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# Taxonomic resolution in dual-polarization weather radar observations of biological scatterers: A systematic review

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**Abstract**

The derivation of biological information—abundance, diversity, movement of organisms—from dual-polarization weather surveillance radars (WSRs) presents an opportunity for novel large-scale biodiversity monitoring. This review takes a systematic approach to ask what degree of taxonomic resolution has so far been achieved in dual-polarization WSR observations. A range of methods are described that can be classified as observational, algorithmic, or modeling-based approaches. While progress toward finer taxonomic resolution (species, genus, family) so far has been limited, machine learning methods demonstrate that the information for at least some degree of taxonomic resolution is present in the data, and electromagnetic modeling provides a valuable research direction. A more systematic, interdisciplinary approach that incorporates zoological understanding, radar physics, and machine learning is recommended for future research.

**KEYWORDS**

aeroecology, dual-polarization, migration ecology, radar entomology, radar ornithology, taxonomic resolution, weather surveillance radar

## INTRODUCTION

### Motivation

Weather surveillance radars (WSRs) are sensitive enough to detect airborne animals over areas of order $10^4$ km$^2$, roughly the area of the county of Yorkshire, UK. WSRs scan roughly every 5 min, with resolution finer than 1 km$^2$, and are organized into networks spanning continents. Taxonomically detailed data, that is, approaching genus or species level, at these scales would present a step change in aeroecological observation compared to traditional methods, allowing for novel insights into species behavior as well as large-scale assessment of conservation policies through biodiversity monitoring (Chilson et al., 2017). Improving taxonomic resolution on dual-polarization WSRs has been recently listed as a key method for growing the biological utility of radar data to tackle outstanding challenges in migration ecology (Bauer et al., 2019, 2024).

The prospect of species-level taxonomic resolution came with the upgrade of WSRs to dual-polarization (Zrnic & Ryzhkov, 1998); dual-polarization WSRs simultaneously transmit and receive horizontally and vertically polarized radiation, providing information about the shape and size of targets that is not available on older, single-polarization WSRs (Stepanian, Horton, Melnikov, et al., 2016). Recent reviews have been conducted on the general progress of WSR-based aeroecology (Bauer et al., 2024; Hu, Cui, et al., 2024); however, a detailed methodological review of studies of biological scatterers in dual-polarization WSR data is missing from the literature. This review systematically collects the current work studying dual-polarization bioscatterer return and asks to what extent taxonomic resolution has been achieved. The studies are diverse in their approaches; this review synthesizes the current methods for understanding and classifying dual-polarization radar products from bioscatterers and presents a set of recommendations for future work.

A Boolean search string is designed and used to generate a set of 41 relevant papers. Within these papers, the general methodological trends are described, followed by several specific thematic analyses; namely, which variables were used, which scattering regime the studied animals fall into, what challenges were encountered, and, finally, whether the authors and journal originate from the physical or biological sciences. We include studies of both direct radar data analysis and ground-up modeling approaches that simulate radar returns from physical principles, as in Stepanian et al. (2018). This ground-up approach has a methodological parallel in the radar study of ice particles, where databases are being compiled containing the scattering properties of thousands of different ice crystal shapes (Lu et al., 2016), and has considerable promise (Mirkovic et al., 2016).

## Biological observation using WSRs

Stepanian, Horton, Melnikov, et al. (2016) provide an excellent, accessible introduction to biological observation on dual-polarization WSRs. A more rigorous, mathematical treatment in a meteorological context can be found in Ryzhkov and Zrnić (2019), and for a more general introduction to WSRs in an entomological context, see Drake and Reynolds (2012, chapter 15). In this review, "class" is used in the taxonomic sense (to refer to Insecta [insects], Aves [birds], Mammalia [bats, within the context of radar]); sub-class-level resolution refers to distinction at a finer taxonomic resolution than class (order, family, genus, or species).

Reflectivity ($Z$), Doppler velocity ($V_r$), and spectrum width ($\sigma_r$) are all measured by both single-polarization and dual-polarization WSRs; in this review, these three variables are referred to as the single-polarization variables. Differential reflectivity ($Z_{\mathrm{DR}}$), cross-polar correlation coefficient ($\rho_{\mathrm{hv}}$) (correlation coefficient for short), and differential phase ($\phi_{\mathrm{DP}}$) are only measured by dual-polarization WSRs; these will be referred to as the dual-polarization variables.

Additional variables can be derived. "Texture" refers to the local spatial variance of the variable. The method for calculating textures differs between studies. Textures are introduced further in Stepanian, Horton, Melnikov, et al. (2016). The depolarization ratio can be calculated from the differential reflectivity and correlation coefficient. The depolarization ratio estimates how much of the power incident in one polarization is scattered into the orthogonal polarization: it is useful for separating meteorological and non-meteorological targets (Kilambi et al., 2018; Melnikov & Matrosov, 2013). Finally, the differential Doppler velocity is the difference between the velocity measured by the horizontal and vertical polarizations (Melnikov et al., 2014).

An important concept in the study of biological scatterers is resonant scattering (Drake & Reynolds, 2012; Stepanian, Horton, Melnikov, et al., 2016). If the scatterer is small compared to the wavelength of the incident radiation, then the scattered power increases with the square of the volume of the scatterer in what is known as the "Rayleigh scattering regime," and if the scatterer is large compared to the wavelength, then the scattered power is proportional to the cross-sectional area of the scatterer; this is the "optical scattering regime." However, if the wavelength is comparable to the dimensions of the scatterer, then resonant effects lead to a highly nonlinear response in the "Mie scattering regime." Meteorological radars operate at wavelengths of 3–10 cm (X,C, and S bands); as such, large insects and birds are firmly in the Mie scattering regime. The subsequent resonant scattering produces more complex signatures in the radar product than one would naively expect and makes discrimination of biological scatterers more challenging than if they were Rayleigh or optical scatterers.

# METHODOLOGY

## Search terms and exclusions

To systematically assess progress toward taxonomic resolution on dual-polarization WSRs, it is desirable to collect all papers that study aeroecological phenomena using the dual-polarization output from WSRs, while also including any attempts to study the problem through ground-up electromagnetic modeling. The search string used is (((polari* OR weather OR meteo*) AND (Radar Cross Section OR Radar OR (electromagnetic AND (modelling OR simulation)))) AND (insect* OR bird* OR bat* OR arthropod* OR aeroeco*OR entomol*)). This search string is used in Web of Science to search title, abstract, author keywords, and keywords based on cited articles (TS = () in the Web of Science advanced search) and in Scopus to search all available article data (ALL() in the Scopus advanced search).

To address the topic of progress in refining taxonomic resolution on WSRs, we only want to consider papers that attempt to study or use dual-polarization variables in the context of WSRs. On these grounds, radar aeroecology papers are excluded that:

1. Do not consider taxonomic resolution, such as Lippert et al. (2022) who studied taxon-agnostic large bird movement on WSRs.
2. Only consider single-polarization variables, even if they are taking measurements using a dual-polarization WSR, such as Cabrera-Cruz et al. (2019).
3. Did not consider a WSR or close research equivalent (Hubbert et al., 2018), such as studies focusing on specific entomological or ornithological radars (e.g., Wang et al., 2024).

Rejecting specific ecological radars excludes a lot of the historic radar aeroecological work (Drake et al., 2017). However, as outlined by Mirkovic et al. (2019), WSRs obtain a different view of animals and, as such, require distinct methodological development. How much the wider entomological and ornithological radar work can be leveraged to understand the dual-polarization WSR radar return is another question and is touched upon in the discussion.

## Systematic paper extraction

A search into Web of Science and Scopus was run on 25 October 2024. After removing duplicates, the search generated 2474 reports. A manual screen of abstracts for relevance using the Abstrackr software reduced this to 394 reports to be assessed for eligibility. The 394 papers were then examined in more detail and excluded if they did not consider the question of taxonomic resolution, did not use a WSR, or only considered single-polarization variables, leaving 41 studies for inclusion in the review. This follows the PRISMA systematic review guidelines (Page et al., 2021). A flowchart illustrating this procedure in more detail is included in the supplementary information.

# GENERAL METHODOLOGICAL TRENDS

The selected papers contain a large range of approaches; broadly, these can be categorized into observational, top-down algorithmic, or ground-up model based methods, where this descriptor labels how any taxonomic inference has been made. The overall trends are summarized in Figure 1. The studies collected span a range of taxonomic resolution; studies that attempt to observe at a finer taxonomic scale than class of bird, bat, or insect are described in the text. At a coarser resolution than this, algorithmic studies have managed to delineate biological from meteorological data (Hamurcu & Yetik, 2018; Lin et al., 2019; Radhakrishna et al., 2019) and separate birds and insects (Hu, Sun, et al., 2024; Jatau et al., 2021; Jiang et al., 2013; Sun et al., 2024a; Wen et al., 2017). Similarly, observational studies have identified patterns and ranges in the polarimetric variables for general biology (Poffo et al., 2018; Van Den Broeke, 2013, 2022) and birds and insects (Gauthreaux et al., 2007, 2019; Huang et al., 2023; Maniraguha et al., 2021; Stepanian, Horton, Melnikov, et al., 2016; Zhang et al., 2005).

## Top-down algorithmic methods

The easiest way to obtain sub-class-level resolution is to look for a specific species that, through known phenology or behavior, one expects to be present, or presence can be validated with other data. This has been done in two instances using dual-polarization data. The first is the study of martin and swallow (Hirundinidae) roosts. Chilson et al. (2019) and Perez et al. (2024) developed neural networks to detect roosts from radar images, and found the use of dual-polarization variables improved performance.

The second example of a specific species study using dual-polarization data is for the Fall Army Worm moth (*Spodoptera frugiperda*). A fuzzy logic algorithm was developed using reflectivity and the three dual-polarization variables to separate insect signatures from weather (Maniraguha et al., 2024a), and then improved through the use of the depolarization ratio (Maniraguha et al., 2024b).

Sub-class level resolution has also been obtained through algorithmic species community identification. A Bayesian classifier was developed by Mäkinen et al. (2022) to classify WSR data and included insects, passerines, and larger arctic birds as three distinct categories. To demonstrate that finer resolution is possible, Gauthreaux and Diehl (2020) built a random forest algorithm with seven biological target classes, made up of four bird categories, two arthropod categories, and bats. Dual-polarization variables are found to increase predictive power, with certain variables being more important when distinguishing between different target classes. A key issue with the work of Gauthreaux and Diehl (2020)

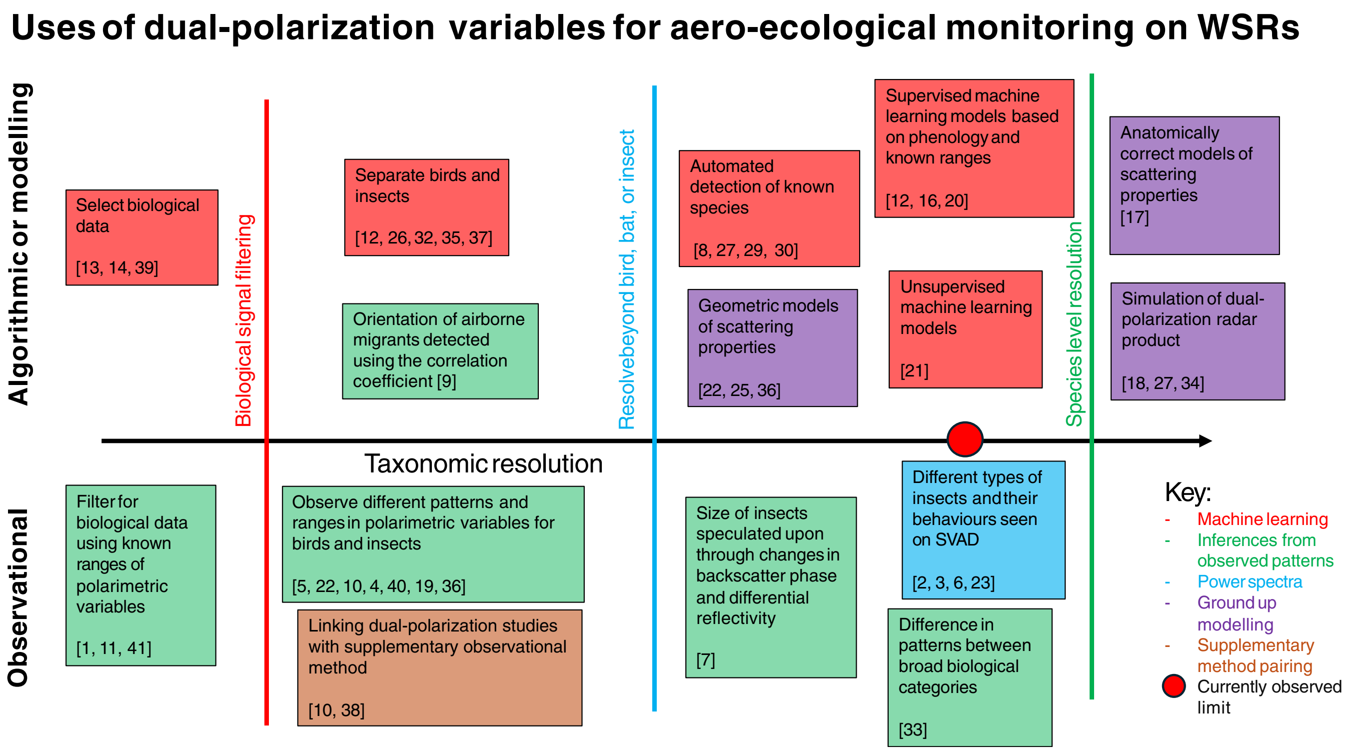


**FIGURE 1** A summary of the general methodological trends used to study biological phenomena in the dual-polarization output of weather surveillance radars (WSRs). The top row contains top-down algorithmic and ground-up modeling approaches, and the bottom row contains purely observational studies. The taxonomic resolution achieved by the method increases from left to right. Relevant papers are included by number; a mapping from number to reference is included as supplementary material. SVAD refers to the use of the spectral velocity azimuth display technique.

and Mäkinen et al. (2022) is the availability of well-labeled data. Taxonomically resolved labels for WSR data are difficult and time-consuming to obtain, and there is a dearth of such labels in the literature; as such, these studies are only able to compile a limited set of labels. In the case of the random forest algorithm, Gauthreaux and Diehl (2020) exclude volumes containing mixed scatterers. One way to partially circumvent the lack of well-labelled data is to dispense with labeling altogether. Lukach et al. (2022) built an unsupervised spectral clustering algorithm that produced four distinct clusters associated with biological scatterers. The observed diversity of clusters is correlated with diversity measures at the ground level in light traps.

Both Gauthreaux and Diehl (2020) and Lukach et al. (2022) convincingly demonstrate that the information is present in the data for some degree of sub-class-level identification; however, neither study provides an algorithm ready to use for identification at this level of taxonomic resolution. Lukach et al.'s (2022) work is restricted by the lack of interpretation of the clusters, and Gauthreaux and Diehl's (2020) work does not achieve a high accuracy when all 7 biological target classes are included.

## Ground-up modeling methods

An alternative to top-down algorithmic or data-driven methods is to simulate the scattering properties of biological scatters. If a priori understanding of scattering characteristics can be used to reconstruct radar observations, we can exploit the same understanding to study the complexity of communities contained within radar data (Mirkovic et al., 2019).

The simplest approach to modeling biological scatterers is to use basic shapes. Lang et al. (2004) and Zrnic and Ryzhkov (1998) show that a prolate spheroid can explain the general qualitative features of biological WSR returns for insects and birds. More recently, Melnikov et al. (2015) show that a prolate spheroid can be used to model the dual-polarization return from an ensemble of insects in the Rayleigh scattering regime. Fitting this model gives an aspect ratio, heading, pitch, and variation of heading and pitch. One issue highlighted here is that the phase difference between the horizontal and vertical channels on transmission, which is an intrinsic and not well-known property of each WSR, strongly impacts the values of the returned radar variables. This is also discussed in Stepanian, Horton, Melnikov, et al. (2016).

Melnikov and Bridge (2024) further explore this issue by fitting the spheroidal model to co-located data from two nearby WSRs and show that different transmit phases are required to explain to fit the model to the data from different WSRs.

A more complex alternative to simple shapes is to make an anatomically correct model and calculate the scattering properties using a simulation software tool. For dual-polarization variables, this has only been done for a 3D model of a Brazilian free-tailed bat (*Tadarida brasiliensis*) using the WIPL-D electromagnetic modeling and simulation software (henceforth, WIPL-D) (Mirkovic et al., 2016). There is limited agreement between the modeled and measured differential reflectivity and some agreement in the horizontal scattered power. Once the model for a single bat has been generated, bat emergences can then be simulated. This is explored further by Stepanian et al. (2018); the model is layered on top of an agent-based model and used to simulate the dual-polarization WSR return for a bat emergence.

## Observational methods

Minda et al. (2008) suggest different signatures in differential reflectivity and correlation coefficient to separate low-altitude migratory birds and large shorebirds. In a study of a severe storm, Hubbert et al. (2018) infer a minimum size of insects based on backscatter differential phase values associated with resonant scattering. The azimuthal separation of the reflectivity and differential phase maxima is used to suggest that the insects fly with a pitch angle, and distinct insect layers are proposed to be different insect types based on different values of differential phase. It is worth noting that inferences from both studies are speculative, with no actual ground truth other than knowledge of likely animal behavior.

One possible way to observe sub-class-level resolution is to supplement WSR observations with other methods, such as citizen science data like eBird (Horton et al., 2018) or a specific biological radar (Gauthreaux et al., 2019). There has been limited use of supplementary methods to support the exploration of the dual-polarization data. An ornithological radar was used to validate the predictions of the class-level random forest classification algorithm designed by Hu, Sun, et al. (2024).

Another powerful observational technique is the spectral velocity azimuth display (SVAD) (Bachmann, 2007; Bachmann et al., 2007; Bachmann & Zrnić, 2007, 2008). The SVAD technique breaks down the radar return by velocity, allowing for separation of bio-scatterers into bird, active insects, and passive insects. A detailed study of the differential phase shows that regions of high variance can be used to identify ascent and descent (Bachmann & Zrnić, 2007), and that there is a clear difference between nocturnal and diurnal insects. SVAD is only available on research WSRs, as operational WSRs do not collect enough samples at each location and do not have a high enough pulse repetition frequency. However, SVAD can be used to analyze the output of radar product simulations (Stepanian et al., 2018).

# THEMATIC ANALYSES

Alongside the general methodological trends observed, three specific themes are considered in more detail. Note that one review paper is included in the authorship analyses but not considered further.

## Variables used

Table 1 gives the count of how many studies use each variable, broken down by the type of study. Differential Doppler velocity is excluded from this analysis, as it is only used by the study that introduces it (Melnikov et al., 2014). The most striking result is the variation in combinations of variables considered between studies. The study-level breakdown of variable combinations can be found at https://doi.org/10.6084/m9.figshare.29117585.v1.

## Scattering regime

For each study, a representative length for the scatterer studied was recorded; if multiple scatterers were studied, then a minimum and maximum length was recorded: the data are summarized in Figure 2. In most cases, a broad range of organisms were studied, and a nominal length was used to represent the class of scatter: 10 mm for insects, 50 mm for bats, 100 mm for birds, and 800 mm for larger birds. This simplification limits the quality of the output; however, two clear observations can still be made. The first is that, through the simplifying lens of these representative sizes, most scatterers studied fall into the Mie scattering regime.

The second observation is that, although there is some variation in the scatterers studied, the distribution is dominated by studies that span from insect to bird on S-band radar. These come from the US and Chinese WSR networks, NEXRAD and CINRAD, respectively. This presents an important consideration for WSR aeroecology: other countries use C and X band WSR systems (Huuskonen et al., 2014; Lukach et al., 2022; Maniraguha

**TABLE 1** Count and percentage (in parentheses) of the number of times each variable is used across the three study types.

| Paper type | No. papers | $Z$ | $V_r$ | $\sigma_r$ | $Z_{DR}$ | $\rho_{hv}$ | $\phi_{DP}$ | DR | Textures |
|---|---|---|---|---|---|---|---|---|---|
| Algorithmic | 18 | 14 (78) | 9 (50) | 8 (44) | 14 (78) | 16 (89) | 14 (78) | 2 (11) | 4 (22) |
| Modeling | 6 | 5 (83) | 2 (33) | 2 (33) | 6 (100) | 3 (50) | 5 (83) | 0 (0) | 0 (0) |
| Observational | 16 | 11 (69) | 7 (44) | 1 (6) | 11 (69) | 11 (69) | 8 (50) | 1 (6) | 1 (6) |

Abbreviations: $\sigma_r$, spectrum width; $\phi_{DP}$, differential phase; $\rho_{hv}$, correlation coefficient; DR, depolarization ratio; Textures, whether any texture variables were used; $V_r$, radial velocity; $Z$, reflectivity; $Z_{DR}$, differential reflectivity.

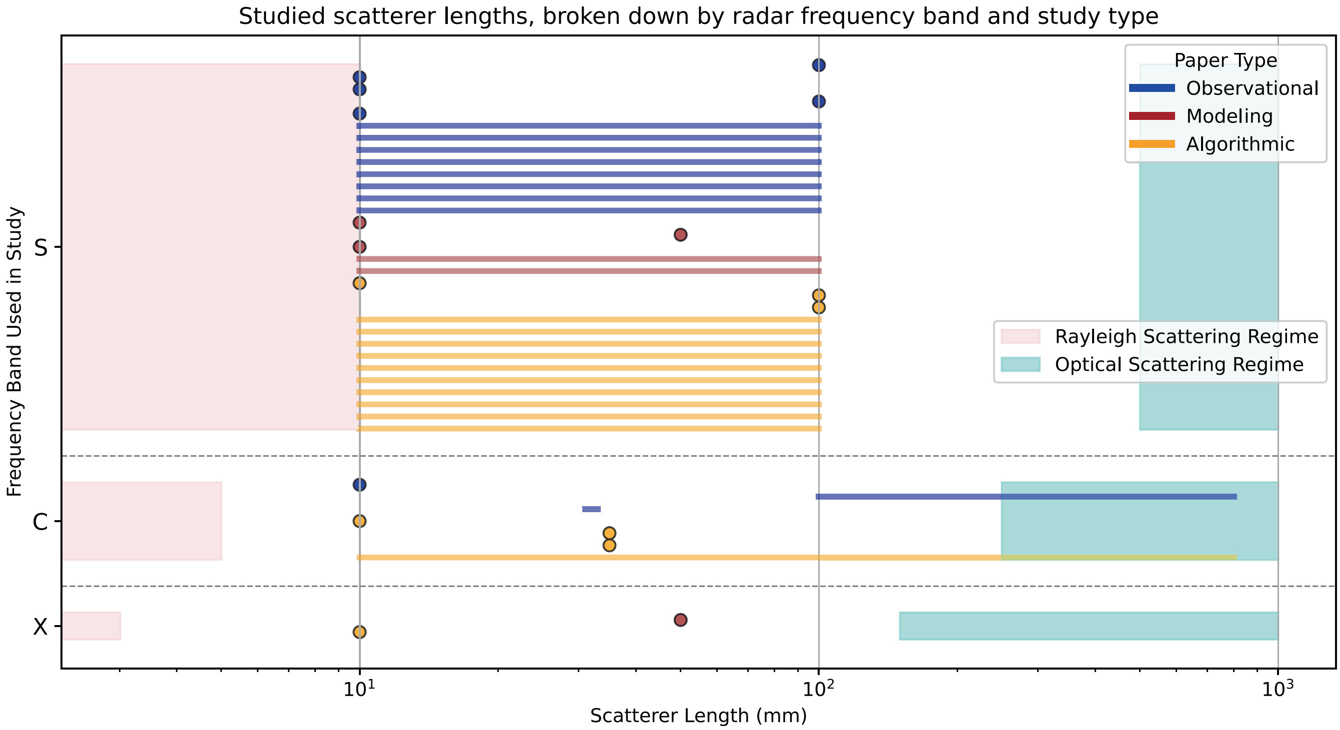


**FIGURE 2** Distribution of scatterer lengths considered across the selected papers, broken down by paper type and radar band. Lines are used to show when a study considers a range of scatterer sizes, whereas points represent a single, specific scatterer size. The radar band used in the paper is indicated by the categorical position on the $y$-axis. The Rayleigh scattering regime extends until the ratio of scatterer length to wavelength is equal to 0.1, and the optical regime begins when the ratio of scatterer length to wavelength is equal to 5. The Mie scattering regime sits between the Rayleigh and optical regimes.

et al., 2024b; Poffo et al., 2018). For the cohesion of the global aeroecological community, it is important that research is driven forward in a manner that is set up to allow for adaptation across different WSR systems with the greatest possible ease, for example, publishing radar cross-section data at multiple radar bands. This data and model interoperability will facilitate the adoption of methods by researchers using different WSR networks and encourage broader scale studies.

## Challenges encountered

From the selected papers, three key challenges stand out on the route to sub-class-level identification: differences between WSRs, the presence of multiple species in the same radar volume, and a lack of ground truth data. A record of how each study engages with these challenges is given in Table 2.

The properties of the transmitted signal vary across WSR systems, even within the same band or network. Two key differences are variation in wavelength and variation in transmit phase, both of which affect the returned radar product (Melnikov et al., 2015). Only five papers engaged with these challenges, but this may be because a lot of studies were only considering one WSR. Sun et al. (2024a) discuss obtaining a comprehensive dataset across radars to mitigate this, and Melnikov and Bridge (2024) explicitly demonstrate the effect of transmit phase on the radar product. Stepanian, Horton, Melnikov, et al. (2016)

**TABLE 2** A count and percentage (in parentheses) of how many of the selected papers explicitly mention each of the three key challenges identified, and how many take steps to mitigate it.

| Engagement with challenge | WSR differences | Mixed resolution volume | Ground truth |
|---|---|---|---|
| Mentions | 5 (13) | 14 (35) | 14 (35) |
| Mitigates | 3 (8) | 2 (5) | 6 (15) |

Abbreviation: WSR, weather surveillance radar.

and Stepanian, Horton, Hille, et al. (2016) present a procedure for estimating differential phase on transmission for a WSR.

The most frequently encountered challenge is radar return containing multiple scatterers. Gauthreaux and Diehl (2020) discuss mixed scatterer communities and explicitly exclude mixed radar returns from their work. One of the only techniques used so far to mitigate this is SVAD, as this separates out scatterers by velocity. However, SVAD is still limited to the separation of actively and passively mobile insects (Bachmann et al., 2007; Bachmann & Zrnić, 2008). No effort has yet been made to simulate a radar product from mixed species communities.

The challenge most engaged with is the issue of ground truth for the biological content of the radar data. This is a significant limiting factor for any study looking to discriminate at the sub-class level. The key attempts to mitigate this have come from using known phenology (Perez et al., 2024), using supplementary observation methods (Hu, Sun, et al., 2024), simulation of radar product from known scatterer types (Stepanian et al., 2018), and the use of unsupervised algorithms (Lukach et al., 2022).

## Author discipline

For the selected papers, a record was taken of the discipline of the lead author, senior author, and journal, categorizing them broadly into either physical or biological sciences. There was only one paper where the lead author, senior author, and journal were biologically oriented, as compared to 28 for physical. There were eight publications in biological journals, seven biological senior authors, and two biological lead authors. In summary, most of the research included in this review is being conducted by physical scientists and being published in journals with physical science themes and motivations.

# SYNTHESIS AND FUTURE DIRECTIONS

Ultimately, there has been very limited achievement of top-down algorithmic separation of biological scatterers into sub-class-level taxonomic categories, primarily due to the absence of labeled WSR data at this taxonomic resolution. However, both the supervised and unsupervised attempts to investigate the data at the sub-class level demonstrate that this information is present to some degree. Regarding our observational taxonomic resolution, there has not been that much progress since the early work of Zrnic and Ryzhkov (1998, 1999), where birds and insects are distinguished in the differential reflectivity—differential phase plane, although observational bird–insect distinction in the dual-polarization variables has since been explored in more detail and extended to textures (Jatau et al., 2021; Stepanian, Horton, Melnikov, et al., 2016). One observational success has been through SVAD, particularly in the study of differential phase (Bachmann et al., 2007; Bachmann & Zrnić, 2007, 2008). Machine learning algorithms trained on power spectra from research radars may be able to obtain higher taxonomic resolution than from standard dual-polarization WSR data. An analysis using an unsupervised clustering technique would give an idea of the available resolution.

The main barrier to both observational and algorithmic approaches is a lack of recorded ground-truth information at the sub-class level to either train algorithms or interpret results (Gauthreaux & Diehl, 2020). Supplementary observation methods are a valuable source of ground truth information. In the single-polarization case, Horton et al. (2018) used the citizen science platform eBird in conjunction with WSRs to study bird migration and were able to produce a relationship between body mass and WSR recorded airspeed. Additionally, specific ecological radars can be used to build training datasets with more taxonomic or morphological information; this has been done to a limited extent for reflectivity data (Gauthreaux et al., 2019; Li et al., 2023; Wang et al., 2023). More broadly, the integration of biological observations with WSR data necessitates observations coincident with airspace scanned by WSRs. Mixed-species observations in high biodiversity areas and recordings of single-species events will both provide valuable ground-truth data for unlocking the potential of WSRs. Further to the supplementary data sources given above, additional measurements could come from in situ aerial sampling, for example, using balloons (Chapman et al., 2004; Florio et al., 2020), or alternative remote sensing techniques such as bioacoustics, which have been used to identify birds to the family level (Stepanian, Horton, Hille, et al., 2016; Van Doren et al., 2023).

In the future, there is additional potential in the capabilities of modern WSRs; modern weather radars with digital transmitters are capable of measuring the linear depolarization ratio and changing differential phase upon transmission. These capabilities could deliver additional information on atmospheric biota (Bringi & Chandrasekar, 2001; Melnikov et al., 2015; Melnikov & Bridge, 2024). Furthermore, if phased array radars begin to replace WSRs, the electronically scanning radar beam will reduce update times below 1 min and offer the possibility for tracking bird flocks or even single birds, bringing new opportunities for taxonomic resolution in bird observation (Palmer et al., 2023).

The use of ground-up modeling to study dual-polarization WSR variables is in its early stages. The work presented here is a subset of the aeroecological community's ground-up modeling work for WSRs: most existing work looks at single-polarization radar return. In the broader literature, Mirkovic et al.'s (2016) bat model has been used to count flying foxes (Pteropodidae) by rescaling the model to the appropriate size (Meade et al., 2019). WIPL-D has also been applied to compute the single-polarization ventral RCS of a noctuid moth (*Xestia xanthographa*) (Addison et al., 2022). The work of Addison et al. (2022) could be extended to mirror the dual-polarization work done with the bat. WIPL-D has been used to study the appropriateness of different geometric models of insects on vertical looking radars (Mirkovic et al., 2019). This could be used to help inform the choice of geometric model for WSR work. One unanswered question in ground-up modeling is the required modeling fidelity (Addison et al., 2022; Mirkovic et al., 2016). If geometric models with a simple defining parameter set can be used, then there is the possibility of inferring these parameters directly from the radar data (Mirkovic et al., 2019). Uncertainties in the output of ground-up modeling are compounded by the question of how to model the internal electrical properties of the animal (Alzaabi et al., 2021; Drake et al., 2024; Mirkovic et al., 2019).

Looking forward, ground-up modeling work can assist with the challenges faced. Incrementally, models could be validated by explaining a small number of radar observations where the ground truth is known. A better understanding of animal scattering properties would help ground interpretations of differential phase observations (Hubbert et al., 2018). Through simulation techniques (Chilson et al., 2012; Stepanian et al., 2018), radar products for user-defined species communities can be generated. This has a host of applications, for example, explaining the output of unsupervised algorithms (Lukach et al., 2022), better informing prior distributions for Bayesian approaches (Mäkinen et al., 2022; Sun et al., 2024b), or providing another labeling tool for supervised algorithms (Gauthreaux & Diehl, 2020; Hu, Sun, et al., 2024).

The approaches detailed in this review are far from unified. Subsets of a larger set of variables are used inconsistently between studies, and species have been studied in a variety of ways in different contexts. Analogous to the traditional ID guide, or similar to the migration analysis toolbox suggested by Bauer et al. (2017), one can envisage the generation of a library of simulated animal scattering properties. Such a library would be comparable to Lu et al.'s (2016) database of ice particle scattering properties, but with many more dimensions of information to account for the additional complexity associated with biological scatterers. This library could be organized into taxonomic groups that are distinguishable in the radar data, and be extended to other information, such as instances of algorithms that can indicate presence, distributions of variables where they have been identified, or fuzzy logic membership functions. These databases would provide a strong basis for a more systematic, grounded approach to the challenge of improving taxonomic resolution on WSRs.

## AUTHOR CONTRIBUTIONS

Tommy Matthews, Christopher Hassall, and Ryan R. Neely III conceived the ideas and designed the systematic review methodology. Tommy Matthews carried out the review and screened the results. Tommy Matthews analyzed the data and interpreted the results with assistance from Christopher Hassall, Ryan R. Neely III, and Valery Melnikov. Tommy Matthews led the writing of the manuscript with contributions from Christopher Hassall, Ryan R. Neely III, and Valery Melnikov. All authors contributed critically to the drafts and gave final approval for publication.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

Data (Matthews, 2025) are available from Figshare: https://doi.org/10.6084/m9.figshare.29117585. The systematic review flowchart, second screening and systematic review spreadsheets, the exports from Web of Science and Scopus searches, and a reduced bibliography for the 41 selected papers are all included there.

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