Title
Going through the motions: incorporating movement analyses into disease research

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**Abstract**

Though epidemiology dates back to the 1700s, most mathematical representations of epidemics still use transmission rates averaged at the population scale, especially for wildlife diseases. In simplifying the contact process, we ignore the heterogeneities in host movements that complicate the real world, and overlook their impact on spatiotemporal patterns of disease burden. Movement ecology offers a set of tools that help unpack the transmission process, letting researchers more accurately model how animals within a population interact and spread pathogens. Analytical techniques from this growing field can also help expose the reverse process: how infection impacts movement behaviours, and therefore other ecological processes like feeding, reproduction, and dispersal. Here, we synthesise the contributions of movement ecology in disease research, with a particular focus on studies that have successfully used movement-based methods to quantify individual heterogeneity in exposure and transmission risk. Throughout, we highlight the rapid growth of both disease and movement ecology and comment on promising but unexplored avenues for research at their overlap. Ultimately, we suggest, including movement empowers ecologists to pose new questions, expanding our understanding of host–pathogen dynamics and improving our predictive capacity for wildlife and even human diseases.

**Keywords**

Disease ecology, exposure, host heterogeneity, movement ecology, transmission.

**INTRODUCTION**

Disease ecology is a fairly young field, especially compared to epidemiology, which dates back centuries. The two fields overlap often and share a similar goal: to understand, predict, and (sometimes) prevent disease outbreaks. However, disease ecologists face at least two additional challenges unique to wildlife research. First, disease ecology frequently requires a broad, multi-species perspective that captures complex and counter-intuitive ecosystem dynamics; for example, invasive Burmese pythons' selective feeding within mammal communities has indirectly increased mosquitoes' feeding on rodents, in turn amplifying the Everglades virus, which causes encephalitis in humans (Hoyer et al. 2017). Second, and equally challenging, is the fact that behaviour is just as important for wildlife as for human disease, but harder for researchers to directly interrogate. Epidemiologists frequently use interviews and observational work to study how human behaviours such as sexual activity, international travel, or outdoor labour become risk factors for infectious disease – often directly inspiring interventions; animal behaviour, while just as important to disease transmission, is harder to observe and predict in nature.

Movement ecology, also a comparatively young field, uses high-resolution spatiotemporal data to make sense of animal behaviour. The ‘movement ecology paradigm’ treats movement as the outcome of behavioural decisions influenced by the interplay of animals’ internal states (e.g. physiological needs), external biological factors (e.g. predation or competition), and the physical environment (e.g. mountain ranges or water sources) (Nathan et al. 2008). Researchers tracking and modelling animal movement can extract behavioural states from telemetry and associated datasets, test hypotheses about what best predicts animal behaviour, and explain how individual behaviour scales up to landscape-level patterns of animal distributions. Recent advances in telemetry technology (Kays et al. 2015), the development of corresponding analytical methods (Long & Nelson 2013), and the integration of complementary datasets (e.g. acceleration data; Spiegel et al. 2015a; Wilmers et al. 2015) have all dramatically increased movement ecologists’ inferential power. Especially in light of these developments, ecologists can decompose the impact of individual behavioural heterogeneity on pathogen spread with much greater ease, making movement ecology a promising avenue for exploring the behavioural underpinnings of how and why diseases spread in wildlife.
Both movement and disease originate in animal behaviour at the individual level, and a feedback loop between the two emerges over time at broader ecological scales. For example, ecological theory suggests that the source-sink dynamics that naturally emerge between high- and low-quality habitat (respectively) can be reversed by an environmentally-transmitted disease, which turns high-quality habitat into an ecological ‘trap’ (Leach et al. 2016). In practice, animal movement is driven by decisions that balance this trade-off between habitat quality and disease risk, and behavioural polymorphisms might even evolve as a consequence (Getz et al. 2015). For example, in an anthrax-endemic region of Namibia, zebra (*Equus quagga*) demonstrate a pattern of partial migration, where dominant herds appear to migrate away from high-quality habitat during the anthrax season, leaving behind lower-ranking resident herds to graze despite the higher disease risk (Zidon et al. 2017). Researchers posing questions solely about movement (why would zebra migrate away from high quality habitat?) or disease (why do some zebra select for areas with higher anthrax exposure risk?) would miss the overall pattern.

Understanding ecological links between movement and disease has direct implications for the way researchers model, forecast, and simulate wildlife disease outbreaks. The most basic models in epidemiology treat disease transmission as a function of the number of healthy and infected individuals in a population, linked by a transmission parameter (β). Doing so implicitly combines contact rates and transmission efficiency into one rate (McCallum et al. 2017), but individual heterogeneity in both is universally recognised as an important contributor to disease dynamics in humans (Lloyd-Smith et al. 2005a) and animals (Paull et al. 2012), and heterogeneity in movement can be an important predictor of this variation (Spiegel et al. 2017a). Where tools in movement ecology can help measure, describe, and predict heterogeneity in transmission between hosts, there are opportunities to pose novel questions relating to the effects of movement on contact (e.g. how do social networks structure contact rates?), the effects of contact on transmission (e.g. how does duration and proximity of contact affect the pathogen dose transmitted?), and the impact of infection on movement (e.g. does infection decrease or increase future contacts?). According to appropriate complexity methods in modelling (Larsen et al. 2016; Getz et al. 2017), the degree to which movement data should be incorporated into disease models depends on the kinds of questions being asked; but simultaneously, the resolution of available data on both movement and disease, and the level of prior knowledge, constrain the questions that ecologists can feasibly answer (Fig. 1).

Here we synthesise the main ways that movement data are currently used to shed light on the processes underlying disease transmission, connecting animal behaviour to broad patterns of wildlife (and human) health. Researchers unfamiliar with one or both fields are encouraged to refer to Boxes 1 and 2 for short primers on disease and movement ecology, respectively. We begin by describing how tools and methods from movement ecology can inform our understanding of how movement affects disease, potentially improving epidemiological models by better representing behavioural variation. Subsequently, we explore a more tentative application showing how movement data might directly improve disease surveillance. Throughout, we emphasise case studies that have successfully applied movement-based methods in these ways and comment on particularly unexplored avenues and underutilised tools. Finally, we highlight the current state of synthesis work at the intersection of movement and disease ecology and discuss the advances in data and models needed to move the field forward. In doing so, we recommend relevant movement ecology tools for studying processes underlying disease transmission (Table 1) and conclude by highlighting the broader implications for conservation and human health.

### MOVEMENT AFFECTS DISEASE

Depending on a pathogen’s mode of transmission, different tools in movement ecology will be more or less suitable for exploring transmission risk. We make the broadest possible division, placing pathogen life histories along a spectrum between direct and indirect transmission (Fig. 2). Direct transmission refers to pathogens that require contact between an infected and susceptible animal at the same place and at the same time. Indirect transmission, on the other hand, describes pathogens that can occupy some intermediate reservoir or vector between hosts (i.e. a host of another species or an environmental reservoir like soil or water), making spatial overlap a more significant requirement than temporal overlap. Whether a pathogen is treated as directly or indirectly transmitted should depend on both the duration of time it can survive outside of hosts and its ability to disperse in the environment separate from host movement. Temporal overlap between animals matters less when infective stages survive for extended periods outside of hosts or when the infective stage moves independently (e.g. when environmental forces induce relatively long-distance dispersion, a feature common in marine systems where pathogens are often at the mercy of currents; Lafferty 2017).

Broad categories of infectious agents (bacteria, viruses, parasites, etc.) are unlikely to map neatly onto direct or indirect transmission. For example, some ectoparasites are directly transmitted among members of a social group (e.g. some species of avian lice; Rózsai et al. 1996), whereas others often spend time freely moving off-host (e.g. several tick species that infect reptiles; Sih et al. 2017). Some pathogens may also alternate between direct and indirect modes; for example, Zika virus and canine leishmaniasis are both vector-borne diseases with rare sexual transmission events. Similarly, influenza is usually directly transmitted through air or direct contact but can sometimes persist in the environment via fomites (non-living object or substance capable of carrying infectious material) for hours or days (Weber & Stilianakis 2008). Whether researchers choose to focus on spatial or spatiotemporal overlap, corresponding to indirect or direct contact, is likely to depend on the scale at which other host processes are modelled, and the spatial and temporal extent of the analysis (see Box 3).

### Direct transmission

Directly transmitted pathogens rely on contact between infected and susceptible individuals. Contact rates (process C
in Fig. 1) are most easily thought of based on the frequency and strength of interactions between animals in a population, a problem that lends itself naturally to network methods (Silk et al. 2017a,b). Meanwhile, the probability of transmission during contact ($P$ in Fig. 1) will depend largely on the duration and nature (e.g. grooming vs. fighting) of the contact needed for pathogens to spread, which can be incorporated into network analyses in various ways.

Networks are a statistical model that abstract population structure as a set of connected nodes, traditionally representing individual animals in the population. Edges indicate the connections between individuals, whether these are defined as interactions of a certain duration or individuals coming within a certain distance of one another. Such information can be displayed graphically through the use of directionality (arrows) or weight (line thickness). Directionality could indicate an epidemiologically-relevant behaviour that impacts the actors differently (e.g. grooming), while weight can be derived from the frequency or duration of such interactions (Cross et al. 2005). The components of a social network may ultimately be spatially implicit (i.e. animals’ position in the network cannot be projected onto a map), but these networks can be informed by movement data in cases where in-person behavioural observation is impractical or infeasible, making them a valuable tool for reconstructing the spread of directly-transmitted disease. Networks can also be constructed in the context of indirect transmission, but these might require different data (e.g. capture histories from an array of traps; Davis et al. 2015) or the inclusion of a time lag to emphasise the spatial component of transmission (e.g. Sih et al. 2017). For a visual example of these concepts, see Fig. 3.

Most networks extracted from movement data are proximity-based social networks (PBSNs). They can be constructed using either special proximity sensors or from movement data using a spatiotemporal threshold value to designate contact between animals (e.g. within Mc meters for at least Tc time units; Farine & Whitehead 2015). Observed association patterns in social networks are often compared to expected patterns in null models (e.g. ideal gas model) or randomised networks to test hypotheses about the mechanisms underlying social structure (Farine 2017; Silk et al. 2017b). For example, by randomising the order of daily movement paths within each individual, rather than between individuals (as is typical in most network randomisation methods), Spiegel et al. (2016) developed a method to assess sociality separate from associations resulting from the spatial structure of the environment. An extension of this approach allowed for the identification of the locations of interactions and revealed the sex-specific patterns underlying the network structure (Spiegel et al. 2017b). These networks have been a key part of efforts to understand how ticks are transmitted in sleepy lizards (Tiliqua rugosa), reptiles with an unusual life-long pair breeding pattern that may facilitate tick transmission (Sih et al. 2017).

Social networks can provide insights into disease spread even in the absence of explicit disease data (Craft & Caillaud 2011). Different species’ social behaviour may correspond broadly to different network structures and corresponding outbreak dynamics; for example, social hierarchies may

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**Figure 1** A movement-focused modelling space in epidemiology. Incorporation of movement at different temporal scales can be used to address pathogen transmission-related questions at three levels (vertical coloured planes). Transmission can be treated either as a single process (as commonly done in SIR models, where S are susceptible, I infectious and R removed individuals – see Box 1; purple plane), a concatenation of a contact process $C$ and probability $P$ of pathogen transmission during contact averaged over individuals (orange plane), or implemented at an individual level (green plane). In addition, transmission can be considered to occur within a homogeneous population, a network of homogeneous groups or subpopulations (metapopulation), or a spatially continuous heterogeneous population. Each labelled dot indicates a unique level of complexity that can be incorporated into the transmission process, while the spanning arrows imply that additional complexity can be incorporated at several different temporal scales (horizontal arrows) and population-structures (vertical arrows).
comparatively limit the rapid spread of epidemics, whereas ‘gregarious’ species with connected, unfragmented social networks are prone to major outbreaks (Sah et al. 2017b). At the population level, the overall characteristics of a network (e.g. average degree of nodes, path lengths, and edge densities) can be vital for understanding the hypothetical implications for transmission (Craft 2015), including vulnerability to epidemic spread (Porphyre et al. 2008; Craft et al. 2011). In a meta-analysis, Sah et al. (2017a) found that modularity (i.e. the strength of division of a network into separable components) has a surprisingly limited effect on outbreak size and duration, especially for higher levels of modularity. However, fragmented networks with high subgroup cohesion still experience comparatively limited and brief outbreaks. In a relevant case study, Hamede et al. (2009) used proximity sensors to build a comprehensive contact network of Tasmanian devils (Sarcophilus harrisii) in a population at risk from the introduction of a directly transmitted parasitic cancer. The entire population was connected in a single network, allowing the spread of a pathogen from a single individual – and therefore, preventing most containment efforts in the event of an outbreak (Fig. 3).

At the individual scale, networks can show where individual heterogeneity in transmission occurs (Lloyd-Smith et al. 2005b; Perkins et al. 2009; Paull et al. 2012). Similar metrics to those employed at the population level can also describe single nodes or edges within a network, potentially illuminating differences among individuals within a population (Silk et al. 2017a; White et al. 2017). For instance, Weber et al. (2013) found that degree (the number of connections a given node has to other nodes), closeness (effective distance between an individual and all others in the network), and flow betweenness (a measure of the role of a particular node in connecting all other pairs of nodes in the network) were associated with tuberculosis infections in badgers (Meles meles). Because causality could not be determined, the researchers concluded that either an individual’s network position could affect infection risk or that infection could affect network position. By showing how heterogeneity among hosts propagates an infection through a susceptible population, analyses such as these could help identify super-spreaders, which in turn could help improve estimates of $R_0$ (i.e. the expected number of secondary cases produced by a single infection in a completely susceptible population; see Box 1: Lloyd-Smith et al. 2005b).

The use of proximity data synchronised with GPS and accelerometer data can help better identify social interactions that are epidemiologically relevant (Nathan et al. 2012; Brown et al. 2011; Paull et al. 2005b; Voss et al. 2010). In some cases, the highly connected individuals, referred to as super-spreaders, can be particularly active transmitters and infect disproportionately more susceptible individuals than other hosts do. In cases where shedding reaches a new host and this exposure event leads to infection, this produces an effective contact; what is considered an effective contact will vary with the mode of transmission of the pathogen in question.

In both humans and wildlife, outbreak dynamics are most readily modelled using a mathematical compartmental systems framework: after dividing the population into epidemiologically-relevant compartments (viz., susceptible: S, infected: I, and recovered: R), difference or ordinary differential equations are used to describe the transitions of individuals between the disease classes over time. Typically these models make an assumption of spatial homogeneity, random contact among individuals, and rapid mixing of individuals within compartments. The course of infection is typically summarised for populations either via an incidence (the rate at which new cases arise) or prevalence (the proportion of the population infected) curve. If at least a low level of prevalence is maintained at all times, a disease is considered endemic. In contrast, an epidemic starts from a handful of introduced or new index cases and spreads throughout a susceptible population as an outbreak before burning itself out. The latter occurs because the proportion of susceptible individuals in the population has either dropped below a threshold density or individuals have altered their behaviour to avoid contact with infected individuals. When an epidemic is truly global (defined by infection across multiple continents), it is referred to as a pandemic. In wildlife, epizootic and enzootic serve as parallel terms to epidemic and endemic. Diseases that originate in wildlife and spread to humans are termed zoonoses and are conventionally of special interest in disease ecology. The process of spillover of zoonotic disease into human populations is complex and often poorly understood due to the complexities of human-wildlife contact. Conversely, spillback refers to the process by which a zoonotic disease is introduced by humans into novel animal host populations (whether domesticated or wild).
Box 2. A Movement Ecology Primer

Movement ecology has developed as a field that draws on telemetry data to explore the causes, mechanisms, and patterns of animal movement, as well as understand its consequences on the ecology and evolution of individuals, populations, and communities. *Telemetry* refers to the process of transmitting and recording the positions of an animal and represents the primary means of detecting animal movements. Early telemetry research relied upon *Very High Frequency* (VHF) radio signals to triangulate the positions of collared or radiotagged individuals. The individual positional fixes obtained can be referred to as relocations, and when treated consecutively, they are often called a *trajectory* or path. The relatively coarse temporal resolution of most relocation data from classical radiotagging methods limits the ability of movement ecologists to observe and differentiate among *fundamental movement elements* (FMEs; e.g., a walking vs. trotting step) that make up the movement path of an individual. However, the relatively infrequent or irregular fixes emerging from such devices can still be used to evaluate patterns of *space use* and *habitat selection*. For example, even coarse movement data can aid in characterising the manner in which an animal utilises its *home range*, which represents the area it traverses while foraging, mating, and caring for young. These areas have been delimited in a number of ways, including: *minimum convex polygon* (MCP) methods, which simply construct a boundary around the outermost points of a trajectory; and *utilisation distribution* (UD) methods, which offer more information regarding the frequency of space use within the home range. Recently, alternative methods that more explicitly account for the temporal component of movement data have been proposed, including the *time-local convex hull* (T-LoCoH) method and *Brownian bridges*, among several others. Even with sparse datasets, these methods are expected to create meaningful generalisations of space use and can form the basis of spatial overlap analyses that aim to determine the level of shared space use among monitored individuals. Several methods for understanding individual and population level habitat selection, such as *resource selection functions* (RSFs), can also be used with relatively coarse movement data. These methods aim to identify the habitat types that an animal prefers, indicated by disproportionately greater use of a habitat than expected based on its availability on the landscape, and create predictive maps of space use.

Today, the majority of movement ecology research depends upon more advanced satellite technology, referred to broadly as *Global Positioning Systems* (GPS), to record animal locations at finer spatial and temporal resolutions. Even with this technology, consecutive relocations typically span a mix of FMEs. Nonetheless, a variety of summary metrics can be used to describe the path, the most basic of which are the *step length* (the Euclidean distance between consecutive relocations) and *turning angle* (the angle of one step relative to the step immediately prior). Higher resolution relocations can also enable *behavioural analyses*, which often rely on *path segmentation* methods to split a movement trajectory into segments that look quantitatively similar (often based on those simple summary metrics). Such analyses can help determine the *behavioural state* of an individual at specific points in time. These states occur at coarser time scales than FMEs but represent short-lived phenomena that can be inferred from GPS data. Similar analyses can also allow for the clustering of longer sequences of behavioural states that are considered collectively as *canonical activity modes* (CAMs; e.g., resting or foraging), which are also readily observable in modern telemetry data. For example, foraging is a CAM that often consists of a variety of behaviours, including searching, eating, and perhaps vigilance, among others. A full movement path, however, often consists of a series of CAMs, and *movement syndromes* are used to describe movement patterns at the scale of an entire trajectory, enabling discrimination among types of individuals (e.g. territorial vs. nomadic individuals). With recent technological advances to the telemetry units worn by animals, supplementary data sets, such as those obtained using *accelerometers* that measure changes in velocity in three-dimensions, have enabled the evaluation of movement behaviours at even finer spatiotemporal scales, getting researchers closer to observing FMEs. Similarly, the advent of *proximity sensors*, which record when two collared animals are within a specified distance of one another, has allowed researchers additional insight into the *spatial proximity* of monitored individuals. These data can be used to inform *contact networks*, which map the associations among individuals in a population.

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that apply more broadly. For example, existing tools can appropriate sampling schemes offer a basis for statistical inferences monitored in a study population (Williams et al. 2014).}

Clustered observations reflect spatial regions that individuals frequent, and can indicate areas where encounters among individuals (tagged or untagged) are more likely. Applying techniques to identify such clusters in data from multiple animals (Webb et al. 2008; Seidel & Boyce 2015; Van Moorter et al. 2016) can aid in identifying population-wide aggregation points with potential epidemiological significance. These aggregation points might reflect underlying environmental heterogeneity (e.g. waterholes) or social contacts (e.g. leks) (McNaughton 1988; Carter et al. 2009); regardless of the mechanism driving aggregation, these locations are likely to be important for estimating relative exposure risk. Various methods can help distinguish social and environmental causes of such aggregation patterns (e.g. Spiegel et al. 2016; Borcherding et al. 2017), potentially offering a way to assess transmission risk.

Areas of dense use are also identifiable through the construction of utilisation distributions (UD), which illustrate the relative frequency distribution of the location of a particular individual over time (Van Winkle 1975). UDs are most commonly derived using kernel density estimation techniques (Worton 1989). Methods for estimating space use at broader scales, especially estimates of seasonal range size and overlap, have been included in epidemiological models. For example, Ragg & Moller (2000) used radiocollars, in conjunction with other methods, to track the microhabitat selection of both active and denning feral ferrets (Mustela furo), a vector of bovine tuberculosis (Mycobacterium bovis) in New Zealand. Ferret movements were found to be concentrated in grazed areas and at ecotones between pastures and vegetation cover, thereby increasing their risk of transmitting tuberculosis to possums and livestock. Similarly, Conner & Miller (2004) used cluster analysis on mule deer (Odocoileus hemionus) location data to identify population units, and used kernel density estimation to delineate seasonal ranges for each population. Subsequent analysis showed that winter ranges rarely overlapped (<1%), likely due to their smaller size, whereas summer ranges had >22% overlap among population units. Therefore, researchers concluded that summer ranging behaviour was likely responsible for the spread of chronic wasting disease (CWD) among subpopulations, whereas winter ranging behaviour had the potential to amplify CWD prevalence within a sub-population if an infected individual was present. In an extension of the study, Farnsworth et al. (2006) used area estimates of summer, winter, and individual home ranges to frame regression models at different scales. They found that movements within individual home ranges had the greatest implications for CWD exposure, highlighting the potential of high-resolution movement data to alter our understanding of the mechanisms underlying observed patterns of transmission.

Indirect transmission

In the case of pathogens and parasites that are transmitted indirectly (Fig. 2), the processes by which one host sheds a pathogen and another host is exposed are independent and might rely upon different host behaviours (e.g. defecation for the former and foraging for the latter). Tools from movement ecology offer a way to consider these processes separately from the perspective of the infected individual and susceptible individual at various time scales (sub-hourly to multi-week time, as depicted in Fig. 1).

High resolution movement data (i.e. sub-hourly; Fig. 1) enable researchers to estimate the frequency and duration of encounters with known pathogen hotspots on a landscape (e.g. mosquito breeding sites at standing water). Though practical considerations might limit the number of animals that can be monitored in a study population (Williams et al. 2014), appropriate sampling schemes offer a basis for statistical inferences that apply more broadly. For example, existing tools can identify associations between habitats or time periods and animal presence, thereby offering insight into overlaps with infectious sites (Fig. 4). Further, if movement data help identify behavioural drivers (e.g. resource distribution and its seasonal changes), then insights from the monitored subset of the population could be used to mechanistically model encounter probabilities or factors contributing to shared space use (e.g. Cross et al. 2005; Spiegel et al. 2015b).

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Novel methods that consider the temporal autocorrelation inherent in movement data enable more detailed home-range
Box 3. Balancing Scales: Simultaneous Modelling of Movement and Epidemiological Processes

Deciding on a spatiotemporal scale for epidemiological models is usually a function of the timescales of host and pathogen processes, including temporal aspects of transmission like latency, persistence in the environment, or replication rates during early infection. The rates of biological processes might not map directly onto the models we build, if the temporal scale of data is necessarily coarser due to the resolution of available movement data. However, some of the greatest successes of movement ecology have involved explicit model formulation with attention to spatiotemporal resolution of processes (Lyons et al. 2013), potentially offering a template for integrated work. We outline some brief guidelines as follows:

**Space pixel.** The corresponding spatial resolution $S$ is related to time through the diffusion relationship:

$$\Delta S = \delta(\Delta t)^{1/2}$$

This is where movement comes in: $\delta$ is a movement diffusion constant estimated from empirical data and will vary among organism types. An alternative approach is to use a velocity relationship:

$$\Delta S = v\Delta t$$

for organisms that mainly execute directed movement at average velocity $v$ at fine time scales. Since empirical tracking data has repeatedly shown that movements of animals (and humans) are often super diffuse, we suggest that former approach as generally more favourable (Raichlen et al. 2014; Spiegel et al. 2015a).

**Coarse graining.** Going from the scale of individual transmission upwards to emergent processes like landscape structure, epidemic wavefronts, or even range shifts requires proportionally aggregating data and model structure, a process typically termed coarse graining. There are various levels of coarse graining, each representing close to a one magnitude of size step up. Coarse graining requires aggregating over a union of pixels using an appropriate integral kernel. Integral kernels can take several forms including the bounded uniform, truncated Gaussian, or other more idiosyncratic choices. Optimal kernel choice can be guided by wavelet analysis of movement data.

**Time pixel.** The minimum time resolution should be based on some fraction of the most fundamental cycle pertaining to the problem; for example, movement data might be recorded at a resolution $\Delta t$ of every 15 min, though this is much shorter than the typical interval in epidemiological models.

**Temporal scaling.** Increasing scales of temporal aggregation can provide different results and absorb more noise in data by matching biologically-relevant timescales. For example, if $\Delta t$ is 15 min then 100$\Delta t$ is approximately one diurnal cycle, 3000$\Delta t$ is approximately a lunar cycle, and 10 000$\Delta t$ is approximately the length of one season in a four season year. Models can also be downscaled, which might be appropriate under highly data intensive conditions. However, as fine-scale processes emerge at finer scales, models might lose predictive accuracy without incorporating finer data or processes.

**Appropriate complexity.** At various spatiotemporal levels of resolution different epidemic models might apply and the question arises as to the appropriate level of complexity in the model (Larsen et al. 2016). For example, models should include a within-host component at the level of $\Delta t = 15$ min, while epidemiological models might include daily rates of detection and isolation of individuals at diurnal levels of resolution, or could include transmission rates that exhibit seasonal variation if epidemics last several months or more. Additionally, incorporation of movement into models might require individual-based approaches for the finest scales of analysis (Getz 2013).

**Multiscale modelling.** As data and models are aggregated, models can be run to reflect the multiple timescales on which movement and epidemiological processes operate. Wavelet decomposition of movement data can inform the most important concurrent scales of movement processes; similar analyses can be performed with time-series epidemiological data, when available.
some of the most developed in movement ecology – can offer predictions regarding where susceptible individuals might be exposed to disease. Habitat-selection methods, such as resource-, path-, or step-selection functions (RSF, PSF, and SSF, respectively), can illuminate landscape features and types preferred by individual hosts or the population as a whole (Leclerc et al. 2016). These methods, used to infer the probability of use of any given resource unit within the range of a population, quantify which habitats animals select within their range (Boyce & McDonald 1999; Manly et al. 2002). By comparing points used by animals in the population to those available within their range, RSFs provide a statistical model of habitat preference (Boyce et al. 2002). In the context of disease, these models can identify habitats where pathogen deposition and, thus, exposure are most likely to occur based upon their relative probability of selection. For example, Morris et al. (2016) built an RSF for elk (Cervus elaphus) ranging in the presence of soil-borne anthrax (Bacillus anthracis) in southwestern Montana. Based on the preferences of the elk and a parallel evaluation of the landscape features that enabled long-term persistence of anthrax spores (with ecological niche modelling), Morris et al. (2016) mapped the areas of highest risk to the elk population.

In cases where pathogens or parasites are difficult to study but follow predictable patterns of occurrence on a landscape, RSFs and other movement tools could allow researchers to identify potential hotspots for vector-borne or environmental transmission (Fig. 4) using geographic information system (GIS) technology. The application of GIS tools is particularly suitable when vector preferences on a landscape are well understood, as in studies of the use of fragmented forests near agricultural land by ticks (a vector for Lyme disease; Allan et al. 2003; Brownstein et al. 2005) or mosquito use of standing water for breeding sites (Perkins et al. 2013). The relevance of these approaches will be strongly dependent on how far vectors can move, as well as the importance of dispersal in the life cycle of vectors and the overall prevalence of disease. A similar application can easily be imagined for pathogens maintained in soil, such as anthrax (Bacillus anthracis) or plague (Yersinia pestis); or in water, such as cholera (Vibrio cholerae) or cryptosporidiosis (Cryptosporidium parvum). The pathogens in all four of these examples follow predictable

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Figure 3 Networks for disease research. Network analyses can serve to identify particular contact network structures that might be conducive to disease spread through a population and identify individuals within networks that make disproportionate contributions to the transmission of a disease (Ryan et al. 2013). A network with relatively low edge density and high path lengths might prevent a directly transmitted parasite (or pathogen) from spreading through a population (networks a and b). Contrastingly, a network with high edge density and low path length could facilitate parasite spread through a population (networks c and d). In addition, the position of the first infected individual (shaded in black) in a network might facilitate or inhibit a parasite from spreading. Individuals with relatively high degree or node betweenness could be super-spreaders (networks a and c), whereas individuals positioned at the periphery of a network, with lower degree and node betweenness, might cause transmission to fade out (networks b and d). At both the population and individual levels, these network characteristics depend on resource distribution, social relationships, and ultimately, the movement behaviours that arise from both. It should also be noted that the same general principles would apply if this schematic were imagined as a spatial network instead of a contact network, with nodes representing locations rather than individuals.
patterns of occurrence and persistence based on abiotic environmental variables (Carlson et al. 2017). The dual RSF framework helps researchers to identify whether host populations select for areas with high infection risk. In addition, such methods can indicate whether certain individuals are using these features more than others, offering insight into the heterogeneity of exposure throughout the population.

**DISEASE AFFECTS MOVEMENT**

Movement tools may also provide a more direct (but under-explored) tool for disease surveillance, as infection often affects host behaviour in observable ways. Pathogens can alter host movements either through vigor loss (i.e. the appropriation of resources towards an immune response) or host manipulation (direct chemical or physical modification by the pathogen). Examples of infection-induced behavioural shifts range from *Cordyceps* fungi in arthropods, which cause hosts to climb to the upper part of a plant before death (Roy et al. 2006), to *Toxoplasma gondii* in rats (*Rattus norvegicus*), which results in higher activity levels and loss of fear in infected hosts (Berdoy et al. 2000). Importantly, such changes can alter movement trajectories (Murray et al. 2015; Cross et al. 2016) in ways detectable by movement tools (e.g. risk-taking behaviour or a dramatic shift in habitat preference), potentially allowing researchers to identify shifts in individuals’ behavioural patterns once individuals become infected.

Movement trajectories can be characterised by sets of metrics extracted from consecutive relocations. These include step length (the distance between two consecutive points), relative turning angle (the angle between the trajectory indicated by two points relative to that inferred from the previous step), and persistence (the tendency of a movement to persist in a particular direction). Since these telemetry data are discrete, if they are not sufficiently fine-scaled, they cannot be used to characterise fundamental movement elements (FMEs, Box 2; Getz & Saltz 2008). They can, however, be used to cluster movement path segments into canonical activity modes (CAMs; Fig. 5; Getz & Saltz 2008) using thresholds, clustering, and behavioural change-point techniques (Gutenkunst et al. 2007; Gurarie et al. 2009, 2016; Van Moorter et al. 2010).

The above movement trajectory metrics might differ sufficiently between healthy and infected individuals to allow them to be used to identify an individual’s disease state. Further, infection with a pathogen could affect daily activity budgets, potentially altering the number or distribution of change points seen across a day. The segmentation of movement paths into CAMs or, at a finer scale, behavioural states (Nathan et al. 2012), represents an active area of study in disease ecology (Edelhoff et al. 2016). For example, Cross et al. (2016) established that infection with mange (*Sarcoptic scabei*) in wolves (*Canis lupus*) was associated with decreased daily movements, with later stages of infection reducing total distance more than earlier stages. In addition, infected wolves spent significantly less time in an active behavioural mode (defined as hourly movements greater than 50 m) than healthy wolves, with degree of infection once again affecting activity level. Similar comparisons can be performed with data collected at a coarser scale, as exemplified by Murray et al. (2015) who demonstrated that the disease state was related to differences in home-range size of coyotes (*Canis latrans*)

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**Figure 4** Calculating spatial risk from movement data. For vectors with known associations to abiotic environmental layers (e.g. land cover or soil type) and movement or presence data. Combined, these maps of resource selection can produce a map of overall transmission risk. Alternatively, a similar approach could be used with a pathogen, such as anthrax, that relies on mappable soil characteristics, such as calcium levels and pH (Mullins et al. 2013). The other layer would correspond with host habitat preferences, including indicators of watering hole locations (i.e. Mean Normalised Difference Water Index; MNDWI) and graze or browse quality (i.e. Normalised Difference Vegetation Index; NDVI).
infected with mange. Movement data derived from complementary sensors, on the other hand, offer researchers even deeper insight into the impacts of disease on movement behaviour. Accelerometers, for example, enable the detection of tremors in individual paths and can help differentiate between bold vs. submissive walking gaits, which can be indicative of different disease states. In a study of cockroaches (Blaberus craniifer), Wilson et al. (2014) extracted the vectorial dynamic acceleration (VDA; Shepard et al. 2008), a metric for characterising the tremors in an animal’s movement, and found that the dynamism in each stride decreased with progressing fungal infection.

While the application of movement ecology to disease diagnostics remains relatively unexplored, an ability to identify infected individuals from movement tracks could be highly useful in systems where diagnosis is difficult, invasive, or lethal (especially important for species of conservation concern). These methods might also enable researchers to infer the approximate onset time of symptoms, in turn improving disease models. The increasing availability of detailed movement data provides researchers an opportunity to develop and validate new methods along these lines.

SYNTHESISING MOVEMENT AND DISEASE

Ecology, as a scientific discipline, advances through the interplay of data, models, and theory: work at the interface of movement and disease ecology is rapidly growing on all three fronts. We briefly comment on how models can bridge data-driven understanding into theoretical results, and then present a systematic literature review showing the biases in how different movement tools are currently used to explain and predict disease dynamics.

Scaling models to theory

Compartmental models (Box 1) are a nearly universal tool for studying human and wildlife diseases (Anderson et al. 1992; Keeling & Rohani 2008) and have been applied to a broad range of host–pathogen systems, with numerous extensions for host-age effects, pathogen-strain effects, or even the influence of pathogens on host behaviour. Compartmental models, however, are not easily adapted to account for the effects of
landscape and population spatial structures on risk of infection (Fig. 4). Accounting for this level of variation requires a representative sample of individuals within the population to be tracked and their contact rates with other individuals (direct transmission) or infectious environmental locations (indirect transmission) recorded. Mechanistic models allow researchers to upscale individual patterns (such as behavioural rules or contact patterns) to a broader population and are frequently used to validate or test experimental results. For example, disease outbreaks are easy to project on simulated networks, allowing researchers to confirm hypotheses about how modularity and fragmentation link animal social structure to outbreak size (Sah et al. 2017a,b). However, directly upscaling animal behavioural rules into spatiotemporal patterns of disease may require researchers to build individual- or agent-based models (IBM, ABM; Grimm et al. 2005).

More specifically, IBMs can use step length, turning angle, canonical activity mode distributions, habitat or resource preferences or even various network-based metrics to generate likely movement paths for all individuals in the population. With basic assumptions about transmission rates as a function of contact duration, these trajectories can be used to simulate disease outbreaks on real landscapes with ‘real’ animal movement principles. A number of IBMs that incorporate mechanistic movement rules to explore disease dynamics have been constructed (Bonnell et al. 2010; Dion et al. 2011; Tracey et al. 2014; Belsare & Gompper 2015). One of these (Bonnell et al. 2010) used individual host energy levels to generate movements toward higher resource patches. These foraging decisions ultimately drove microparasite transmission dynamics among red colobus monkeys (Procolobus badius) as they shifted their distributions on the landscape in search of food.

An obvious drawback of IBMs compared to compartmental models is the high computational demand associated with running simulations at this scale, though this limitation is becoming less prohibitive with the increasing availability of high performance computing. Perhaps a more serious limitation, IBMs involve many more parameters than compartmental models, thereby increasing difficulties associated with verification and validation procedures (Filatova et al. 2013). In addition, IBMs generally include stochastic elements, which can make statistical inference using IBMs very challenging (Hartig et al. 2011). While recent methodological advances have overcome some of these limitations, they remain impediments to the broader application of IBMs in disease modelling. Continued efforts to synthesise movement and disease ecology, however, are likely to inspire the development of new solutions for translating risk (based on movement behaviours on a specific landscape) into generally applicable rates for epidemiological models.

We also caution that mechanistic models (individual-based or otherwise) that explicitly incorporate movement rules from...
empirical data might not be transferable across space, or even across seasons or years. For instance, if environmental change alters behaviour (e.g. annual migration targets shift in response to climate change), even mechanistic models based on empirical movement data might become inaccurate. This could be problematic for predicting pathogen dynamics in response to rare movement events (e.g. atypical long-distance dispersal events) or transmission (e.g. cross-species spillover events). Some tools exist in epidemiology to address model building based on limited data (e.g. fitting R hats for rare spillover diseases; Blumberg & Lloyd-Smith 2013; Kucharski & Edmunds 2015), but this problem requires special attention in the context of movement research and given the ongoing anthropogenic changes to local and global environments.

Current State of the Synthesis

In a review of Web of Science, we found 70 papers published between 2000–2017 using movement tools in disease research (see Supplementary Appendix 1 for details). For the purposes of the review, we did not include agent-based modelling studies without empirical basis, though we noted they followed similar biases. This literature review revealed a notable bias across study organisms (Fig. 6). Most studies focused on pathogens that can spillover to human and domestic animal populations, including bovine tuberculosis (Mycobacterium tuberculosis), anthrax (Bacillus anthracis), brucellosis (Brucella abortus), foot and mouth disease (FMD; Aphthae epizooticae), and chronic wasting disease (CWD). Hosts with relatively large bodies (e.g. ungulates, carnivores, and mesocarnivores) were substantially more common than those with small bodies (e.g. birds, reptiles, amphibians, and small mammals). These biases might reflect the high data requirements for many of the methods in movement ecology, meaning that only extensively monitored systems are regularly considered at the level of individual hosts. Alternatively, the taxonomic bias in hosts could be indicative of technological limitations that, until recently, prohibited the tracking of animals with smaller bodies with advanced instruments. It should be noted, however, that taxonomic bias patterns closely track phylogenetic hotspots of zoonotic and agriculturally relevant pathogens.

For the 70 studies that met the criteria for inclusion, all methods of analyses used by the researchers were sorted into four broad groups: spatial overlap, habitat selection, network analyses, and behavioural analyses. In several cases, more than one of these methods were used in a single study, resulting in a total of 91 analyses. Spatial overlap was the most frequently used analysis, with 41 cases applying some form of overlap method. These ranged from examinations of home range dynamics (e.g. Yockey et al. 2013) to studies that attempted to measure the number of contacts between animals (e.g. Woodroffe & Donnelly 2011), often using proximity sensors to do so (e.g. Marsh et al. 2011). Habitat selection analyses were also quite common, with 24 cases using selection functions (e.g. Morris et al. 2016) or performing basic comparisons between habitat types (e.g. Parsons et al. 2014). Similarly, studies that drew upon the wide array of network analysis tools were fairly common, with 19 constructing some form of network, often with the use of proximity sensors (e.g. Hamede et al. 2009). The least common form of analyses encountered during the literature review were behavioural analyses, where researchers explicitly measured the probability of a particular behaviour (e.g. dispersal; Caron et al. 2016) or compared individuals of two different behavioural classes (e.g. migratory vs. resident; Pruvot et al. 2016). Only six cases of behavioural analysis appeared in the resulting literature. Since the role of behaviour in influencing disease dynamics is well established, this represents an under-explored avenue for investigation of disease systems.

There was a demonstrable correlation between the mode of transmission exhibited by a pathogen and the methods ultimately selected to study it. Although some studies (13) did not identify a transmission mode, many emphasised whether the pathogen studied had a direct (20) or indirect (11) transmission route. Many studies (26), mostly on bovine tuberculosis, mention that both transmission modes are possible, but researchers often selected their methods based on one or the other (4 of the 26 emphasise direct transmission, while 7 focus on indirect). Of those studies focused on the indirect mode of transmission, spatial overlap methods were used in approximately 56%, habitat selection in about 44%, network analyses in nearly 17%, and behavioural analyses in only 6%. By contrast, studies of direct transmission used network-based analyses (46%) and behavioural analyses (17%) more frequently, but spatial overlap methods were nearly as common as in studies of indirect transmission (50%), and habitat selection methods were far less common (13%). These differences are to be expected: pathogens with particular transmission modes require the use of tools and methods relevant to the movement processes that underlie them.

DISCUSSION AND FUTURE DIRECTIONS

Complex patterns in ecology frequently emerge from simple rules at fine scales. Basic rules of animal behaviour drive the complex interplay of animal movement and disease dynamics, with serious implications for wildlife and human health. Incorporating movement behaviour into epidemiological models could improve predictions of disease dynamics, provided the additional level of complexity is handled correctly (Getz et al. 2017). While we have highlighted specific well-developed pairs of pathogen transmission mode and analysis methods (like networks and direct contact pathogens, or landscape models and vector-borne disease), we also note that many pathogens exploit several transmission strategies, and researchers will correspondingly need several methods in these cases. Developing protocols that include movement data in basic disease research, and vice versa, will be an important first step towards making these advances more feasible – and towards making broad advances in ecological theory, as some disease ecologists have begun to do with network methods (Sah et al. 2017a).

Movement tools will likely increase in value with ongoing improvements in biologging technologies (Kays et al. 2015). For example, advancements in radar and radio-frequency technologies allow tracking of a broader range of insect movements (Kissing et al. 2014), offering the potential to include these movements when considering vector-borne disease...
dynamics. Further, accelerometer-based data and very-high resolution GPS tracking (e.g. 1 Hz fix rates) will help researchers parse movement tracks at an even finer scale than current path segmentation methods allow (McClintock et al. 2017). In doing so, proximity-based social networks could be further informed with the behavioural states of individuals, potentially clarifying the epidemiological relevance of such points of contact (Spiegel et al. 2016; Sih et al. 2017; Spiegel et al. 2017b). The decreasing costs of these technologies could soon offer opportunities to monitor entire populations, thereby shifting researchers from extrapolating risk across a population to measuring contact rates directly. More comprehensive surveillance may also enable the development of models that more accurately infer dose exposure, based on duration of contact between animals and infected hosts or environmental reservoirs, vastly improving models of the heterogeneity in transmission efficiency.

Though the host–environment and host–pathogen interactions reflected in movement data can offer significant insight into disease dynamics, important processes might also occur at the pathogen–environment (or vector–environment) interface. In benthic marine systems, for example, suspension-feeders that filter large volumes of water while feeding can be particularly vulnerable to infection by microparasitic pathogens floating in the water (Lafferty 2017). This accumulation process has been modelled through the incorporation of particle diffusion (Bidegain et al. 2016), but the nature of these pathogens and their deposition makes the precise tracking of their movements in such dynamic environments very difficult. Thus, the validity of forecasts based on host movement alone is in question when pathogen-environment interactions (e.g. pathogen movement, rates of growth or decay, or the length of vector life history stages) occur at time scales comparable with the host–pathogen interactions themselves (e.g. lengths of latent and infectious periods). When response time scales are comparable, coupled host-pathogen–environment models are required. Though this has not been the emphasis of much of the recent work in movement ecology, the expansion of methods and technologies to accurately track minute particles through three-dimensional space is a frontier worthy of exploration. The resulting models could replace assumptions regarding the diffusion of such particles and further aid in our understanding of contact processes in highly dynamic environments.

Although we have focused on host populations, these tools also apply to multi-species transmission, such as in the spillover of wildlife diseases into livestock, or spillback of diseases from domesticated animals into wildlife (Barasona et al. 2014). Furthermore, these methods could just as easily be used to assess the risk of zoonotic spillover into human populations. Currently, ecological niche modelling is a popular proxy for zoonotic disease risk, but this only summarises high-level landscape patterns (often treating host-pathogen systems as one coupled phenomenon); replacing these, or combining them, with movement models like RSFs can more accurately characterise average or seasonal patterns of host movement, and therefore risk to human health. In particular, in the case of pathogens that affect free-ranging and often migratory hosts such as bats (i.e. Ebola, Marburg, or Nipah viruses), overlap analyses could illuminate potential risk zones for future spillover events. With additional data collection using advanced monitoring devices, researchers can move beyond treating overlap (spatial or spatiotemporal depending on the pathogen or parasite in question) as a proxy for contact; in fact, we note the clear but unexplored potential for animal movement studies to act as part of a realtime early warning system for difficult-to-surveil zoonoses.

With a common language and mutual appreciation for their respective disciplines, disease ecologists and movement ecologists can collaborate to help solve pressing problems. Like Ebola or Nipah, most emerging diseases spill over from wildlife (Jones et al. 2008). Controlling such diseases is difficult, and interventions can be controversial (e.g. wildlife cullings), infeasible (e.g. mass wildlife or livestock vaccination), or ineffective; for example, culling badgers can spread bovine tuberculosis because badgers will move into treated areas (Woodroffe et al. 2006). Studying animal movement might help predict disease spread, help explain why some interventions fail, and identify new interventions, such as wildlife relocations or vaccination. Furthermore, movement ecologists can benefit from considering how parasites alter animal movement, thereby accounting for otherwise unexplained variation in movement among individuals. Advances in disease diagnosis, combined with new technologies that remotely monitor an animal’s physiology and motion make this an opportune time for studies to embrace both disease ecology and movement ecology.

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AUTHOR’S CONTRIBUTIONS

ED and WG conceived of the idea. ED and DS contributed equally to the writing and revision. CC, OS and WG contributed to framing, writing, and editing. ED, DS and WG created the figures.

REFERENCES


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