Review

The Ecology of Human Mobility

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Mobile phones and other geolocated devices have produced unprecedented volumes of data on human movement. Analysis of pooled individual human trajectories using big data approaches has revealed a wealth of emergent features that have ecological parallels in animals across a diverse array of phenomena including commuting, epidemics, the spread of innovations and culture, and collective behaviour. Movement ecology, which explores how animals cope with and optimize variability in resources, has the potential to provide a theoretical framework to aid an understanding of human mobility and its impacts on ecosystems. In turn, big data on human movement can be explored in the context of animal movement ecology to provide solutions for urgent conservation problems and management challenges.

Human Mobility and Big Data

Mobility is a central component of human activity, receiving significant allocation of resources, including time, commodities, and energy, with transportation now accounting for 20–25% of global energy use [1]. Development of an understanding of the patterns and drivers of human mobility is, therefore, a key to optimizing this critical element of human lifestyles in a world increasingly facing resource limitation and growing human impacts on the biosphere.

Until relatively recently, studies of human mobility have focused at the extreme ends of the spectrum of the scale of movement patterns. At the smallest scales (metres to kilometres), the field known as human behavioural ecology [2] has applied models of optimal foraging theory derived from animal ecology to identify the key factors shaping foraging subsistence behaviour in hunter–gatherer communities [2]. At the largest scales (thousands of kilometres), the drivers of migrations of humans within and between countries have been analysed in terms of optimization (see Glossary) of ‘push’ and ‘pull’ factors [3,4]. However, these studies focus on only a very limited part of the spectra of human mobility as it occurs in society today, because the majority of these movements occur in the context of the day-to-day existence of the 50% of the world’s population that lives in cities [5]. Empirical studies of human mobility at these scales were galvanized a decade ago in a seminal paper that based inferences on human movement patterns on the analysis of circulation of banknotes in the United States [6] (Figure 1). This contrasts with studies of animal behaviour where technological developments starting with the ring-banding of birds [7] and culminating with state-of-the-art animal borne satellite tracking tags [8] (Figure 1) have allowed accurate and detailed tracking of the individuals of many species and have been a major driver of the theory and study of animal movement ecology [7].

From the outset of the study of animal movement it has been deemed ethically acceptable to attach or implant tracking devices to animals to generate detailed data sets of movement patterns. Until very recently, however, this has not been the case for humans, hence the use of
proxies for the tracking of human movement patterns such as banknotes [6] or the distribution of family names [8]. However, the arrival of the geolocated smartphone, effectively a tracking device now voluntarily carried by billions of people, has generated massive volumes of geo-referenced movements, which now constitute big data (see [9]). The data from these devices describe human mobility and behaviour with unprecedented resolution, and for the first time in human history, individual patterns of human movement [9–11] and interactions [12–14] can be revealed at almost every spatial scale with a remarkable degree of detail, immediacy, and precision (Box 1). With the advent of smartphones and other new technologies such as

![Figure 1. Timeline of Technological Advances in Animal Movement and Human Mobility. Timeline shows the technological advances from animal movement and human mobility research since 1900 to present. Pop-up satellite archival tags (PSATs) are data loggers with a means to transmit the collected data via satellite developed for gill-breathing animals that spend little time at the surface. The International Cooperation for Animal Research Using Space Initiative (ICARUS) is a new animal tracking antenna on the International Space Station that would allow smaller tags to send data back through the low-orbit satellite. The dollar bill represents the first published paper on human mobility, which tracked records of dollar bills across the United States as a proxy for human movement [6]. Abbreviation: GPS, global positioning system.](image-url)
wearable fitness trackers, data on mobility at scales relevant to the day-to-day lives of the majority of human populations exceed by many orders of magnitude the combined total of all data that are available for any other species on the planet. At the same time, the sheer scale combined with the difficulties of manipulating and analysing these big data has meant that the study of patterns in human movements available from these sources has largely been the province of complex systems analysts. Not surprisingly, results have been interpreted using the paradigms, such as broad distributions and complex networks, of a research community dominated by computer scientists and physicists. For the most part, analyses of these data have taken a ‘data mining’ approach [15] and little effort has been invested in studies that are hypothesis-led or based in ecological theory. We argue that ecological approaches could inform a deeper understanding of the drivers of human mobility given that such data are much wealthier in motivational content than any data available for non-human subjects. Only human mobility couples movement patterns to both social media and electronic interactions that can explicitly link movement to individual motivations and outcomes [14,16]. Together, this can provide unique insights into the relationships between patterns of human mobility and the impact of humans on the ecosystems they inhabit and in so doing, offer solutions to the pressing conservation and management challenges that now confront society. Here, we review the most salient studies of human mobility and show how these contribute towards a framework for the ecology of human mobility.

**Human Mobility: Insights into Populations from Individual-Based Data**

The accessibility and volume of geo-referenced data sets of individual human movements have propelled the search for emergent patterns at population scales. In the following sections, we provide examples of analyses that have expanded our understanding of patterns in human movement, their links with social structures within societies and show how these reveal parallels to animal studies.

**Statistics of Displacement**

The analysis of individual human trajectories shows that the net displacement of humans between two consecutive positions at time \( t \) and \( t + \Delta t \) (i.e., \( \Delta r = |r(t + \Delta t) - r(t)| \)) can be described by a power law distribution, \( P(\Delta r) \sim \Delta r^{-\alpha} \), where \( \alpha \) is a characteristic scaling exponent. Consequently, individual trajectories cannot be easily characterized by a single displacement, since both short and long movements can occur. Such a power law distribution is characteristic of a Lévy distribution (i.e., Lévy flight, or random walks) with the scaling exponent \( \alpha < 2 \) (e.g., [6,10]). The underlying scaling of human movement thus conforms to the same pattern described for many animals, notably marine predators. For these species, including sharks, bony fishes, reptiles, and seabirds, Lévy flight is a behaviour that optimizes the rate at which an animal encounters prey in patchy environments [17,18].

**Site Fidelity**

Similar to many animals, the most frequent human movements occur around a small set of highly visited locations, typically homes, workplaces, shops etc. [19,20]. A high degree of site fidelity is thus common to the movement of both many animals (e.g., breeding grounds, foraging areas, resting sites) and humans. The displacement range (measured by the gyration radius) for humans can be described by a power law distribution with exponent \( \alpha = 1.65 \) truncated by an exponential with a characteristic distance of 350 km [10]. This outcome is a consequence of very heterogeneous mobility patterns, with the majority of individuals moving within a restricted range, whereas others travel over a region that is orders of magnitude larger (with a gyration radius ranging from 1 to 1000 km). For animals, site fidelity is thought to be an outcome of predictable resource availability [21] and there are clear parallels for human movements given that the urban environments are also very predictable in the distribution of resources (schools, homes, workplaces, etc.).

**Glossary**

**Animal movement ecology:** describes the patterns, mechanisms, drivers, and effects of the movement of whole organisms from mammals to microbes. The movement ecology paradigm, a related concept [76], characterizes animal movement as dependent on four components: internal state (reason to move), motion (ways to move), navigation (timing and direction of movement), and external factors that can affect the movement.

**Big data:** is widely agreed that big data share the characteristics of the ‘three Vs’: ‘volume’ – data sets are very large and increasing in volume; ‘velocity’ – data arrive in a continuous stream with ever increasing velocity; and ‘variety’ – data are provided by a wide range of sources (e.g., sensors, social media, transaction records, video) that is both structured and unstructured.

**Collective behaviour:** refers to the coordinated and emergent behaviours that occur when individuals aggregate into groups. Classic examples are the behaviour of fishes in schools or the flight of flocks of birds. Emergent properties involve the transfer of information among group members and group decision making so that movements are synchronized.

**Data mining:** a phenomenological approach to data exploration where there are no a priori concepts as to what would be a ‘useful’ outcome from the analysis, such as the support or rejection of theoretical predictions. It can be both predictive, in which case models used to predict system states are developed directly from the data, and descriptive, in which analyses uncover patterns within large data set.

**Optimization:** in the study of animal movement ecology, optimization is the theory that animals, through natural selection, seek to maximize benefits and minimize costs of decision making in a landscape of variable resources. Two critical elements of this process include ‘currency’ (the factor that the animal must maximize), which in movement contexts is typically energy intake, and ‘constraints’, which are the limitations placed on the currency, for example, search or transit time.
Collective Patterns of Movement

Aggregation occurs in both animals (e.g., fish, birds, mammals) and humans [22]. The behaviour imposes constraints on movement patterns and a variety of models derived from physics have been used to understand and quantify the collective patterns that emerge from these behaviours. Analyses of commuting fluxes (recursive travelling between home and work) have been a common subject of studies of collective patterns in human mobility. The distributions of these fluxes are heavy tailed [23–26], that is, distributions whose tails are not exponentially bounded. Spatial distributions of animal movement show similar patterns of recursive travel, in many cases between foraging, resting, and reproductive habitats. These distributions of travel have been modelled using approaches based on Brownian motion such as Brownian bridges that aid definition of home ranges and quantify patterns of space use within the range (e.g., [27]).

Relationships between Human Mobility and Social Interactions within Populations and Meta-Populations

Daily encounters among individuals are the main driver of the formation of social relationships [28]. Individuals tend to spend more time with people who are friends and family, making a strong link between physical location and social relationships. Consequently, the location of any individual can be predicted from the locations of friends and family and bonds of friendship can be predicted from spatial and temporal co-occurrence of multiple individuals that are visited regularly by any individual. The probability of being ‘socially connected’ (i.e., having friendship bonds with others) decays with distance \( d \) as \( d^{-a} \) [29,30]. Geolocated data on social interactions, derived from telephone communications or interactions through online social networks, have been used to measure the relationship of social bonding and geography [30–32]. Bluetooth [33] and radiofrequency identification tags have been developed that store proximity data to map patterns of social networks (the SocioPatterns project; http://www.sociopatterns.org/) [34]. This latter approach has been used to map contact patterns in schools [35,36], a hospital ward [37], and conferences [38]. The concept of movement by humans in physical spatial networks [12] has now been expanded into virtual, digital space through the analysis of proximity networks in online virtual worlds [39] and social media platforms [12,39]. This use of human movement data to understand social interactions is paralleled by a growing interest in the use of multi-individual tracking strategies to study the structure and dynamics of social networks in populations of wild animals [40,41].

The Ecology of Human Mobility

The aforementioned examples suggest that the ecological principles that explain the movement patterns of marine and terrestrial animals also govern human mobility. A central paradigm of the study of animal ecology is that a detailed understanding of movement offers insights into how variability in the distribution of resources across landscapes affects the performance of individuals and, in turn, population-level demography [42,43]. We argue that this concept is equally applicable to the study of humans and can provide new insights into emergent behaviours of human populations and the impacts of their movement patterns on the ecology of ecosystems they inhabit. Furthermore, the analytical approaches developed to link mobility to social networks offer a powerful tool for gaining insights into the social organization of animal species [44] (see Outstanding Questions). We illustrate these points with key examples in the following sections.

Epidemics

Compartmental reaction–diffusion models [45] have long been used to describe the dynamics of population invasion and range expansion in populations of a broad range of species (e.g., [46]). These models are now also being applied to human populations, notably in the context of the dynamics of epidemics, where individuals (or ‘agents’) are divided into different classes
Human mobility has been studied at different levels of resolution. (A) Individual trajectories of 10,000 people across the United States derived from geolocated Twitter data from June 2015. When analysed as random walks, these data reveal scaling laws that describe the paths followed by humans, the most basic being the displacement that occurs in a certain time window, \( \Delta r = r(t + \Delta t) - r(t) \), whose distribution is heavy-tailed and consistent with a power-law \( P(D) \sim D^{\alpha} \) of exponent \( \alpha = 1.59 \) or 1.75. (B) To illustrate this point, we show the analysis of the worldwide trajectories of 3 million Twitter users in June 2015, which shows a displacement distribution consistent with a power law of exponent \( \alpha = 1.0 \). The inset shows the superdiffusive scaling of the average displacement with time \( \langle \Delta r \rangle \sim T^b \), with \( b = 1.27 \). (C) The network formed by fluxes of people commuting between counties in the United States [data from US census 2001 (see http://www.census.gov)], only the top 20% of the dominant fluxes shown. Fluxes are explained by population distributions and distances between locations (encapsulated by the gravity and radiation models of movement). (D) The fit of the data in (C) (boxplots) to the gravity model (red lines) \( N_{ij} \sim A N_i^a N_j^b / d_{ij}^g \), where \( N_{ij} \) is the number of people living in county \( i \) and working in county \( j \), \( N_i \) (\( N_j \)) is the population of county \( i \) (\( j \)), and \( d_{ij} \) is the distance between the centroids of counties \( i \) and \( j \), with parameters \( a = 0.35, b = 0.37, g = 1.00 \).
depending on their infectious state. How agents meet and spread the infection follows patterns dictated by human mobility [47] and are thus central to these models. A metapopulation approach is commonly used in order to cope with the computational challenge of having a vast amount of agents that human populations can provide, particularly on whole country or global scales [48]. These models operate both at large scales and also within constrained environments such as hospitals, schools, or conference venues and at these smaller scales, have been used to study the spread of disease and to model appropriate health-care responses. Recently, Vanhems et al. [49] showed that in a hospital environment, health-care workers were the subpopulation of individuals who were more likely to act as ‘super-spreaders’ of contagion and thus should be targeted for vaccination [50]. On larger, global scales, the impact of multiscale networks of human mobility has been shown to be crucial in the forecasting of infection routes for global pandemics [23,50,51]. Notably, these have shown how the advent of air transportation has facilitated epidemic spread. For example, in the Middle Ages the wavefront of infection of the Black Death spread at around 200 km/year [52], whereas today transport rates of humanity have accelerated, so that such fronts no longer exist [23]. Importantly, knowledge of human patterns of mobility and social networks offers the opportunity to model the spread of contagion to reduce the impact of disease [23]. Such models show that epidemics spread quickly to remote locations (through air transportation connections), whereas at local scales, the spread patterns follow highly frequented routes typical of commuting flows. Understanding the impacts of human transport systems for epidemics is directly relevant to the diffusion of pathogens and invasive species in ecosystems, as many of these rely on human vehicles, notably airplanes, cars, and ships for long distance transport. These allow pathogens and invasive species to expand their distributions across natural barriers to movement, broadening their range and impact [53].

Diffusion of Innovations, Opinions, and Cultural Traits

The diffusion of innovations can be modelled in a manner similar to that of epidemics. The basic premise of the model is that adopters can be classified as innovators or as imitators and the speed and timing of adoption of an innovation depend on both the degree of their innovativeness and strength of imitation among adopters. Both mobility (through face-to-face contact) and social networks contribute to the social contagion of innovations [54].

The diffusion of cultural traits such as words [55], language [56], and opinions [24] has been shown to be dependent on human mobility in both real and digital space (i.e., face-to-face contacts mediated through movement and online connections), although the dynamics of social interchange might vary. Recent studies have used databases provided by geolocated tweets to study the stability of culture and the impact of seasonal tourism on the heterogeneity of cultural patterns within society [56]. For animals, the biological and evolutionary significance of social learning has remained a controversial issue, despite clear evidence of this process in fish, reptiles, birds, and mammals [57]. The analysis of movement patterns to inform the study of social learning in humans might prove a useful direction for future investigation of parallels between social learning in animals and the development of culture in humans.
Behaviours during Stress
In the case of natural disasters or emergencies in confined environments, understanding the collective behaviour of crowds might help devise better strategies to cope with such events [58,59]. Studies of human movement during panic situations show that optimal strategies for escape from hazardous situations, such as a smoke-filled room, involve a mixture of individualistic behaviour and collective ‘herding’ instinct [60]. At larger scales, mobile phone data have been used to track the movements of people after the 2010 earthquake and subsequent cholera outbreak in Haiti [61], Hurricane Sandy in the United States [62], and other disasters [59]. Rapid description of such movement patterns via data from mobile phones and other devices could allow aid and disaster relief to be targeted more effectively for communities. Overall, such analyses provide compelling evidence that human escape reactions conform to the patterns of coordinated collective behaviour described for animals. These result in the synchronized behaviours exhibited by schooling fish and flocking birds under attack [63]. The finding that animal escape responses rely on rapid and efficient transfer of information among individuals, and the diffusion of reactions among neighbours [64], might help develop predictive frameworks for the response of humans to emergencies or stress, a major issue for public safety.

Linking Human Mobility and Animal Movement for Conservation and Management Outcomes
The analysis and conceptualization of the big data produced by geolinked devices and social networks allow patterns of human and animal movement to be superimposed and synthesized to recognize, understand, and solve urgent conservation and management problems. Three key examples of this approach are outlined here.

Fishing
Accurate and reliable data on the behaviour of fishers fundamentally underpin the successful management of a fishery. The analysis of big data provided by smartphones and social networks is poised to revolutionize this process, replacing conventional surveys that are limited both in accuracy and in spatial and temporal extent due to cost [65]. Mobile phone apps produce synoptic, real-time data that not only reveal patterns of fishing pressure and catch and effort data [66], but also connectivity in movement patterns of fishers that can also be used to track the risk of the spread of invasive species. At the scale of stocks, information from social networks can be used to optimize fishing practices across entire fisheries to minimize bycatch, enhance sustainability, and reduce environmental impacts [67]. Globally, the introduction of automatic ship identification systems makes it possible to observe the behaviour and movement patterns of entire fishing fleets and to map compliance with management strategies. For the first time, this offers a cost-effective means to address the issue of illegal fishing on the high seas [68].

The Illegal Trade in Wildlife
Trade in wildlife is now acknowledged to be a global crisis. The practice is pushing the most valued species to extinction and depriving many developing countries of billions of dollars of resources. The quantities of animals and plants involved are truly staggering, as are the losses to the front-line park ranger community tasked with protecting these resources; it is estimated that over one thousand rangers have been killed in the line of duty during the last decade (United Nations Environment Programme; http://www.unep.org/documents/itw/ITW_fact_sheet.pdf).

Geolocated devices can play a key role in combating this trade and in safeguarding the lives of rangers. In India, the smartphone app ‘Heji’ allows rangers to monitor the movement and sighting patterns of tigers in protected reserves, and to also place encounters in context, by adding information on water resources, forest fires, and importantly, suspicious human activity.
Similarly, ‘Wildapp’ is used by rangers in Africa to collate social and environmental data and track movements of rangers and encounter rates with dead animals. Wildapp is producing data vital to determining poaching rates (https://ilabafricastrathmore.wordpress.com/2016/09/20/the-wild-app-helping-conserve-our-wild-animals/). In Kenya ‘tenBoma’ collates information from rangers and satellite remote sensing, and uses mobile phones confiscated from poachers to expose the social networks that facilitate the trade (http://www.ifaw.org/sites/default/files/IFAW-tenBoma.pdf). The latter program illustrates an important point: the same big data and software platforms that can aid conservation can also facilitate the illegal trade in wildlife.

Human Mobility As a Threat to Animals

Our transport systems are responsible for the deaths of many millions of animals and trillions of insects each year [69]. Road and train networks fragment habitats, form barriers to migration, act as conduits for the spread of invasive species, and are a source of light, noise, and

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**Box 2. Ship Strikes and Marine Megafauna**

Maritime traffic volumes and vessel speeds have grown rapidly over the last few decades. Shipping is responsible for the transportation of 90% of global trade [83] (http://www.imo.org) and in 2014, there were 89,464 registered vessels undertaking commercial passage [81]. Figure shows the average monthly density of all vessels, calculated on a logarithmic scale per 1 km² grid cell for 2014. There has also been an emergence of new trade routes in areas that were once relatively untrafficked, such as the northern sea route through the high Arctic, where there is projected to be average annual increase in shipping of 20% per year over the next 25 years [82]. The global increase in shipping has led to a corresponding increase in the number of ship strikes on marine megafauna, particularly on those species that spend long periods of time near the surface [83] such as whales, sirenids, turtles, and whale (Rhinodon typus) and basking (Cetorhinus maximus) sharks. There are numerous documented cases of both serious injuries and mortalities caused by ship strikes on this fauna [84]. Ship strikes are exacerbated by the size and the speed of vessels and the likelihood of collision increases in situations where high volumes of maritime traffic overlap with areas important to marine megafauna such as migratory corridors, feeding, or breeding grounds [84,85]. This threat is of most concern for small populations in near-shore habitats with high levels of maritime traffic. For example, collisions with vessels are a causative factor that have prevented population recovery in the North Atlantic right whale (Eubalaena glacialis) despite the cessation of commercial whaling [86]. Similarly, vessels are implicated in the decline in abundance of some whale shark populations [87] and of some marine turtles (e.g., Chelonia mydas), which display strong site and migratory route fidelities to areas that overlap with high densities of shipping [88].

Mitigation through Mobility

The combination of fine-scale information on ship movements through the AIS system [68] and advances in our understanding of animal movement behaviour through extensive telemetry [7] has enabled real opportunity for effective mitigation. Since US NOAA regulations lowered ship speed limits in the vicinity of right whale habitats in 2008, deaths from vessel strikes have declined [89] and devices such as Whale Alert: A Tool for Reducing Collisions Between Ships and Endangered Whales [90] are now being developed to initiate real-time mitigation. Big data approaches combined with insights from refinements of animal movement models provide the potential for real-time dynamic and cost-effective mitigation of this otherwise growing threat.
particulate pollution that alter animal behaviour and survivorship. Dead and injured animals and insects on roads and verges can attract scavengers that are then also at greater risk of mortality [70].

Until recently, mitigation of these effects has been difficult because the quantification of roadkill is time consuming and effort intensive, limiting the spatial and temporal scope of data collection. However, there is a recent proliferation of smartphone apps that apply citizen science approaches to register roadkills. These apps provide data that allow ranking of species vulnerability, seasonal patterns, and monitoring and detection of rare species in roadkills. Importantly, the data provided by the apps allow identification of roadkill hot spots and landscape connectivity issues across broad areas, so that managers can take evidence-based actions to mitigate effects. The data can also be used to increase vehicle safety by incorporating warnings of collision hot spots into global positioning system navigation systems for cars [71]. These issues and mitigation approaches are paralleled in marine systems where ship strike poses a major threat to marine megafauna (Box 2).

Future Insights on Human Mobility – Lessons from Animal Ecology and Solutions for Management and Conservation

The aforementioned examples show how studies of emergent patterns in human trajectories at different spatial scales are consistent with theory and observations derived for animal movement. Thus, ecological movement theory can inform our understanding of biological and social processes in human societies beyond the phenomenological approach prevalent to date. How do we facilitate this shift? One obvious route forward utilizes the approaches of earlier studies that examined the movement patterns of hunter–gatherer societies and large-scale migration patterns [2]. Many of these applied an optimization framework equivalent to optimal foraging theory in animal ecology [72,73] to describe and understand the drivers of movement patterns. Such frameworks are clearly applicable to analyses of big data because they are robust in the face of differences in patterns of mobility between humans and animals (Box 3) and can be applied in contexts well beyond foraging. In some limited circumstances these ideas are already well developed, such as cost and benefit studies of commuting and urban sprawl [74,75]. However, the new generation of wearable devices and the linking of digital social networks to mobility patterns offer a means to bring a far greater degree of complexity and detail to optimization studies.

In turn, the flexibility, detail, and immediacy of data gathered by smartphones and geolocated devices offer new opportunities to improve management and conservation outcomes for some of the most important ecological issues faced by human society. Minimizing adverse impacts

Box 3. Similarities and Differences in Human and Animal Mobility
The mobility patterns of humans are most similar to those of many marine animals because, through the use of technology, we have escaped the constraints of body size that apply to the movements of most terrestrial species that transport themselves on land [91]. Some of the other species that have also escaped the constraints of terrestrial locomotion are those that are either deliberately or inadvertently included by humans in their travels, such as microbes, domestic animals, and invasive species. Clear examples of convergence in the studies of animal movement and human mobility are the identification of scaling laws that characterize movement patterns such as Lévy flight, the characterization of spatial patterns in residency such as fidelity, recursive movements, and home ranges, and in the spread of invasive species and epidemics. In the case of human epidemics the convergence is complete, since the microbe both infects and is transported by the human host. However, these comparisons also reveal a fundamental difference in human and animal search behaviour because today, many human ‘foraging’ movements are directed; humans often know where the item is before they embark on a journey to find it. For example, humans are likely to use prior knowledge or to do a search online to find a restaurant, bar, or specific good for sale and then go directly to that place where the service or item is available. Analysis of the most extensive data sets of human movements within cities show that this is the case – the majority of movements within a city by people occur between a home and a workplace [10,20,92,93]. Thus, unlike animals, most human movements might not necessarily involve (at least extrinsic) searching behaviour.
and ensuring sustainable harvests of resources are central to humanity’s future. The analysis of big data provided by geolocated devices offers a multitude of opportunities because it provides a cheap and simple means to gather comprehensive and synoptic data sets that allow visualization of patterns and interactions within human movement and social networks at spatial scales that have never been available in the past.

Concluding Remarks
The infiltration of mobile phones into human societies is now almost complete, with 6.8 billion subscribers (i.e., 96% of the world population in 2013) [9]. The rapidly developing study of the patterns of mobility of human populations derived from these big data provided by mobile phones and other digital devices has many clear parallels with studies of animal movement. However, a key difference between the two fields is that the emergent patterns found by the combined analysis of individual animal trajectories form the evidential basis of the theory of animal movement ecology [76], whereas human studies do not yet have an equivalent theoretical framework that operates across all spatial scales. Some argue that such a framework is unnecessary, because ‘with enough data, the numbers speak for themselves’ [77] (http://www.edge.org/3rd_culture/anderson08/anderson08_index.html). In

Predicted growth in the number and capacity of electronic devices will not only increase the amount of data they provide on human mobility, but also the velocity at which they are generated and the complexity of information these data contain. Wearable devices, such as the ‘Fitbit’ shown in (A) provide a new data stream that opens a window into movement and body physiology [94]. This development mirrors the field of telemetry and biologging in animals [7] where tracking tags (B – southern elephant seals, Mirounga leonina, note tag on head of seal) not only transmit location data but also store data from a variety of sensors that can record body position in three dimensions and internal (e.g., heart rate) and environmental (e.g., temperature, depth, altitude) variables. As they have done for animals, wearable devices will allow the development of theories connecting human behaviour, body condition, and health to movement and activity [95,96]. In turn, this will be coupled with innovations that connect objects within human environments to the Internet. Tracking devices are now commonplace not just on people, but also on all forms of transport (e.g., cars, ships, planes) and the environments in which they move are being linked by technologies such as smart grids, smart cities, and smart homes. By 2020 it is predicted that human society will have 50 billion Internet-connected devices, with average ownership of 6.58 devices per person [97]. As a result, humans will move within an environment described as the ‘Internet of Things’ [98]. Data on movement patterns, the internal state of the person moving, the environment traversed, and the mode of transport used will be available at all times and in all environments on the planet, including those that were once both data-poor and costly to monitor. This has implications for many aspects of social organization and behaviour. It will speed the diffusion of innovations, culture, and opinions as well as allow much closer regulation of behaviour. For example, the remoteness and expense of monitoring the open ocean have meant that these environments have long been a haven for illegal fishing. Today, vessels are being equipped with automatic identification systems that report positions to satellites to ensure compliance with fisheries regulations [99]. This type of monitoring can be done remotely and at a fraction of the cost of most other types of compliance enforcement.

Movement studies of animals, particularly those involving telemetry and biologging (Box 4) are now generating big data. To what extent can the analytical techniques that have been applied to human mobility now inform and improve the exploration and understanding of animal mobility? • Big data analyses of human movement have been driven by complex system analyses. Animal movement studies provide a framework within which to pose hypotheses about human movement, but to what degree do external drivers produced by the complexity of human sociality skew the potential outcomes? • The analysis of data sets of constraints and motivations for human movement poses ethical issues, even when these use existing public data sets, because the more detail that is added to the profile of the person who is making a movement, the higher the likelihood that he or she could be individually identified from results. This is an important issue for research that uses big data and will be particularly relevant in the context of optimization studies. • Big data can be used to understand and optimize the management of legitimate activities for resource extraction such as fishing, but can also empower and facilitate illicit and unregulated behaviours that now threaten the future of species and even entire habitats. How do we curb such behaviours when connectivity within the same software platforms can be critical to both the legal and illegal use of resources?
realities, all explorations of big data sift through an array of variables and include only subsets of these in analyses, so that preconceptions of researchers must always influence results [78]. Optimization theory provides a relevant, simple, and transparent framework for this process. Because human mobility data can be linked to social networks, economic transactions, and the physiological state of an individual, the currency and constraints both motivating and limiting movement patterns can be explored in very fine detail. The volume, scope, and immediacy of these big data offer robust and novel insights into some of the major problems surrounding the sustainable use of ecological resources and the minimization of human impacts on terrestrial and aquatic ecosystems that now confront society.

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