the storage of recordings. Passive acoustic monitoring methods have been studied to be complementary to traditional survey methods in studying species assemblages [6], as the technological and in-person methodologies produce complementary benefits.

Due to the prior lack of advancement in classification software, studies have generally focussed on evaluating the effectiveness of acoustic monitoring for a single or few species, and only in recent years have studies focussed on surveying species assemblages. The use of modern AI and classification software has been shown to be an effective tool for species classification [7], and when employing suitable data subsetting, automatic classification has a low false positive rate, which has been found to have similar or lower misidentification rates to observers in the field [8].

During this study, we have focussed on primarily monitoring bird species. The presence of certain bird species can tell you a lot about local habitats and the health of your land. They can also be an effective indicator species; the change of diversity and abundance of many bird species can reflect the wider change of the local environment and other species groups, such as insects that they prey on. Due to their vocal nature, the majority of species can be identified due to sound alone. We also recorded for a short window during night for bat species, to test whether multiple species groups can be monitored from the same automated recording unit.

AIMS AND OBJECTIVES

The primary objective of this study was to make bioacoustic monitoring more accessible for use in woodlands and afforestation/reforestation sites, evaluating its reliability and effectiveness as a technique for biodiversity monitoring.

Here, we surveyed a variety of woodlands across Scotland, testing the reliability of the hardware and set up, with some deployments of ARUs undertaken by the research team, as well as deployments undertaken by non-expert users, with ARUs set up and shipped in advance. From data gathered and lessons learned from these approaches, we also aim to produce standardised guidance for woodland monitoring.

We estimated that we would identify a minimum 50 species across all surveys, and examine the results to determine the effectiveness of bioacoustic monitoring of individual species and species assemblages.

METHODOLOGY

STUDY AREA AND SAMPLING STRATEGY

Our study was conducted across 12 woodland sites in various regions of Scotland, selected to represent a broad spectrum of habitats. We only focussed on only surveying native woodland, which meant we operated in a varied sample of woodland habitats, and included some sites which had areas of new woodland growth. The intent behind the selection of these diverse sites was to capture an extensive array of bird and bat acoustic signatures, representative of the biodiversity in these varied environments.

Our study area and sampling strategy aimed at achieving a comprehensive bioacoustic assessment of the selected woodland environments while maintaining a practical and efficient deployment of ARUs. At each site, we deployed 2-5 automated recording units (ARUs), ensuring a broad coverage of the woodland area. These ARUs were distributed evenly across each site, strategically placed to minimise overlap of recorded sounds and maximise area coverage. The spatial configuration of ARUs was such that no two devices were more than 500 metres apart or less than 250 metres apart from each other.

Surveys were scheduled in different seasons to test the durability and reliability of the bioacoustic recording hardware in a wide range of weather conditions, temperatures, and environmental factors. These varied conditions provided a robust assessment of the performance and durability of our recording devices and batteries.

RECORDING EQUIPMENT

The bioacoustic monitoring hardware utilised in this study consisted of automated recording units (ARUs), capable of capturing a wide range of frequencies, including those of bat echolocation. The recording hardware included the programmable Open Acoustics Audiomoth Dev v1.0, with custom 3D-printed housing. All ARUs were weather-protected and capable of autonomous operation for extended periods.

These ARUs were programmed to perform continuous, 24h monitoring, recording at intervals over a one-month period at each site. The recording interval used was 15 seconds recording every two minutes. When recording at intervals, for the same total recording effort, shorter file lengths (e.g. 15 seconds every two minutes) are better than longer recordings (e.g. 15 minutes every two hours). This has been found to produce greater species richness [9].

For a two hour window each night, recordings were taken at a higher frequency (192KHz) for bat identification. Whilst this is not expected to be comprehensive for bat monitoring, the purpose of this setup was to test the feasibility of multi-frequency recording for different species groups with the same ARU.

Automated Recording Units (ARUs) were attached to suitable trees for all of the surveys. Programming for the ARUs was completed in advance, simplifying the deployment process.

DEPLOYMENT

While bioacoustic monitoring incorporates advanced technology, it also possesses characteristics that make it accessible as a non-technical monitoring technique for many users. Once the ARUs are set up and programmed, the monitoring is fully automated. This means that it doesn't require constant oversight or intricate manual adjustments, making it user-friendly for non-specialists to deploy.

4 of the 12 deployments were completely undertaken by non-expert users, with the recording devices shipped in advance of the survey period, and users set up following provided guidance. A further 4 deployments involved non-expert users retrieving the ARUs and returning them via post.

DATA ANALYSIS

The use of AI and software has been shown to be an effective tool for species classification [10], and when employing suitable data subsetting, automatic classification has a low false positive rate [11]. The analysis process used during the study can be divided into two parts from which we get two outcomes:

- Part 1: Species Detection – identification of the species detected during the survey period
- Part 2: Measuring activity via vocalisations – a characterisation of species activity and/or relative measure of abundance

Species detection involves assessing which species are identifiable in the audio data. This is done by a three step process:

1. Automated AI analysis & classification
2. Custom filtering
3. Human verification

The relative level of activity of each verified species is then measured by assessing the number of calls or vocalisations identified. Timing information is captured alongside each of the recordings, so that key temporal trends can be studied further.

The acoustic data collected were processed using automated AI species classification. The algorithms had been pre-trained to recognise the vocalisations of the target bird and bat species. There are, limitations in automatic detection using AI classification due to various factors:

- Some species have similar calls to others, and can be misidentified
- Anthropogenic noises being identified as wild animal vocalisations (e.g. vehicles, machinery noises, domestic animals)
- Noise from running water, rain and wind masking a call or alter a recording

As a result, there is a chance of false identification of species. To overcome these limitations of automated classification, we carry out two further filtering steps to improve the identification accuracy. Following the automated classification, we applied statistical modelling and custom filtering to examine the validity of results. This involved a series of custom rules, algorithms, filters which used historical species data [12], and knowledge to assess confidence in the results. The application of statistical algorithms play an important role in filtering results to apply an additional layer of data validation, distinguishing between potential true detections and false positives.

Multiple factors can contribute to a species having a low confidence rating (e.g. a low probability of the species being present in a particular geography, or the confidence of the AI classification being low). The "low confidence rating" species will then be validated by human verification, which involves manually listening to a subset of recordings in order to verify that they have been correctly classified.

The principal data output attached to each verified species is the number of individual identifications/vocalisations found by the AI. Once we have verified that a given species has been successfully identified then we calculate the total number of vocalisations.

RESULTS

RESULTS

The results of our bioacoustic surveys across 12 diverse woodland sites in Scotland highlight the potential of bioacoustic methods for studying biodiversity in these environments. In this section, we present the data sets we obtained and the key findings that emerged from our analysis.

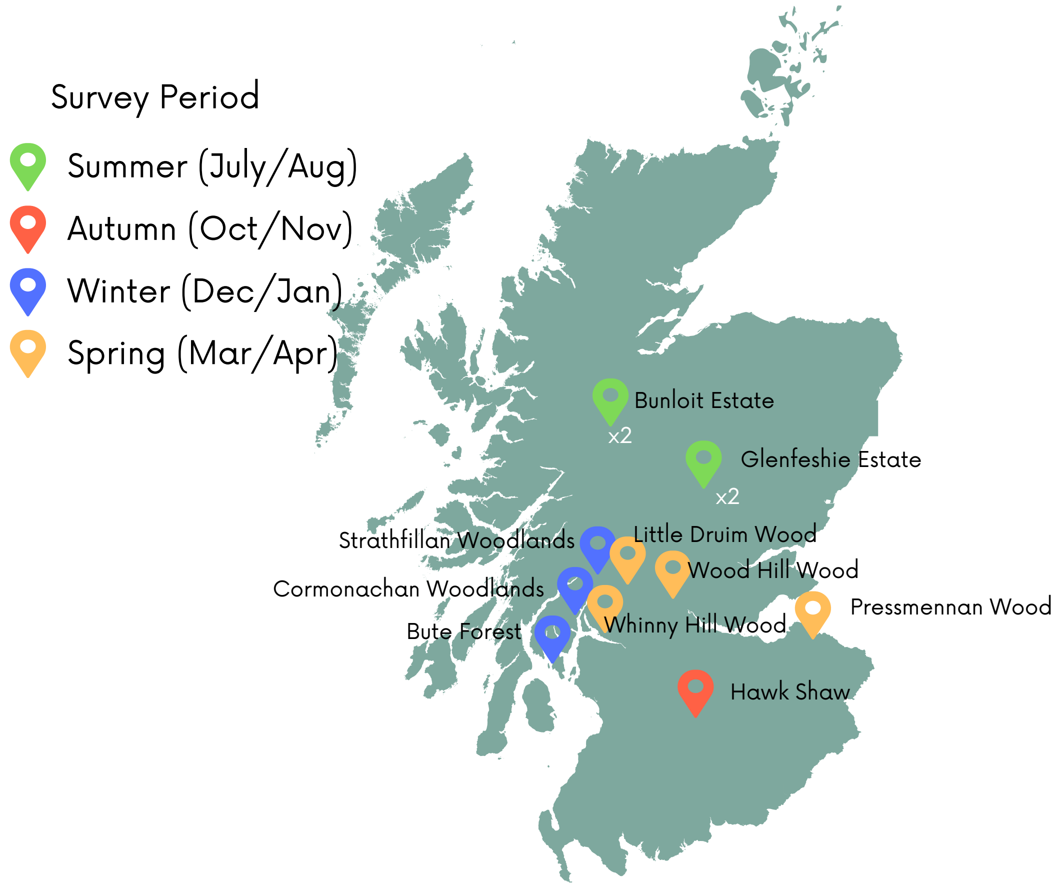
Our study successfully identified a total of 78 bird and 5 bat species across the surveyed sites, including key woodland indicator species expected to be present at the respective locations during the survey period. The automated recording units (ARUs) captured almost 200,000 minutes of audio data, which, once processed through our data pipeline, gave us valuable insights into the richness of species assemblages, temporal and spatial changes in biodiversity, and specific species' behaviour and activity patterns.

The outcomes of the surveys are summarised in the following table, which lists the results obtained from each site.

Site Name	Total Number of Recording Devices	Survey Timing	Bird Species Identified	Bat Species Identified
Glenfeshie Estate (Mixed Woodland Site 1)	2	July/August	23	4
Glenfeshie Estate (Mixed Woodland Site 2)	2	July/August	33	3
Bunloit Estate (Oak/Birch Woodland)	3	July/August	37	4
Bunloit Estate (Mixed Woodland)	2	July/August	36	3
Hawk Shaw (Regenerating Mixed Woodland site)	5	October/November	27	0
Strathfillan Woodlands	3	December/January	32	0
Cormonachan Woodlands	3	December/January	30	0
Bute Forest	3	December/January	29	0
Little Druim Woods	3	March/April	43	2
Pressmennan Wood	3	March/April	44	0
Whinny Hill Wood	3	March/April	37	0
Wood Hill Wood	3	March/April	33	0
Total Number of Devices	**35**			

Birds and Bats exhibit seasonal behaviour, which is reflected in the differing soundscapes we hear across different months of the year. We successfully identified species across all seasons, proving the resilience of the recording technology in different weather conditions, and the capacity of bioacoustic to be undertaken in all seasons.

In addition to the surveys listed above, several test surveys were undertaken in different environments and with different set ups for longer monitoring periods. These have been listed in appendix B, but have been included in the results above, as the primary objective of the study was to investigate use in native woodlands, with a minimum two recording devices per survey.



The deployment of multiple Automated Recording Units (ARUs) in bioacoustic monitoring is important for achieving accurate and comprehensive data. Firstly, the spatial coverage of a single ARU is limited, with various factors impacting the acoustic properties of an environment (e.g. density of trees blocking sounds, sources of background noise).

Deploying multiple ARUs allows for broader survey coverage, capturing a more diverse range of species and potentially different microhabitats within the larger area. This is particularly relevant in environments with varied topography or habitats. Additionally, the use of multiple ARUs helps to address variability in species detection. Certain species may prefer specific microhabitats and their vocalisations might not be detectable by a centrally located ARU. Therefore, a network of ARUs increases the chance of capturing these species-specific vocal behaviours. Lastly, deploying multiple ARUs also provides a redundancy that helps counter any potential data loss due to malfunctioning or other unforeseen circumstances with a single unit, thereby ensuring the robustness and reliability of the survey data.

On average, a single ARU identified 76±2% of the total species identified across all ARUs used in each survey. For surveys conducted with 3 recording devices, analysing all combinations of 2 recording devices identified on average 93±1% of the total species identified.

The above shows the distribution of recording devices at Pressmennan woods overlayed on a satellite image of the woodland. The number shown is the number of species identified at each recording location.

BIRD SPECIES IDENTIFIED

A total 78 bird species were identified across all surveys, with all surveys successfully identifying a significant number of species. The complete list of species identified is listed below. Several of the species identified are not woodland residents, and will have been identified from calls made in neighbouring land/wetlands, or alternatively migratory calls whilst flying above the woodlands.

Common Name	Scientific Name	Conservation Status (BoCC5)
Coal tit	*Periparus ater*	green
Goldcrest	*Regulus regulus*	green
Robin	*Erithacus rubecula*	green
Wren	*Troglodytes troglodytes*	amber
Treecreeper	*Certhia familiaris*	green
Common chiffchaff	*Phylloscopus collybita*	green
Common wood pigeon	*Columba palumbus*	amber
Blue tit	*Cyanistes caeruleus*	green
Longtailed tit	*Aegithalos caudatus*	green
Great tit	*Parus major*	green
Chaffinch	*Fringilla coelebs*	green
Tawny owl	*Strix aluco*	amber
Blackbird	*Turdus merula*	green
Song thrush	*Turdus philomelos*	amber
Canada goose	*Branta canadensis*	introduced
Eurasian siskin	*Spinus spinus*	green
Spotted flycatcher	*Muscicapa striata*	red
Common pheasant	*Phasianus colchicus*	introduced
Stock dove	*Columba oenas*	amber
Great spotted woodpecker	*Dendrocopos major*	green
Mistle thrush	*Turdus viscivorus*	red
Meadow pipit	*Anthus pratensis*	amber
Carrion crow	*Corvus corone*	green
Nuthatch	*Sitta europaea*	green
Common buzzard	*Buteo buteo*	green
Redwing	*Turdus iliacus*	amber
Bullfinch	*Pyrrhula pyrrhula*	amber
Dunnock	*Prunella modularis*	amber
Woodcock	*Scolopax rusticola*	red
Common raven	*Corvus corax*	green
Greylag goose	*Anser anser*	amber
Western jackdaw	*Corvus monedula*	green
Crested tit	*Lophophanes cristatus*	green
Hooded crow	*Corvus cornix*	green
European stonechat	*Saxicola rubicola*	green
Eurasian jay	*Garrulus glandarius*	green

Common Name	Scientific Name	Conservation Status (BoCC5)
Goldfinch	*Carduelis carduelis*	green
Whooper swan	*Cygnus cygnus*	amber
Common redstart	*Phoenicurus phoenicurus*	amber
Oystercatcher	*Haematopus ostralegus*	amber
Mallard	*Anas platyrhynchos*	amber
Collared dove	*Streptopelia decaocto*	green
Grey wagtail	*Motacilla cinerea*	amber
Common reed bunting	*Emberiza schoeniclus*	amber
Lesser redpoll	*Acanthis cabaret*	red
Eurasian teal	*Anas crecca*	amber
Willow warbler	*Phylloscopus trochilus*	amber
Tree pipit	*Anthus trivialis*	red
Common kestrel	*Falco tinnunculus*	amber
Pinkfooted goose	*Anser brachyrhynchus*	amber
Herring gull	*Larus argentatus*	red
Eurasian magpie	*Pica pica*	green
Grey heron	*Ardea cinerea*	green
Pied wagtail	*Motacilla alba*	green
Ring ouzel	*Turdus torquatus*	red
Barn swallow	*Hirundo rustica*	green
Rook	*Corvus frugilegus*	amber
Red crossbill	*Loxia curvirostra*	green
House martin	*Delichon urbicum*	red
Western barn owl	*Tyto alba*	green
Grasshopper warbler	*Locustella naevia*	red
Common swift	*Apus apus*	red
Eurasian curlew	*Numenius arquata*	red
Common moorhen	*Gallinula chloropus*	amber
Black redstart	*Phoenicurus ochruros*	amber
Honey buzzard	*Pernis apivorus*	amber
Blackcap	*Sylvia atricapilla*	green
Sparrowhawk	*Accipiter nisus*	amber
Common kingfisher	*Alcedo atthis*	green
Little grebe	*Tachybaptus ruficollis*	green
Yellowbrowed warbler	*Phylloscopus inornatus*	amber
Common merganser	*Mergus merganser*	green
Common goldeneye	*Bucephala clangula*	red
Fieldfare	*Turdus pilaris*	red
European greenfinch	*Chloris chloris*	red
Peregrine falcon	*Falco peregrinus*	green
Sedge warbler	*Acrocephalus schoenobaenus*	amber
Common scoter	*Melanitta nigra*	red
Great blackbacked gull	*Larus marinus*	amber
Common gull	*Larus canus*	amber

WOODLAND INDICATOR SPECIES

Whilst monitoring overall species diversity is an important measure of ecosystem health in a given area, we also examined a subset of woodland indicator species.

Woodland indicator species are a particular subset of species whose presence, abundance, or behaviour can provide meaningful information about the ecological conditions of a woodland habitat. These species often have specific habitat requirements that make them particularly sensitive to certain environmental factors such as the type and age of the woodland, the presence of certain other species, or the quality of the habitat. Their presence or absence, therefore, serves as a reliable indicator of the state of the woodland environment, providing tangible clues about its health, maturity, and biodiversity. In addition, because birds are universal and a well studied taxonomic group, drivers for change are better understood than other species groups.

JNCC (www.jncc.gov.uk) has produced a UK bird indicator species lists for woodlands, producing an overall woodland bird species indicator [12], showing relative changes in the abundance of common native birds of farmland and woodland and of freshwater and marine habitats in the UK. In 2019 the breeding woodland bird indicator for England was 27% lower than in 1970.

By comparing our results with the JNCC General and Specialist Woodland indicator species lists [12], we have successfully identified almost all relevant species. After removing species which are not known to be resident to the areas where surveys were taking place (or not resident when the surveys were taking place, such as migratory birds species), we identified 100% of Generalist Woodland species, and 89% of Specialist woodland species.

JNCC Generalist Woodland Indicator Species

Common Name	Scientific Name	Identified
Lesser whitethroat	*Curruca curruca*	No (not in regions where surveys conducted)
Song thrush	*Turdus philomelos*	Yes
Longtailed tit	*Aegithalos caudatus*	Yes
Great tit	*Parus major*	Yes
Eurasian wren	*Troglodytes troglodytes*	Yes
Eurasian blue tit	*Cyanistes caeruleus*	Yes
Eurasian bullfinch	*Pyrrhula pyrrhula*	Yes
Dunnock	*Prunella modularis*	Yes
Common chaffinch	*Fringilla coelebs*	Yes
Tawny owl	*Strix aluco*	Yes
Common blackbird	*Turdus merula*	Yes
European robin	*Erithacus rubecula*	Yes

JNCC Specialist Woodland Indicator Species

Common Name	Scientific Name	Identified
Eurasian treecreeper	*Certhia familiaris*	Yes
European green woodpecker	*Picus viridis*	No (not in regions where surveys conducted)
Eurasian blackcap	*Sylvia atricapilla*	Yes
Eurasian sparrowhawk	*Accipiter nisus*	Yes
Red crossbill	*Loxia curvirostra*	Yes
Common chiffchaff	*Phylloscopus collybita*	Yes
Eurasian siskin	*Spinus spinus*	Yes
Willow warbler	*Phylloscopus trochilus*	Yes
Spotted flycatcher	*Muscicapa striata*	Yes
Common nightingale	*Luscinia megarhynchos*	No (not based in Scotland)
Tree pipit	*Anthus trivialis*	Yes
Eurasian blue tit	*Cyanistes caeruleus*	Yes
Goldcrest	*Regulus regulus*	Yes
Western capercaillie	*Tetrao urogallus*	No (not in regions where surveys conducted)
Eurasian nuthatch	*Sitta europaea*	Yes
Lesser redpoll	*Acanthis cabaret*	Yes
Great spotted woodpecker	*Dendrocopos major*	Yes
Lesser spotted woodpecker	*Dryobates minor*	No (not based in Scotland)
European pied flycatcher	*Ficedula hypoleuca*	Yes
Wood warbler	*Phylloscopus sibilatrix*	No
Garden warbler	*Sylvia borin*	No
Common redstart	*Phoenicurus phoenicurus*	Yes
Eurasian jay	*Garrulus glandarius*	Yes
Willow tit	*Poecile montanus*	No (not in regions where surveys conducted)
Marsh tit	*Poecile palustris*	No (not in regions where surveys conducted)

COMPARING RESULTS AGAINST TRADITIONAL SURVEY METHODOLOGIES

Traditional methodologies - direct visual observations and point counts - have for decades been the primary means of obtaining bird population data. However, these techniques, while valuable, often fall short in accuracy due to environmental constraints, observer bias, species detectability, and the changing behaviour of birds due to the presence of humans. Benefits of observational techniques include identifying species which are less vocal, and some similar species (e.g. the Carrion Crow and Hooded Crow) cannot be differentiated by their call alone.

A key advantage of bioacoustics to complement traditional surveying is the capacity for long-term passive monitoring. This can be a benefit for identification of certain species; some species can be secretive and difficult to identify when only surveying for a short period of time. Monitoring the presence of such species can be more successful when monitoring over a longer period of time. Nocturnal species can also be identified without multiple field visits at different times of day.

We conducted a comparison of the results obtained from our bioacoustic surveys with those of historic traditional surveys. The traditional surveys had employed classic methods of data collection such as visual observations and manual species counts. This comparison would allow us to assess the congruence between these two fundamentally different survey methodologies. However, due to limited datasets available for the sites surveyed (e.g. historic BTO surveys), we did not have sufficient data to draw conclusions around a comparison between methodologies. We have included the results in appendix B.

TEMPORAL DATA ANALYSIS

In addition to providing a general overview of species assemblages, we also explored specific case studies, such as tracking the activity of the Chiffchaff, a migratory bird species. We used data from surveys conducted in March/April to evaluate the potential of bioacoustic monitoring as a tool to monitor changes in migratory behaviour.

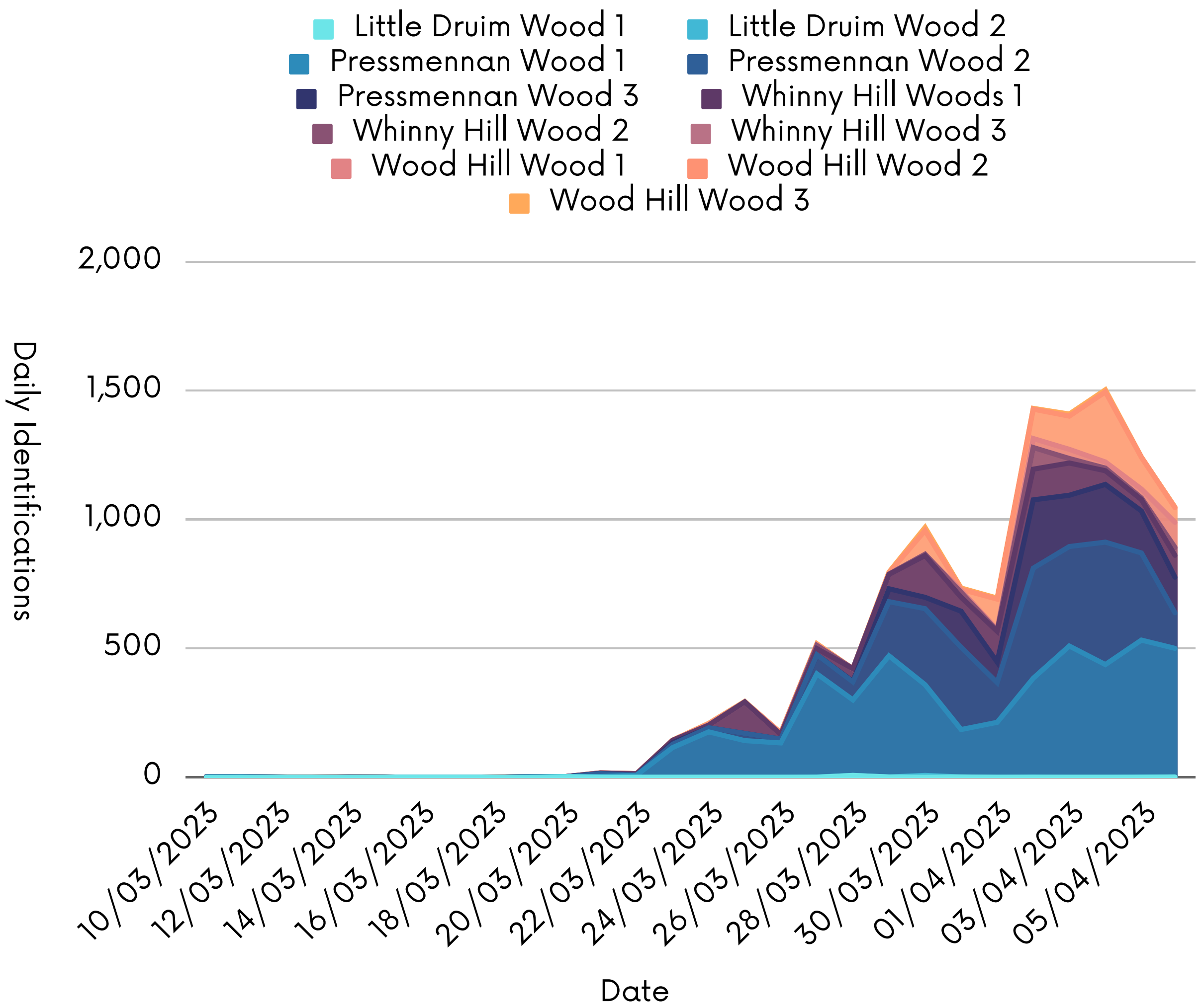
Every spring, the Chiffchaff embarks on a significant migration journey from its wintering grounds in Africa, specifically the Mediterranean and West Africa, to breeding territories in the UK and other parts of Europe. This annual migration typically starts in late February or early March, with the first arrivals appearing in the southern parts of the UK around mid-March. As spring progresses, the Chiffchaffs continue to spread northwards, reaching the northernmost parts of the UK by late March or early April. The timing of Chiffchaff migration is influenced by several factors, most of which revolve around environmental conditions and resource availability, and may also be further impacted by climate change.

Chiffchaff (Phylloscopus collybita), a summer resident to Scotland

When processing the recorded audio, identifications for each species were tagged with their respective time and date, so the total daily identifications could be calculated per location. The number of daily identifications of the Chiffchaff were then counted across the monitored woodland sites for the March/April surveys.

As shown in the chart below, there is a clear increased trend of Chiffchaff activity recorded, starting around the 22nd March. This bioacoustic approach thereby offers a non-invasive and accurate means to study the timing of certain migratory species' arrivals/departures.

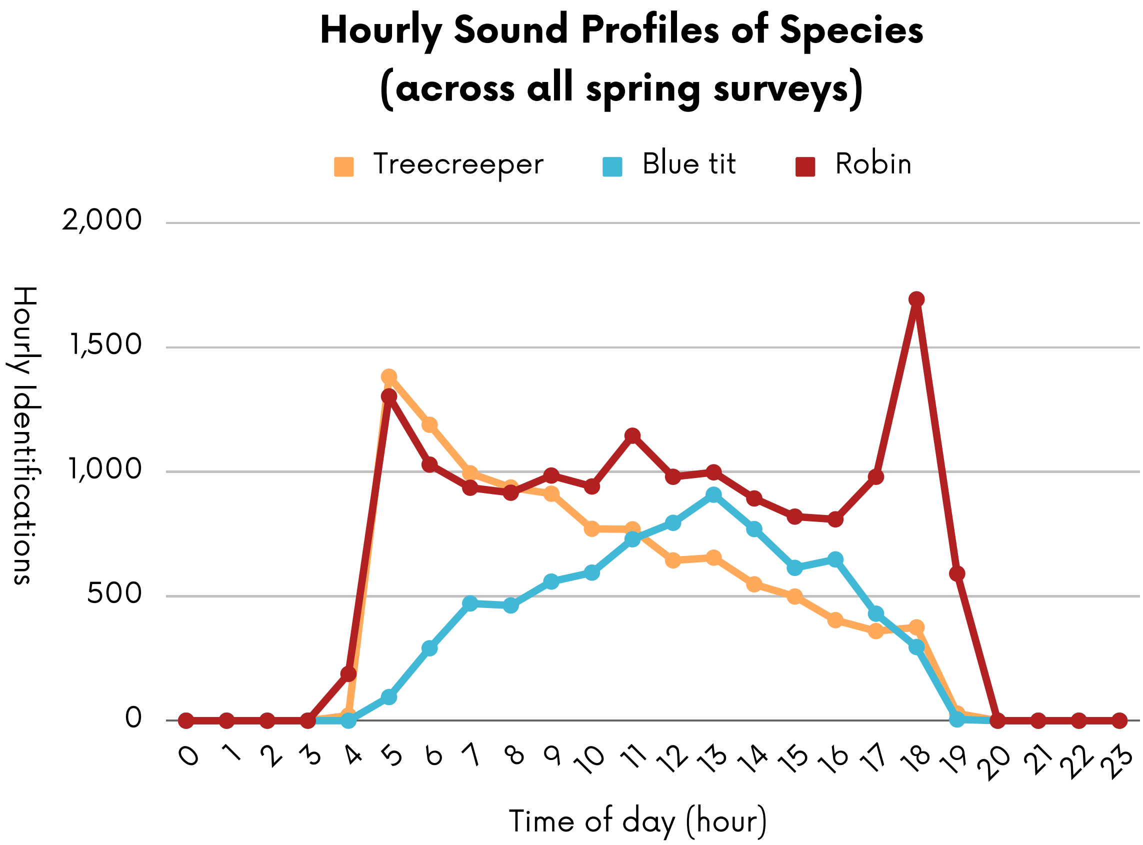
Daily Chiffchaff identifications at different woodland sites during Spring surveys



The number of Chiffchaff identifications increases later in the survey period as they arrive from their migration. Activity was earliest in the Sourthern-most wood, Pressmennan Wood

Due to the continuous recording of the recording units, we can also examine the daily "sound profiles" of different species. Bird species often focus their calls at different times of the day due to a combination of ecological and physiological factors. One of the primary reasons is to reduce noise competition; the interference from calls of other species can obstruct a bird's own vocalisation, making it challenging for potential mates or rivals to hear it.

As we can see from the chart below, each species has distinct times of day when they are most vocal, and further study using these bioacoustic methods could provide greater insight into the behaviour of species in different assemblages and environments.



BATS

Many bat species in the UK, such as the barbastelle and Bechstein's bat, are closely associated with woodlands. These habitats provide a rich source of insect prey and numerous roosting sites. Ancient woodlands, in particular, can be especially important, offering a diverse structure and variety of tree species that support a high diversity and abundance of insects for feeding.

Passive bioacoustic monitoring can be used to study and survey for bats, although recording needs to be set up for a higher recording frequency. Bats use echolocation - a system of acoustic signals - to navigate and find prey in the dark. Different species of bats use different frequencies, typically in the 20 KHz - 120KHz range, each of which serves as a unique acoustic signature that can help in identifying the species.

Recording at these higher frequencies (generally at 192KHz or 384KHz) requires greater storage for audio data, and increased battery power when recording. Therefore, there is generally a tradeoff for the amount of high-frequency recording that can be undertaken per day when undertaking long-term monitoring. To evaluate whether the ARUs could be used for long-term monitoring of both bat and bird species (using the same device), we chose to record at intervals for 2 hours per night (22:00 - 23:00) & (01:00 - 02:00). We identified a total of 5 species: common pipistrelle (Pipistrellus pipistrellus), soprano pipistrelle (Pipistrellus pygmaeus), brown long-eared bat (Plecotus auritus), Daubenton's bat (Myotis daubentonii), and Natterer's bat (Myotis nattereri) across the four surveys undertaken during the summer months when bats are most active.

Both Natterer's bat and Daubenton's bat have been listed in the results, however differentiating species within the Myotis genus using bioacoustic monitoring can be challenging due to the similarity of their echolocation calls. Many Myotis species, such as the Natterer's bat (Myotis nattereri) and Daubenton's bat (Myotis daubentonii), emit calls that fall within similar frequency ranges and have overlapping call characteristics. Their calls are often broadband, frequency-modulated sweeps that do not have the distinctive "peak" frequencies seen in some other bat species. In addition, the call characteristics of Myotis species can vary with the situation, depending on factors such as the bat's activity and the complexity of the environment. These factors can make it difficult to reliably identify Myotis species based solely on their echolocation calls, necessitating the use of other identification methods, to confirm species identity. It is therefore recommended that bioacoustic monitoring is used alongside alternative survey methods when studying these species.

Common pipistrelle (Pipistrellus pipistrellus)

Pipistrelles are the most common and widespread of all British bat species. There are two very similar species, common pipistrelle and soprano pipistrelle, which are only differentiated by the frequency of their call. A single pipistrelle can consume up to 3,000 insects in one night. The Soprano pipistrelle was the most frequently identified species across all sites, followed by the common pipistrelle.

Brown Long-eared bat (Plecotus auritus)

As well as catching insects in free flight, brown long-eared bats are gleaners, and often fly slowly amongst foliage, picking insects off leaves and bark. Their echolocation calls are very quiet, making them hard to detect. Their calls can also be very similar to the grey long-eared bat, although these are only found on the South coast of England.

A recent study has shown that passive recording yields higher detection probabilities over active recording methods for bats [15], although the methodologies involved recording throughout the night, rather than a shorter time period as used in this study. Active recording can produce clearer calls as surveyors can move to the most appropriate location for recording. Whereas passive sampling may yield lower quality calls, procedures are easily repeatable and data can be used to measure temporal variation in activity throughout the night, and due to the longer duration of total recording time, can detect species which are missed through active recording.

RECORDING HARDWARE

A vital component of our study involved testing the reliability and longevity of the bioacoustic recording hardware. Our deployment of automated recording units (ARUs) across diverse woodland sites in different seasons presented an excellent opportunity to evaluate the hardware's overall performance in different environmental conditions.

We are pleased to report that no devices failed or were found to have incomplete data. Therefore it is encouraging that there was a 100% success rate. However, we decided to continue to improve the reliability of components within the device build in order to reduce the chance there are any future failures in the field.

ARU deployments in Bute Forest (top left), Strathfillan Woodlands (top right), Little Druim Wood (bottom left), Wood Hill Wood (bottom right)

ONLINE ENGAGEMENT

During the Project, we used audio and video recordings from surveys taken to create new online engagement around bioacoustics and the benefits of biodiversity monitoring. Against a target of 5,000, the combined reach of social media posts related to the project was 4,791. In addition to our own posts, project partners shared photos from deployments, as well as results and reporting from their respective surveys. Highlands Rewilding included survey findings in their "Second Natural Capital Report" (December 2022).

We also produced a short video, which includes video and audio footage taken from site visits in Scotland. The video is available on our website here

FINDINGS & DISCUSSION

Our bioacoustic monitoring surveys successfully identified a total of 78 bird species and 5 bat species across all survey sites, including several woodland indicator species. This highlights the efficacy of bioacoustic monitoring as a tool to study species diversity and population dynamics in woodland environments. Several noteworthy species were detected, reinforcing the richness and diversity of bird life in Scottish native woodland sites.

We successfully identified key woodland indicator species, which when studied as a group, may be a useful bioacoustic indicator of woodland health, alongside wider measurements of species richness to determine biodiversity. In addition, by monitoring these indicator species, woodland owners and land managers can gain valuable insights about the overall condition of the woodland, allowing them to make informed decisions for its management and protection.

As a case study, we focused on the Chiffchaff, a migratory bird species, analysing the number of daily identifications during the spring to track its arrival in the woodland sites. Our findings showed a clear increase in Chiffchaff identifications over time, indicating the start of their migration season. This data corresponds well with historical records of Chiffchaff migration timings, demonstrating the value of bioacoustic monitoring as a tool for studying avian migration patterns.

In terms of hardware, this study has demonstrated that bioacoustics can be an accessible and cost effective means of bioacoustic monitoring. Importantly, an end-to-end solution has been shown to be viable and usable by experts and non-experts alike. The recording devices themselves performed well across all woodland sites and under various weather conditions, from harsh winter storms to the heat of the summer. Battery life and storage capacity were found to be adequate for continuous month-long monitoring, and the devices' ability to operate autonomously significantly reduced the need for human intervention during the survey period. Whilst we have demonstrated the recording for bat species can be delivered using the same ARU, we would recommend using separate recording devices for in-depth study of the two species groups, and also recommend further study into the optimum sampling methodology for bat monitoring in woodlands.

Overall, our study has successfully shown that bioacoustic monitoring can provide valuable insights into species assemblages, individual species behaviours, and biodiversity changes in woodland environments. These results offer a promising pathway to monitoring and conserving biodiversity in these crucial habitats moving forward. We hope that these findings will help guide future research and conservation efforts.

Thank you again for supporting this valuable project advancing monitoring technology that will help us better understand and protect our woodlands. We could not have achieved this without your support.

APPENDIX A

FURTHER TEST SURVEYS

In addition to the surveys listed in the results section, several test surveys were undertaken in different environments to evaluate different use cases

- One further survey was taken at a conifer plantation woodland (Sitka pine) on the Bunloit estate. The number of species identified (25) was comparatively lower than the native woodland surveyed on the estate, with the same number of recording devices used (2).
- A further single device test survey was also undertaken at the Glenfeshie estate, in a small open area of recently planted native trees. A single recording device was used, identifying 19 species in the area during the survey period, with no significant difference in recording quality seen compared to recording in mature, closed woodland.
- A different recording unit was also tested for long term monitoring utilising a different battery set up with greater capacity. The ARU was tested for continuous monitoring over a three month period at a woodland site in the Glenfeshie estate, identifying 35 species across the three month period. Monitoring took place between December - February, to test the recording device in cold conditions over an extended period. Recording was successful throughout the entire period.

The results from these surveys have not been included in the results discussed in the report, as the primary objective of the study was to investigate use in native woodlands, with a minimum two recording devices per survey.

Preliminary investigations demonstrate that bioacoustic technology is an effective tool for long-term monitoring in a variety of habitats, but more focussed study is needed to establish any differences in results or required deployment.

APPENDIX B

COMPARING BIOACOUSTIC RESULTS VS. TRADITIONAL METHODOLOGIES

There was limited data available from sites surveyed, with the exception of the four Woodland Trust sites, where historic BTO survey data was available via the NBN Atlas. Species identifications from all surveys undertaken in the past 10 years within the dates when the bioacoustic surveys were conducted (8th March - 6th April) [13,14]. On average, the bioacoustic surveys matched 85.2% of the species identified from the traditional surveys.

Survey Site	Bioacoustic Survey Species Count	Traditional Survey Species Count	Species Identified from both techniques	% Traditional Survey species identified with bioacoustics
Pressmennan Woods	*44*	45	33	73.33%
Whinny Hill Woods	*37*	20	19	95.00%
Woodhill Woods	*33*	29	21	72.41%
Little Druim Woods	*43*	8	8	100.00%

There were additional species identified from both techniques that were not identified by the other. On average, a further 19.0 species were identified from the bioacoustic surveys, whereas on average a further 5.3 species were identified from the traditional surveys. There are benefits to both techniques, and integration of bioacoustics into traditional survey techniques presents a powerful combination, enhancing both the range and quality of ornithological data. It allows for the comprehensive understanding of avian communities, enabling scientists to conduct thorough biodiversity assessments, habitat studies, and produce informative trends over time. Simultaneously, such hybrid approaches help in formulating effective conservation strategies by identifying species at risk, monitoring their population trends, and assessing the impacts of changes on their habitats and the environment.

APPENDIX C

BIRD SPECIES IDENTIFICATION FREQUENCY

Common Name	Scientific Name	Conservation Status (BoCC5)	Number of Sites where species was Identified	Total Identifications
Coal tit	*Periparus ater*	green	11	22869
Robin	*Erithacus rubecula*	green	12	20159
Wren	*Troglodytes troglodytes*	amber	12	19797
Goldcrest	*Regulus regulus*	green	12	19480
Treecreeper	*Certhia familiaris*	green	11	15012
Chiffchaff	*Phylloscopus collybita*	green	6	12509
Wood pigeon	*Columba palumbus*	amber	7	8990
Blue tit	*Cyanistes caeruleus*	green	11	8224
Longtailed tit	*Aegithalos caudatus*	green	12	6992
Great tit	*Parus major*	green	10	4888
Chaffinch	*Fringilla coelebs*	green	12	4000
Tawny owl	*Strix aluco*	amber	12	3728
Blackbird	*Turdus merula*	green	8	3302
Song thrush	*Turdus philomelos*	amber	10	2880
Canada goose	*Branta canadensis*	introduced	3	2649
Siskin	*Spinus spinus*	green	12	2050
Common pheasant	*Phasianus colchicus*	introduced	1	2002
Stock dove	*Columba oenas*	amber	2	1554
Great spotted woodpecker	*Dendrocopos major*	green	11	1406
Mistle thrush	*Turdus viscivorus*	red	10	1323
Carrion crow	*Corvus corone*	green	11	1309
Nuthatch	*Sitta europaea*	green	5	1069
Buzzard	*Buteo buteo*	green	10	1052
Redwing	*Turdus iliacus*	amber	9	1051
Bullfinch	*Pyrrhula pyrrhula*	amber	7	1039
Meadow pipit	*Anthus pratensis*	amber	6	1010
Dunnock	*Prunella modularis*	amber	11	988
Spotted flycatcher	*Muscicapa striata*	red	4	985
Eurasian woodcock	*Scolopax rusticola*	red	4	903
Common raven	*Corvus corax*	green	11	747
Greylag goose	*Anser anser*	amber	7	724
Western jackdaw	*Corvus monedula*	green	4	724
Crested tit	*Lophophanes cristatus*	green	2	447
Hooded crow	*Corvus cornix*	green	8	358
Eurasian jay	*Garrulus glandarius*	green	8	320
Stonechat	*Saxicola rubicola*	green	1	273
Goldfinch	*Carduelis carduelis*	green	7	261
Whooper swan	*Cygnus cygnus*	amber	2	238

APPENDIX C

Common Name	Scientific Name	Conservation Status (BoCC5)	Number of Sites where species was Identified	Total Identifications
Common redstart	*Phoenicurus phoenicurus*	amber	3	198
Oystercatcher	*Haematopus ostralegus*	amber	5	190
Mallard	*Anas platyrhynchos*	amber	2	165
Collared dove	*Streptopelia decaocto*	green	2	151
Grey wagtail	*Motacilla cinerea*	amber	5	148
Reed bunting	*Emberiza schoeniclus*	amber	3	142
Eurasian teal	*Anas crecca*	amber	2	134
Willow warbler	*Phylloscopus trochilus*	amber	4	126
Common kestrel	*Falco tinnunculus*	amber	2	113
Lesser redpoll	*Acanthis cabaret*	red	8	108
Tree pipit	*Anthus trivialis*	red	4	102
Pinkfooted goose	*Anser brachyrhynchus*	amber	5	101
European herring gull	*Larus argentatus*	red	4	88
Eurasian magpie	*Pica pica*	green	2	84
Grey heron	*Ardea cinerea*	green	4	72
Pied wagtail	*Motacilla alba*	green	3	67
Ring ouzel	*Turdus torquatus*	red	2	60
Barn swallow	*Hirundo rustica*	green	2	58
Rook	*Corvus frugilegus*	amber	5	49
Common house martin	*Delichon urbicum*	red	2	45
Red crossbill	*Loxia curvirostra*	green	4	43
Western barn owl	*Tyto alba*	green	3	43
Grasshopper warbler	*Locustella naevia*	red	2	41
Swift	*Apus apus*	red	1	40
Curlew	*Numenius arquata*	red	3	40
Moorhen	*Gallinula chloropus*	amber	1	30
Black redstart	*Phoenicurus ochruros*	amber	1	20
Honey buzzard	*Pernis apivorus*	amber	1	19
Blackcap	*Sylvia atricapilla*	green	1	18
Sparrowhawk	*Accipiter nisus*	amber	2	16
Kingfisher	*Alcedo atthis*	green	2	15
Little grebe	*Tachybaptus ruficollis*	green	1	13
Common goldeneye	*Bucephala clangula*	red	1	7
Common merganser	*Mergus merganser*	green	1	7
Fieldfare	*Turdus pilaris*	red	2	6
European greenfinch	*Chloris chloris*	red	1	6
Peregrine falcon	*Falco peregrinus*	green	1	5
Common scoter	*Melanitta nigra*	red	1	4
Great blackbacked gull	*Larus marinus*	amber	1	3
Common gull	*Larus canus*	amber	1	2

APPENDIX C

BAT SPECIES IDENTIFICATION FREQUENCY

Common Name	Scientific Name	Number of Sites where species was Identified	Total Identifications
Natterer's Bat	*Pipistrellus pygmaeus*	1	1
Common Pipistrelle	*Pipistrellus pipistrellus*	5	494
Soprano Pipistrelle	*Pipistrellus pygmaeus*	5	704
Brown Long-eared Bat	*Plecotus auritus*	4	20
Daubenton's Bat	*Myotis daubentonii*	1	1

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