From Agricultural Benefits to Aviation Safety: Realizing the Potential of Continent-Wide Radar Networks

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Migratory animals provide a multitude of services and disservices—with benefits or costs in the order of billions of dollars annually. Monitoring, quantifying, and forecasting migrations across continents could assist diverse stakeholders in utilizing migrant services, reducing disservices, or mitigating human–wildlife conflicts. Radars are powerful tools for such monitoring as they can assess directional intensities, such as migration traffic rates, and biomass transported. Currently, however, most radar applications are local or small scale and therefore substantially limited in their ability to address large-scale phenomena. As weather radars are organized into continent-wide networks and also detect "biological targets," they could routinely monitor aerial migrations over the relevant spatial scales and over the timescales required for detecting responses to environmental perturbations. To tap these unexploited resources, a concerted effort is needed among diverse fields of expertise and among stakeholders to recognize the value of the existing infrastructure and data beyond weather forecasting.

It is increasingly recognized that migrating organisms have ecological effects on resident communities and ecosystems (Bauer and Hoye 2014), and these can represent a multitude of services and disservices that are relevant to human infrastructure, agriculture, and welfare. Services provided by migrant animals include economic benefits in the order of billions of dollars annually (Boyles et al. 2011); likewise, their disservices and human–wildlife conflicts (e.g., bird–aircraft collisions) produce significant costs, both economically, and in terms of human and animal lives (Allan and Orosz 2001, Marra et al. 2009). If we want to make better use of the services migratory animals provide, reduce their disservices, and mitigate human–wildlife conflicts, we require large-scale and long-term monitoring tools for quantifying and, ultimately, forecasting migrations across continents (Kelly and Horton 2016).

Among the various existing methods, radars are excellent tools for monitoring mass movements of aerial organisms. They have been used in ecological research for decades (e.g., Gauthreaux and Belser 2003) but have recently undergone a renaissance with the emergence of aeroecology as a distinct research field (Chilson et al. 2012a, 2012b, Shamoun-Baranes et al. 2014) and the recognition of the airspace as habitat that may also need conservation (Diehl 2013, Lambertucci 2014).

A variety of radar systems exists, from specialized bird- or insect-detecting radars to meteorological radars. Although the latter are primarily designed to detect precipitation, they can also detect a wide range of "biological targets." Meteorological radar has mostly been used in ornithological research (a) to quantify aerial biomass fluxes of birds, as well as flight speeds and directions across altitude profiles and over time (e.g., Dokter et al. 2011, Farnsworth et al. 2016); (b) to quantify migratory stopovers from low-elevation scans at the moment of synchronized mass departures around sunset (Buler and Dawson 2014); and (c) to detect locations and emergence behaviors at localized roosts (e.g., Bridge et al. 2016). Recent upgrades of meteorological radars to dual polarization have improved the distinction between meteorological and biological targets, between various taxa aloft (Stepanian et al. 2016), as well as their body alignments (Horton et al. 2016). Meteorological radar observations of bats have so far remained limited to mass foraging

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flights from roosts (Horn and Kunz 2007, Krauel et al. 2015). Interestingly, mass movements of small insects also show prominently in meteorological radar data, and their movements typically dominate meteorological radar returns during daytime (Nieminen et al. 2000, Drake and Reynolds 2012). Insects have the potential to provide tracers of wind in "clear-air" (nonprecipitation) conditions, but insect movements with a directed body orientation can be observed over large geographic areas (Rennie 2014), and the observed velocities may not be representative of the wind flow.

Because meteorological radars are organized in continent-wide networks within a permanent and continuously operational infrastructure, they can provide standardized long-term and large-scale monitoring and quantification of aerial migrants, in addition to their meteorological products. Using such networks for following aerial migrants would exceed the spatial and temporal coverage of current methods by orders of magnitude and provide essential information for groundbreaking and complementary applications, as well as answer important long-standing and novel questions in migration ecology and beyond (Kelly and Horton 2016).

As we will detail in the following, the products of radar networks are, or could be, relevant to a diverse array of stakeholders, including airport and windfarm operators, agricultural managers and farmers, public-health agencies, policymakers, and conservation practitioners (figure 1). However, as yet, the potential of existing radar networks has remained largely untapped for diverse reasons: First, the societal benefits of the existing radar infrastructure beyond meteorological purposes are not broadly recognized. Second, no standards have been established for quality, sharing, and archiving of "biological" radar data. Furthermore, meteorological radar operators tend to be focused on providing "clean" meteorological radar scans for aviation and short-term weather forecasting, often regarding biological signals as contamination to be removed instead of as a valuable data product. Finally, many operational applications such as early-warning systems for agriculture, flight safety, or the spread of vector-borne diseases remain to be developed.

Therefore, we aim here at raising the awareness of stakeholders (and of society as a whole) to the benefits of using radar networks for monitoring aerial migrations. To this end, we outline the services and disservices of aerial migrants for human well-being and ecosystem functioning and provide examples of how radars are currently used to monitor aerial movements. Furthermore, we highlight the challenges that need to be addressed regarding future extensions, which require joint efforts by meteorologists and ecologists, radar and signal-processing engineers, and information scientists.

Services and disservices of aerial migrants

Migrations involve immense numbers of individuals and constitute massive shifts of biomass that influence communities and ecosystems through the transport of nutrients, energy, or other organisms and through trophic interactions (Bauer and Hoye 2014, Hu et al. 2016). The sheer presence of migrants may create human–wildlife conflicts; their transport and trophic effects may be essential and economically beneficial but can also pose health risks or inflict damage.

Examples of the multitude of highly desirable services include Brazilian free-tailed bats (*Tadarida braziliensis*), which consume large quantities of migrant moths, such as corn earworm (*Helicoverpa zea*), one of the most important agricultural pests in North America (Boyles et al. 2011). Migratory bats have also long been acknowledged for their pollination services (of, e.g., columnar cacti and agave), which play vitally important roles in the plants' fruit production (Fleming and Valiente-Banuet 2002, Kunz et al. 2011). Similarly, migratory birds can enhance the dispersal of plant seeds or small invertebrates and therefore increase the genetic exchange between (fragmented) populations and potentially assist with ecosystem recovery (van Leeuwen et al. 2012, Viana et al. 2016). Among other ecosystem services, migratory bogong moths (*Agrotis infusa*) are an important food source for wildlife and aboriginal people in Australia (Green 2011). Although the overall economic benefit of these services is difficult to estimate, the value of, for example, Brazilian free-tailed bats to the agricultural industry in terms of crop damage avoided and reduction in pesticide use amounts to billions of dollars per year (Boyles et al. 2011).

In contrast to these services, migrants can also directly inflict harm or damage, either by feeding on crops or by affecting important ecosystem functions. For instance, a square-kilometer-sized swarm of locusts (e.g., *Schistocerca gregaria*) contains about 40 million individuals that will eat the same amount of food per day as about 35,000 people (*www.fao.org/ag/locusts/en/info/info/faq*). Similarly, many migratory goose populations have thrived over the past decades, and their foraging is increasingly causing conflicts with agriculture and raising concern for the functioning of their Arctic breeding grounds as a global carbon sink (Van Der Wal et al. 2007).

Another harmful effect of migrants is their role in the long-distance transport of parasites and pathogens of plants, animals, and humans (e.g., Reynolds et al. 2006, Altizer et al. 2011, Dao et al. 2014, Chapman et al. 2015): Many insects not only are agricultural pest species *per se* but also vector a variety of plant viruses (e.g., *Rhopalosiphum padi* aphids vector barley yellow dwarf virus). Also, bats may carry agents of serious human diseases (e.g., the recent Ebola outbreak in Western Africa originated from migratory straw-colored fruit bats, *Eidolon helvum*; Peel et al. 2013). And finally, migratory birds have regularly been blamed for spreading pathogens such as avian influenza virus, West Nile virus, or other disease vectors (e.g., Tian et al. 2015).

The often-immense numbers of migrants may create serious human–wildlife conflicts: For instance, the annual costs of bird collisions with aircraft are up to $1.2 billion worldwide (Allan and Orosz 2001)—a widely publicized example being US Airways flight 1549, which made an emergency landing on the Hudson River after colliding with a flock

*Figure 1. A variety of stakeholders can benefit from better using the services of aerial migrants, reducing their disservices and mitigating human–wildlife conflicts—a few of which are exemplarily depicted in the outer images. Photos and graphics (clockwise from top): (a) Flock of birds surrounding an airplane, copyright Konwicki Marcin (*shutterstock.com*). (b) Bird watchers during Batumi Raptor Count in Georgia, copyright Albert de Jong. (c) Visualization of bird migration data as identified from weather radars in Belgium and The Netherlands, modified from Shamoun-Baranes and colleagues (2016). (d) Veterinarians taking preventive measures to contain spread of avian influenza, copyright Irina Gor (*shutterstock.com*). (e) Lesser long-nosed bat (*Leptonycteris yerbabuenae*) pollinating a saguaro cactus, copyright Merlin Tuttle. (f) Locust swarm, copyright aaabbbccc (*shutterstock.com*). (g) Brazilian free-tailed bat (*Tadarida brasiliensis*) catching a moth, copyright Merlin Tuttle. (h) Distribution of Natura 2000 sites in the European Union (2014), copyright European Environment Agency (EEA). (i) Flock of foraging barnacle geese (*Branta leucopsis*) copyright Hugh Jansman. (j) Geese passing wind turbines, copyright roundstripe (*shutterstock.com*).*

of geese (Marra et al. 2009). Collisions with manmade structures such as power lines, wind turbines, or towers can disrupt their normal functioning and kill large numbers of birds and bats annually, but there is great variation in estimates of costs, fatalities, and their ecological significance (Cryan et al. 2014).

The potential of continent-wide radar networks

A prerequisite for managing the effects of migrants on ecosystems and their interactions with humans is basic information: Where are migrants going, when, and how many? These are fundamental questions in migration ecology for which radar methods are particularly useful as they can assess directional intensities, such as fluxes and migration traffic rates (Drake and Reynolds 2012), and/or biomass transported along migration pathways (Hu et al. 2016).

Small-scale, local radars are used at airports worldwide to enhance aviation safety by monitoring bird movements in near real time (Gauthreaux and Schmidt 2013). For instance, in the United States, the Netherlands, and Belgium, operational weather radars are used for warnings that inform ground-based bird control units of potential threats or that lead to changes in aircraft takeoffs and landings in order to reduce the risk of bird strikes (see, e.g., *www.flysafe-birdtam.eu*; Shamoun-Baranes et al. 2008). Some countries have also developed predictive (i.e., forecast) models from radar monitoring, which provide advanced warnings of potential risks from birds (Van Belle et al. 2007). However, such forecasts are still rare because robust predictive models can only be developed with data collected over several years at specific areas, and they need to convert bird densities to warnings that can easily be interpreted by air-traffic controllers, flight planners, and pilots.

Similarly, collision risk at wind turbines could be severely reduced with radar-based *shutdowns on demand*—that is, when radar monitoring is installed in regions with high numbers of wind turbines and the detection of high numbers of birds passing through will automatically interrupt operation (Marques et al. 2014).

Special-purpose entomological radars have been used for more than 40 years in applied research on the migration of insect pests (Drake and Reynolds 2012). These include investigations on pests such as African armyworm (*Spodoptera exempta*) and cotton bollworm moths (*Helicoverpa armigera*), rice planthoppers, Australian plague locusts (*Chortoicetes terminifera*), and aphids (Drake and Reynolds 2012), but there have been rather few attempts at operational use. Currently, radar inputs into decision-support systems take two forms: those from dedicated vertical-beam profiling systems and those from operational networks of weather-surveillance radars. An example of the first is the monitoring and forecasting of Australian plague locust (*Chortoicetes terminifera*), which rely on the inputs from autonomously operating insect-monitoring radars that detect major nocturnal movements (Drake and Wang 2013). Examples for the second are early warnings of pest insects invading cropping regions, which rely on meteorological and research radars integrated with trap catches and atmospheric dispersion modeling. Prominent among these are the warnings of mass immigrations of bird cherry aphids (*Rhopalosiphum padi*) and diamondback moths (*Plutella xylostella*) into southern Finland (Leskinen et al. 2011) or corn earworm moths into the southern United States (Westbrook et al. 2014), which have been identified from weather-radar outputs.

Thus, there are already many (economically) important applications of radar monitoring; however, most of these are local or small scale and target only a subset of the problems raised above. We could greatly benefit if we would extend them to the spatial scales relevant to migratory movements, to the longer timescales required for detecting responses to anthropogenic or environmental changes, and to other novel applications. Once such monitoring has become standard, long-term archives of aerial migrations would provide more complementary and comprehensive data than small-scale scattered studies and set an important baseline for detecting changes in spatial distribution and timing of aerial migrations in response to environmental perturbations such as large-scale habitat alterations or long-term climatic changes. Basic data on key migration routes and stopover sites provided by radar monitoring can be used to prioritize conservation efforts (Gauthreaux and Belser 2003) and support the establishment of aerial protected areas (Diehl 2013).

Furthermore, weather-radar networks would also provide the long-term data sets of broader spatial scope needed to develop robust (forecast) models and improve early-warning systems such that actions can be initiated before migrants actually arrive in an area of interest. Although still largely speculative, these networks could identify the pathways used by potential disease vectors, which may assist national health agencies in containing zoonotic diseases and prevent outbreaks by the early application of control measures—similar to the timely application of control measures that currently reduces the spread of insect agricultural pests into surrounding areas and controls massive infestations (e.g., Drake and Wang 2013).

Thus, standardized large-scale and long-term monitoring will not only lead to an improved understanding of animal migrations but could also ultimately support key areas of industry, such as agriculture and the (wind) energy industry, as well as facilitate the implementation of preventative measures to mitigate human–wildlife conflicts, and thereby assist in nature conservation and the planning of protected areas.

A roadmap for implementing continent-wide radar networks

Continental radar networks already exist for meteorological data and products, such as the Operational Programme for the Exchange of Weather Radar Information (OPERA network) in Europe (Huuskonen et al. 2014). In addition, Next Generation Radar (NEXRAD) is used in the United States, and large radar networks are also operational in Russia and China. Adapting these to monitor aerial migrations as recently initiated in Europe through the European Network for the Radar Surveillance of Animal Movement (*www.enram.eu*; Shamoun-Baranes et al. 2014) and in the United States (Kelly et al. 2016) would yield extraordinary added value and provide answers to the problems raised above. This would be a cost-effective solution for establishing long-term and near-real-time ecological monitoring and early-warning networks. However, although several milestones have been reached, there are a number of challenges that need to be addressed before we can tap these resources (see table 1 and points 1–5 below). Several of these challenges are probably common to all radar networks but there are also some specific differences. For instance, a major obstacle in Europe is the diversity in national weather radars in terms of radar types, settings during operation, and quality of data for biological purposes, as well as rules, regulations, and national cost models that may limit access to, and the exchange of, data.

Table 1. Recent milestones and remaining challenges in implementing continent-wide networks of weather radars.

	Topic	Recent milestones	Remaining challenges
Radar data collection, exchange, and infrastructure	Radar data collection and exchange	• Standardization of meteorological data formats • Setup of radar data centers, such as ODYSSEY (OPERA data center) and NOAA's national centers for environmental information (NCEI)	• Create European archive and harmonize national historical archives • Harmonize scanning schemes between countries • Provide open access to data • Exchange of complete raw radar data
	Radar hardware and settings	• Upgrades of weather radars to dual polarization	• Conform radar settings between countries • Improve low-altitude (less than 100 meters) coverage • Apply meteorological filters only after retrieval of biological signals
	Big-data information technology	• Algorithms for extraction of biological signals integrated into meteorological data center in Europe • NEXRAD data on Amazon Web Services	• Install (cloud-)computing infrastructure for processing radar data • Setup data portal for biological radar products
From radar data to biological information	Classification of biological targets, ground-truthing, and validation	• Automated algorithms for – generating vertical profiles for broad-front migration – distinction of rain-, insect- and bird-dominated cases – peak-emergence flights • Body shape and alignment from dual-polarimetric data • Cross-validation between bird, insect, and weather radars in some regions	• Develop algorithms for – accurate removal of precipitation – identification of insects and bird–insect mixtures – quantification of flocking and soaring bird migration • Cross-validate radar types in as-yet underrepresented regions
	Integration of data from multiple sources, visualization	• Correction methods for bias with distance from radar • Visualizations based on vertical profiles for data exploration and outreach	• Close gaps between individual radars • Merge scans of different radars • Combine data of multiple radars into contiguous velocity–density fields • Integrate radar data with complementary data on, for example, habitat use, land cover, ringing, individual tracking, etc.
	Operational services	• Regional flight safety model • Pest insect warning systems	• Develop continent-wide flight safety models • Develop warning systems for migration of disease vectors

The most important common challenges are probably to raise the awareness of public agencies, radar operators, and stakeholders of the value of radar networks beyond meteorology; to install additional data infrastructure and implement efficient classification algorithms; and to develop operational services for existing and novel applications, possibly complementing weather-radar data with other data (table 1).

Radar data collection and exchange. Although great progress has been made in harmonizing and exchanging meteorological data at national and international levels in Europe (e.g., by the EUMETNET OPERA program; Huuskonen et al. 2014), this still features high on the task list for biological data. Currently, many countries do not store and exchange the complete basic weather-radar data needed to extract biological information (*polar volume data*, also referred to as *level-2 data* in the United States). Furthermore, data quality substantially differs between countries, and radar settings may not always yield high-quality biological data, such as when filter settings are too exclusive for the weak (but highly detectable) biological signals or when biological signals are removed before data are stored. Finally, data policies that often vary between countries due to political and organizational differences need to be harmonized and should preferably be embedded in open-data policies.

Data infrastructure. Access to radar data is often the prime practical bottleneck for biological applications. Therefore, we need investments in infrastructure for data archiving and efficient access to data, in computational power for processing and analyzing the voluminous data, and in personnel for creating reliable, reproducible, and real-time radar products. Ideally, data would be archived in publicly accessible cloud storage, similar to the NEXRAD archive in the United States. These actions should lead to a well-designed and documented data infrastructure and workflow to support collaborative research and the development of sustainable services.

Toolbox of classification algorithms. Improving the distinction between biological and nonbiological targets in weather-radar data will also benefit meteorologists because biological targets frequently contaminate meteorological data, and clearly (or more comprehensively) excluding "bioscatter" will improve meteorological products (Rennie et al. 2015). However, the classification of biological targets also needs improvement; this can be achieved in part through cross-calibration efforts using different sensors under a broad range of environmental conditions and across geographic regions (Dokter et al. 2011). Furthermore, dual-polarization radar has great potential for improving target classification (Stepanian et al. 2016). Finally, robust algorithms for extracting animal migration parameters should be implemented into a basic "toolbox" that runs on all weather radars in a network.

Operational services. Once weather-radar networks are functional for monitoring aerial migrations, we should aim at providing sustainable services with access to archived and near-real-time data for research and development, as well as operational applications such as early-warning systems for agriculture, flight safety, or spread of vector-borne diseases. We realize that particularly the latter might still be largely speculative at this stage and will require much research to be accomplished, but nevertheless, their potential benefits would be enormous. Operational services should also include intuitive visualizations that convey the scope and magnitude of migration for diverse stakeholders.

Complementing (weather) radar data. The coverage of weather radars for weather surveillance is almost continuous, but this is not the case for biological targets. Therefore, the spatial coverage of existing weather-radar networks for biological information could be enhanced with additional sensors or supplemented with specialized radars. For example, small-scale biological radars can provide information on species composition in important areas along migration flyways (Zaugg et al. 2008, Hu et al. 2016) or sample the lower air layers that are not covered by weather radars, such as for impact-assessment studies in the wind-energy sector (Marques et al. 2014).

Furthermore, there is a wealth of complementary data that could be integrated with radar data, such as data on flight behavior based on individual biologging data, on species composition from citizen-science projects such as eBird (Sullivan et al. 2014) or Euro bird portal (*www.eurobirdportal.org/ebp/en*), or on the aerial migrants' load of other hitchhiking organisms investigated through aerial netting or epidemiological sampling (Laughlin et al. 2013).

In conclusion, to reach the goal of using operational weather-radar products to routinely monitor aerial migrations, we call for the weather-radar community and policymakers to recognize the value of their infrastructure and data (beyond weather forecasting), as well as making investments in operationalizing biological-radar products.

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