Weather surveillance radar as an objective tool for monitoring bat phenology and biogeography

Phillip M. Stepanian¹ 2, Charlotte E. Wainwright¹, Winifred F. Frick² 3, Jeffrey F. Kelly¹ 4

¹Corix Plains Institute, University of Oklahoma, Norman, USA
²Ecology & Evolutionary Biology Department, University of California Santa Cruz, Santa Cruz, USA
³Bat Conservation International, Austin, USA
⁴Department of Biology, University of Oklahoma, Norman, USA

Abstract: Bats provide a wealth of vital services to humans, such as pollinating plants and managing populations of insects that act as agricultural pests and disease vectors. Despite their direct importance, it is inherently difficult to monitor bats across large spatiotemporal scales, in part due to their nocturnal activity and long-distance, high-altitude flights. Networks of weather surveillance radars provide continuous measurements of the airspace at continental scales, revealing the abundance, distribution, behaviour, and phenology of bats aloft. Using a network of polarimetric Doppler weather radars in the USA, we demonstrate applications of this technology to monitor large bat colonies, highlight recent discoveries made using radar surveillance of bats, and discuss future prospects for extending these techniques as part of a standardised system of global bat monitoring infrastructure.

1 Introduction

Bats are effective bioindicators of environmental conditions and provide a host of ecosystem services that humans rely on in agriculture and public health [1]. Bats also face a number of threats including landscape changes, loss of habitat, human encroachment, and spread infectious diseases [2]. With billions of dollars at stake in the USA alone [3], there is a growing imperative to monitor and assess bat populations so that conservation efforts can be applied efficiently and effectively. While the need for these observations exists, practical difficulties in obtaining standardised measurements of volant taxa have made developing objective surveillance techniques and protocols—especially over large spatiotemporal scales—an ongoing challenge [4].

The presence of bats on radar displays has been documented since the late 1960s, and the capability of using remote measurements of bat colonies for ecological applications was immediately recognised [5]. Despite the obvious potential, it was nearly 40 years later until the first long-term study of bat abundance and biogeography was performed using the US national network of weather surveillance radars (NEXRAD) in 2008 [6]. Since this pioneering study by Horn and Kunz [6], our fundamental understanding of these data has continued to mature, and analytical methods for extracting their underlying biological information have progressed [7]. In the following sections, we provide a brief overview of weather radar as it applies to bat observations, review recent research findings that have been made possible through radar observations, and discuss the potential of applying these techniques over large spatial (continental) and temporal (decadal) scales to obtain a general understanding of the effects of global change on bat colonies.

2 Weather radar theory and methods

The US network of Doppler weather surveillance radar operates at S-band and routinely detects airborne animals in flight, making it an ideal infrastructure for monitoring the ecology of the lower atmosphere (i.e. aeroecology) [8]. The network has been fully upgraded to dual-polarisation technology, allowing new possibilities for identifying and discriminating taxa aloft by their radar scattering characteristics [9]. Moreover, advances in electromagnetic scattering [10] and radar simulation [11] have enabled new methods for quantifying the number of organisms in the airspace [12]. By applying the suite of these techniques, we have enabled long-term analyses of the radar data archive to explore the ecology of bats.

3 Results of recent research

Weather radar has the capability of revealing the biogeography of bat colonies as they emerge into the airspace (Fig. 1), enabling quantitative mapping of population distributions. The ability to map these distributions over time will be especially important for determining the risks associated with anthropogenic and natural hazards. One example is determining the effect of severe weather events on bat mortality and habitat destruction, such as the case of Hurricane Harvey in August of 2017 (Fig. 2). In these instances, impacts on bat colonies are acute, but the overall long-term impacts on populations are not well-understood. Radar observations have the capability of providing surveys of these effects and their persistence in time.

Outside of extreme events, the persistent hazards of global change threaten to harm bat populations, further motivating radar surveillance. A previous study used 11 years of radar measurements to show that bats at five colonies exhibited behavioural responses to changes in weather and climate, engaging in riskier behaviour (i.e. emerging in brighter conditions) when experiencing drought [13]. In recent work, we found that a large bat colony has been steadily changing its migration phenology over decadal timescales, while increasing the number overwinter individuals at the site [14]. The ability of radar to provide nightly estimates of bat abundance allows observations across the full phenological cycle over decadal time spans (Fig. 3). Moreover, these rich datasets can be combined with corresponding meteorological and environmental observations to deduce the correlates of bat abundance, distribution, migration, and phenology. In such cases, routine radar surveillance can yield a better understanding of the ecological implications of global change, but more work is still needed to determine the spatial extent and wider impact of these changes.
4 Global prospects

Although much of the existing effort on weather radar surveillance of bat populations has focused on the NEXRAD network in the USA, weather radar infrastructure is widely considered a global imperative and much of the Earth's landmass is overlooked by weather radar (Fig. 4). Systems of shared calibration standards and methods have been developed by the weather radar community, and groups such as the World Meteorological Organisation continue to provide benchmark infrastructure goals for individual nations. As the value of weather radar in ecological applications continues to be realised, a growing multidisciplinary, multinational community of physical scientists, engineers, and biologists are developing the capacity to use these methods to benefit a wide breadth of stakeholders [15]. Strengthening research partnerships, cooperative data-sharing policies, and data quality standards hold the key to applying the global suite of radar infrastructure to some of the most pressing questions on large-scale influences of global change on bat populations. Furthermore, as remote-sensing continues to play a greater role in ecological and environmental studies, our capacity to observe animal systems at comparable spatiotemporal scales will motivate large-scale adoption of radar methods.

5 Conclusion

Despite being deployed with the mission of weather surveillance, NEXRAD has provided new information on the ecology, biogeography, and phenology of bat populations, revealing new and unknown information that would be difficult—if not fully impractical—to obtain through other methods. While radar certainly cannot replace field surveys and biologging for some applications, its capacity for providing standardised observations makes it an exciting prospect for inter-continental comparisons. Indeed, the global nature of weather radar infrastructure, coupled with common calibration standards and analytical methods, could yield a truly global view of bat ecology in a changing world.

6 Acknowledgements

P. Stepanian received funding for this work through a Marshall Sherfield Fellowship. We would like to thank the Turkish State Meteorological Service for maintaining and providing the WMO global radar site location database.

Fig. 1 20-radar composite of the south-central USA showing the large-scale ascent of bats following sunset. (Top) Aerial abundance of scatterers before sunset overlaid on local land cover. (Bottom) Aerial abundance of scatterers after sunset overlaid on nocturnal illumination. Brighter shades of red indicate more aerial scatterers.

Fig. 2 Four-radar composite of the south-central USA showing the approach of Hurricane Harvey along the Texas Gulf Coast. The pictured region is outlined in the large-scale map in the upper-right corner. Using dual-polarisation measurements, we have discriminated between reflectivity contributions coming from meteorological scatterers (grayscale) and animals aloft, providing a view of bats emerging into the strong northerly winds ascent of bats following sunset. (Top) Aerial abundance of scatterers before sunset overlaid on local land cover. (Bottom) Aerial abundance of scatterers after sunset overlaid on nocturnal illumination. Brighter shades of red indicate more aerial scatterers.
References

[1] Jones, G., Jacobs, D.S., Kunz, T.H., et al.: ‘Carpe noctem: the importance of bats as bioindicators’, Endangered Species Res., 2009, 8, pp. 93–115

[2] Voigt, C.C., Kingston, T.: ‘Bats in the anthropocene: conservation of bats in a changing world’ (Springer Open, New York, NY, USA, 2016)

[3] Boyles, J.G., Cryan, P.M., McCracken, G.F., et al.: ‘Economic importance of bats in agriculture’, Science, 2011, 332, pp. 41–42

[4] Loeb, S.C., Redhouse, T.J., Ellison, L.E., et al.: ‘A plan for the North American bat monitoring program’. Technical Report No. SRS-208, United States Department of Agriculture, 2015

[5] Williams, T.C., Ireland, L.C., Williams, J.M.: ‘High altitude flights of the free-tailed bat, tadarida brasiliensis, observed with radar’, J. Mammal., 1973, 54, pp. 807–821

[6] Horn, J.W., Kunz, T.H.: ‘Analyzing NEXRAD Doppler radar images to assess nightly dispersal patterns and population trends in Brazilian free-tailed bats (Tadarida brasiliensis)’. Integrative Comparative Biol., 2008, 48, pp. 24–39

[7] Chilson, P.B., Frick, W.F., Kelly, J.F., et al.: ‘Partly cloudy with a chance of migration: weather, radars, and aerocology’, Bull. Am. Meteorol. Soc., 2012, 93, pp. 669–686

[8] Kunz, T.H., Gauthreaux, S.A., Hristov, N.I., et al.: ‘Aerocology: probing and modeling the atmosphere’, Integrative Comparative Biol., 2008, 48, pp. 1–11

[9] Stepanian, P.M., Horton, K.G., Melnikov, V.M., et al.: ‘Dual-polarization radar products for biological applications’, Ecosphere, 2016, 7, pp. 1–27

[10] Mirkovic, D.; Stepanian, P.M., Kelly, J.F., et al.: ‘Electromagnetic model reliably predicts radar scattering characteristics of airborne organisms’, Sci. Rep., 2016, 6, pp. 1–11

[11] Stepanian, P.M., Mirkovic, D., Chilson, P.B.: ‘A polarimetric Doppler radar time-series simulator for biological applications’, Remote Sens. Ecol. Conserv., 2018, 4, pp. 1–18

[12] Chilson, P.B., Frick, W.F., Stepanian, P.M., et al.: ‘Estimating animal densities in the atmosphere using weather radar: To Z or not to Z’?, Ecosphere, 2012, 3, pp. 1–19

[13] Frick, W.F., Stepanian, P.M., Kelly, J.F., et al.: ‘climate and weather impact timing of emergence of bats’, IET Syst. Biol., 2012, 7, pp. 1–19

[14] Stepanian, P.M., Wainwright, C.E.: ‘Ongoing changes in migration phenology and winter residency at bracken Bat cave’, Global Change Biol., 2018, 24, pp. 1–11

[15] Bauer, S., Chapman, J.W., Reynolds, D.R., et al.: ‘From agricultural benefits to aviation safety: realizing the potential of continent-wide radar networks’, BioScience, 2017, 67, pp. 912–918

Fig. 3 Seasonal variability in the population of Bracken Cave from 20 March 1995 through 30 November 2017. Polar coordinates show the estimated number of bats (radius) as a function of day of year (angle) for each radar-sampled emergence (points). Point colour also corresponds to population size, with cool colours representing smaller populations.

Fig. 4 Global distribution of all active weather radar sites registered with the World Meteorological Organisation (WMO) as of April 2018. Note that several large radar networks have not been registered with the WMO database (e.g. China, Russia), but still represent near-comprehensive aerial coverage of their national airspace.