The movement patterns of free-roaming dogs inhabiting an offshore island of Singapore

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# Overview

Establishing or restoring ecosystem health is a critical goal for conservation biologists and ecologists, and one of the major causes for concern is the introduction of non-native species into an ecological community (Macdonald, King, and Strachan 2008). Unfortunately, the migration and distribution of human populations across the globe gave rise to the purposeful or incidental introduction of many species (including domestic commensals) into a vast range of habitats and consequently, ecosystems. This phenomenon can be problematic for biodiversity conservation as the introduction of non-native species can ‘weaken’ an ecosystem that is already affected by habitat fragmentation and degradation. [[So, I would like to see some examples of famous invasive species here. Also relevant might be this concept/distinction of non-native vs invasive; might be important to bring this up in this LIT REVIEW.]] Introduced species may then conveniently assume the role of a scapegoat aimed at misdirecting attention from more fundamental systemic issues. For example, Gurevitch and Padilla (2004) argues that the rapid rate of extirpation in unionid mussels were caused by poor habitat management (e.g., degradation, pollution) and the blame should be diverted away from the introduction of the non-native zebra mussles (*Dreissena polymorpha*).

Domestic commensals living with strong associations with human communities can be problematic for biodiversity conservation especially when these animals are intricately tied to the economic, social, and political values and views of the human community (Simberloff 2001). For example, Medina et al. (2011) reviewed that the free-roaming domestic cat (*Felis silvestris catus*) are the primary drivers for at least 14% of the global bird, mammal, and reptile extinctions and are a prominent threat to almost 8% of critically endangered birds, mammals, and reptiles. This is due to a myriad of reasons: 1) the impact of the free-roaming cat were displaced globally, including remote islands, alongside the patterns of human migration (Medina et al. 2011), 2) cats are dietary generalists and can consume a large variety of prey (Campos et al. 2007; Forsyth et al. 2014), 3) most native (island) species may be naive towards mammalian predators [kierGlobalAssessmentEndemism2009]. Therefore, the free-roaming cat, despite being a relatively small-sized predator, can be disruptive for biodiversity conservation and it’s infamy for being controlled is far-reaching (Medina et al. 2011).

On the other hand, the domestic dog (*Canis familiaris*) has received far lesser notice despite being the one of the most abundant carnivores in the world (Young et al. 2011). In comparison to the free-roaming domestic cat, the free-roaming domestic dog can be a problematic pest in many urban and natural landscapes (Feldmann 1974), and can be prey and compete with a much wider variety of species (Butler et al. 2013). Yet, there is a scarcity of conclusive information on the ecological impacts of the free-roaming domestic dog, and this might stem from 1) the anecdotal documentation and/or reports on canid-wildlife conflicts(Mitchell and Banks 2005), and 2) a paucity of research on the domestic dogs’ potential population-level impacts or role within an ecosystem (Hughes and Macdonald 2013). As such, there is a need to examine these animals to enhance the efficacy and progress of biodiversity conservation programs in fragmented dog-inhabited landscapes, and facilitate the recovery and maintenance of at-risk wildlife populations.

# The origin of the domestic dog

The global estimate for the domestic dog population is seldom reported and such estimates are typically derived from unclear methodologies (Matthew E. Gompper 2013). For example, large-scale estimates are often derived through dog:human ratios which are the result of diverse survey methods and density estimations produced by interested stakeholders such as pet product manufacturers, veterinary associations and establishments, and animal welfare shelters or organisations (Matthew E. Gompper 2013). That being said, the most recent global-level estimate for dog numbers within the present literature was cited at 700 million dogs by Hughes and Macdonald (2013), and this estimate is expected to increase with the growth and expansion of human populations.

Unfortunately, the estimates obtained from the dog:human ratio are usually taken from a single point in time; multiple estimates rarely exist, especially for countries without a unified system for dog population management (Matthew E. Gompper 2013). In addition, there are difficulties in accounting for dog numbers derived from different degrees of dog ownership between regions, such as the the unaccountable presence of un-owned free-roaming dogs. For example, estimates of dog numbers may differ between regions due to effects from the societal norms of local dog ownership and/or dog management strategies. In addition, dog population densities in urban, rural and natural areas may fluctuate greatly based on 1) waste disposal practices and management, and 2) presence and provision of critical human-derived resources (e.g., medicine, shelter, protection). For example, the domestic dog population in the United States increases by 3 to 4% annually while an inverse pattern was observed in Australia, where the domestic dog populations declined by 15% between 1998 to 2009 (Matthew E. Gompper 2013).

Having evolved from the gray wolf (*Canis lupus*), the domestic dog (*C. familiaris*) is still presently regarded as a subspecies of the wolf despite being phenotypically distinct (Matthew E Gompper 2013). In addition, evolutions of the introduced dog, the dingoe (*C. lupus dingo*), in the Australian landscape further confounds delineation between the domestic dog, their wild and feral counterparts (e.g., coyote (*C. latrans*), jackals (*C. mesomelas*)), and their hybrids (e.g., coydog (*C. latrans* × *C. lupus familiaris*), wolfdog). Hence, the term ‘dog’ can be confusing from a taxonomic and scientific perspective. However, for the purpose of this literature review, the term ‘dog’ is used specifically to address the domestic dog while their wild or hybrid counterparts will be specifically mentioned. In addition, owing to the general lack of dog-related studies in the present state of canid literature, references to the dogs’ wild counterparts may be used to exemplify the ecological role of other members within the Canidae family.

Despite its ambiguous taxonomic status, a genomic study into the evolutionary origins of the dog suggests that the domestication relationship between humans and *Canis* occured after the origin of domestic plants and agriculture where the shift away from a more carnivorous diet catalyzed the domestication of the dog (Larson and Bradley 2014). As such, the association with humans (e.g., food dependency) appears to be the stimulas for the close relationship between primitive *Canis* and humans, which is still being presently observed in modern times. For example, today’s dogs take on complex and diverse roles (e.g., as pets, working or protection animals) with varying levels of dependency and integration into different types of human communities. Even when not owned, the direct and indirect dependency on human-derived materials (e.g., food, shelter, protection) has allowed the dogs’ tremendous growth and distribution to mirror the growth and expansion of human population and settlements across the globe.

Outside of roles defined by human ownership (e.g., pets, working dogs), there have been many efforts made to define and describe the categories of ‘unowned’ dogs (Matthew E. Gompper 2013). For example, Banks and Bryant (2007) differentiates the dog plainly between owned and unowned, while other nomenclatures such as rural, village, feral, wild and free-roaming (Boitani and Ciucci 1995; Butler and du Toit 2002; Fleming et al. 2001; Manor and Saltz 2004; Ruiz-Izaguirre 2013, respectively) were used to contextually and ecologically categorise the ‘unowned’ dog. However, most authors would agree that these categories are flexible and non-restrictive as dogs can switch or fall into more than one category (Vanak and Gompper 2009). Therefore, to reduce the confounding terms and complexity of categorising dogs, it could be more meaningful to examine the dogs’ ecological impact and function through the spatial and circumstantial context of their ownership (or lack of).

# The ecological impact of the free-roaming dog

Regardless of ownership, the dog is dependent on the provision human-derived supplementary resources (e.g., commercially prepared pet food) or foods that were scavenged (e.g., foraging for human refuse). In a natural landscape, the provision of supplementary resources, regardless of intent, are often an ecologial subsidy and will facilitate the population growth of animals that subsists on them. For example, Webb, Boarman, and Rotenberry (2004) reported that anthropogenic subsidies (e.g., human refuse and waste) have signifcantly contributed to the dramatic increase in the abundance of the Common ravens (*Corvus corax*) and Burger et al. (2007) noted similar findings with the glaucous gulls (*Larus hyperboreaus*) and shorebirds at a migratory stopover. In addition to population density increases, the provision of supplementary resources can lead to behavioural pattern shifts as observed in wild Slovenian red deers (*Cervus elaphus*) where smaller home range sizes (e.g., reduced extent and/or frequency of roaming patterns) were developed after being supplementally fed by hunters to increase their hunting value (Jerina 2012).

Being an adaptable generalist have aided dog populations to attain higher densities in comparison to their wilder counterparts, particularly in landscapes where dogs are viewed upon commensally . This is true in urban or semi-rural landscapes where the free-roaming dog have been reported to opportunistically capitalize (i.e., reduced territoriality, increased foraying distances) on the availability of food and shelter (e.g., garbage sites; Tiwari et al. (2019)) in human communities or climatic events (e.g., religious feasts, stormy weather; Tiwari et al. (2018)), even when they are not the intentional receipient of said resources. For example, dog population densities have been found to range from 468 dogs per km2 in semi-urban Philippines (Childs et al. 1998) to 6 – 21 dogs per km2 in rural Kenya (Kitala et al. 2001) in comparison to coyote populations ranging from 0.2 to 0.44 per km2 and wolf populations from 0.005 to 0.4 per km2 (Carbone and Gittleman 2002).

With the capacity form loose yet highly territorial groups (Matthew E. Gompper 2013), the artificially enhanced free-roaming dog population may result in the increase in predation pressure on prey species where their rate of predation can far exceeds the dogs’ rate of consumption and the energetic requirements (i.e., surplus killing). Surplus killing is a commonly seen predatory behaviour in canid species for two primary reasons: 1) ineffective prey response due to novel interactions with introduced dogs, and 2) large packs of canids are capable of defending kills and continue hunting despite having acquired sufficient food (see Kruuk (1972)). An Australian study reported 83 red kangaroos (*Macropus rufus*) were preyed upon by a pack of five dingoes over a period of seven weeks and the dingoes were only consuming portions from half of the killed kangaroos (Shepherd 1981). Similarly, Bayarbaatar, Young, and Fine (2009) noted that free-roaming dogs may be a threat to the Mongolian saiga (*Saiga tatarica mongolica*) as they reportedly consumed more than 10,000 calves annually during harsh winter conditions where saigas are in poor health, as well as in stages of neonate birthing and rearing.

Apart from affecting prey numbers, artifically enhanced populations not only provides the free-roaming dogs with the numerical advantage to outcompete other predator species in acquiring resources, it also provides the dogs the capacity to compete with a wider range of top predators (e.g., wolves; *C. lupus*), mesopredators (e.g., jackals; *C. mesomelas*), as well as non-mammalian carnivores (e.g., monitor lizards *Varanus spp.*) in semi-rural or urban landscapes (see Vanak et al. 2013). In Zimbabwe, Butler and du Toit (2002) reported that free-roaming dogs monopolized the supply of carrion and outcompeted the principal competitors (e.g., vultures, lions (*Panthera leo*) and spotted hyaenes (*Crocuta crocuta*)) on the peripheries of nature reserves owing to their high densities (6.5% growth per annum), physical and numerical dominance and greater tolerance to anthropogenic disturbances.

However, the presence of artificially enhanced populations of dogs does not always result in dog-wildlife conflicts. In Bale Mountains National Park, Ethiopia, Atickem, Bekele, and Williams (2009) reported no overlap in the diet as well as home ranges between the Ethiopian wolf (*C. simensis*) and free-roaming dogs even though dogs occured in large densities (10 dogs km-2). This is because dogs fed predominantly on human-derived foods (e.g., waste products, fecal matter, carcasses) while wolves preyed primarily on rodents, and dogs remained in the immediate vicinity of human settlements which wolves tend to avoid. On a seperate note, Athreya et al. (2016) reported that leopards (*Panthera pardus*) in western Maharashtra preyed almost completely on domestic livestock (e.g., goats, cows) and dogs, with their high densities, were the most preyed item (39% of entire diet). However, despite the diet preference for the domestic dog or cat as prey items, the leopards’ encroachment into human houshold (to prey on the dog) has invariably exacerbated the leopard-human conflict.

As a relatively large-bodied predator, dogs can assume the role of an apex predator in a natural system free from a larger mammalian predator or a landscape where larger-bodied carnivores are persecuted. For example, the abandoned dogs of the Galapagos islands filled the role of a missing apex predator and preyed on many native species (e.g., marine iguanas, nesting marine birds) that were naive to dogs (Barnett and Rudd 1983). Similarly, the dingo (and their hybrid counterparts) in mainland Australia dominated over most subordinate native mammalian predators during direct encounters (Doherty et al. 2019; Short, Kinnear, and Robley 2002) due to their advantageous body size as well as their ability to hunt in packs. For example, Mitchell and Banks (2005) found a high degree of overlap in the diet composition between dingoes (and wild dogs) and foxes which possibly resulted in temporal avoidance or localized habitat shifts in the two species.

Asides from the lethal effects of predation, the mere presence of a predator can also affect prey species in subtle yet apparently harmful ways. For example, dogs may be able to suppress prey populations through non-consumptive means (e.g., harrassment) which can cause disruption of normal activities or states where anti-predatory behaviours such as increased vigilance, flight, refuge seeking and/or freezing would occur. This has been found in Israel where Manor and Saltz (2004) concluded that the presence of free-roaming dogs were a threat to mountain gazelles (*Gazella gazella gazella*) recuitment, and their acts of harrassement (e.g., chasing of adult and kid) were reduced the gazelle’s reproductive success and survival rates. Similarly, native bandicoots (*Paremeles nasuta*; Carthey and Banks (2012)) and Indian foxes (*Vulpes bengalensis*; Vanak and Gompper (2010)) were less likely to forage and/or traverse through dog-dominated landscapes even when these areas were potentially higher in human-derived resources.

Another growing concern in the interaction between free-roaming dogs and wildlife lies in dog’s potential role as disease vectors towards wildlife (Hughes and Macdonald 2013). Previously, a series of well publicized and large-scale die-offs of wild carnivore populations occured following the introducton of pathogenic viruses originating from free-roaming dog populations (Knobel et al. 2013). As a result, this critical issue of addressing dog-transmissible diseases was quickly recognized as important drivers of wildlife population dynamics and demanded a multi-disciplinary approach despite the long-standing recognition in the importance of disease and health in wildlife conservation.

At present, dogs are the primary cause for 99% of the rabies-induced human fatalities reported worldwide and are hosts to more than 60 other transmissible zoonoses (Tenzin et al. 2015). Viruses that are particularly infectious towards carnivores such as canine distemper, parvovirus, rabies and rotavirus can be found in the feces of infected dogs (Yan et al. 2020), and reports citing cross-species infections have been reviewed extensively by Knobel et al. (2013). A local example noted by Mendenhall et al. (2016) reported that two common palm civet cats (*Paradoxurus musangus*) tested PCR-positive for parvovirus infection, and the tested strain bears similarities to the Canine Parovirus clade that has infected dogs in China and Uruguay.

In spite of all the aforementioned interactions between dogs and wildlife, dogs can also potentially assume a beneficial role and exert a positive impact through an ecosystem. In Australia, the presence of dingoes benefitted the native dusky hopping mice (*Notomys fuscus*) through the suppression of smaller mesopredators (e.g., feral cats and foxes; Letnic, Ritchie, and Dickman (2012)), and this form of control over introduced species could be beneficial for ecosystem restoration (Newsome et al. 2015). The suppression of invasive species such as the cat and fox is a welcomed interaction in Australia as these mesopredators are responsible for the mortalities of many native species; Woinarski et al. (2017) reviewed that feral cats in Australia killed 35.6 birds km-2 yr-2 and 99% of these mortalities were native bird species.

Amidst the obvious risks (e.g., surplus killing, harrassment) imposed by dogs (and their wild and hybrid counterparts) in an ecosystem, the value of introducing or conserving the dog in natural landscapes and ecosystems is debatable. Canid researchers, particularly dingo conservationists in Australia, proposes re-introducing the dingo to restore degraded rangelands and supporting native wildlife conservation (Newsome et al. 2015). As aforementioned in an example by Letnic, Ritchie, and Dickman (2012), the idea of dingo re-introduction is based on theories and results of studies suggesting that the presence of the dingo supressess smaller mesopredators, which in turn benefits smaller prey species through reduced predation pressure. In addition, the suppressive effects of the dingo may also extend towards medium-sized grazers (e.g., feral goats and kangaroos) that contributes significantly (in high densities) to vegetation degradation in natural landscapes (Letnic, Ritchie, and Dickman 2012). Therefore, the question lies as to whether the free-roaming dog, with its similarities to its wild counterparts (e.g., dingoes and their hybrids), can exert similar suppressive pressures through an ecosystem and contribute to native biodiversity conservation in a similar fragmented landscape (i.e., lack of an apex terrestrial predator).

# The Movement Ecology framework for research

Movement is a fundamental characteristic in life, driven by the processes that determines the fate of individuals, and the structure and dynamics of populations, communities and ecosystems. Causal links between organismal movement patterns and environmental change or degradation are highlighted by the interactions between anthropogenic habitat fragmentation (or degradation), changes climate and land-use patterns, and the introduction of invasive species. Therefore, having a cohesive understanding of the causes, patterns, mechanisms and consequences of organismal movement can be instrumental in controlling the spread of pests, invasive alien species, and infectious diseases, and managing and restoring degraded landscapes.

Scientific information pertaining to the movement patterns of the free-roaming dog is often one-dimensional (see below) and the availability of information on their potential impacts and interactions with wildlife is limited (Hughes and Macdonald 2013). As mentioned previously, Atickem, Bekele, and Williams (2009) concluded that dogs were unlikely to be a serious threat towards the Ethiopian wolf (*C. siamensis*) by arguing that the diet composition and home range between both species had little overlap. However, their findings could be better supported if other facets of movement, such as temporality, were examined. Having temporal information on the movement patterns of both dogs and wolves not only affirm the lack of spatial overlap between both species, it can also be used to examine temporal avoidance between dog and wolf. This notion of exploring the ‘where’ and ‘when’, as well as the ‘how’, and ‘why’ are the core principles of the ‘Movement Ecology’ framework.

Movement Ecology is a recently developed framework that has been gaining significant traction with more recent ecological studies (Holden 2006). This framework of research aims to examine the spatial behaviour of an organism through a single unified theory with the use of large and diverse datasets (e.g., acceleration, Global Positioning System (GPS) re-locations). Recent advancement in modern telemetry systems have allowed researchers to collect substantial volumes of high-resolution data on the movement patterns of animals. The collection of such data not only offers a better understanding of the movement patterns of animals at varying spatial and temporal scales, it also provides researchers with an in-depth insight into the effects of the physiological, demographic, and ecological contexts on spatial behaviour (Wilmers et al. 2015).

The Movement Ecology framework examines the mechanisms in the interactions directing an animal’s movement path through four main components: the internal state, the motion and navigational capacity, and the external factors. The ‘internal state’ refers to the physiological state and associated motivation for an organism to move. In the free-roaming dog, the ‘internal state’ can refer to the intrinsic (i.e., driven by cognitive ability, assessing resources, learning the environment) and/or extrinsic (i.e., driven by physiological state; e.g., hunger, escape from predation) form of motivation . The ‘motion capacity’ describes the biomechanical means of movement (e.g., running, walking) and the ‘navigational capacity’ refers to the dog’s ability to orient itself in space and time given its sensory or cognitive capacity (e.g., dens, latrines, watering holes). Lastly, the ‘external factors’ refer to the biotic and abiotic components within an environment that influences the movement of said animal (e.g., anthropogenic disturbances, climatic conditions). Therefore, by examining the free-roaming dogs’ movement through these four components, the framework allows researchers to understand the causes, mechanisms, and patterns of movement at the individual, population, and community level.

To examine the free-roaming dogs extent of interaction with wildlife (e.g., predation, harrassment), Vanak and Gompper (2009) suggests that the dog’s capacity to roam freely and the location of the studied dog are important factors to consider as they have direct implications on the likelihood and frequency of any probable wildlife interaction. For example, dogs with constrained movements within urban landscapes (e.g., pet dogs) are less likely to interact with wildlife in comparison to unconstrained dogs (freely roaming) in natural or rural landscapes. As most dogs are also highly dependant on human-derived supplementary resources, it may also be equally important to consider their direct and indirect access to non-wild food sources to further define the extent of interaction between dog and wildlife.

With the proposed considerations mentioned above, one could characterize and predict the type of dog-wildlife interaction based on the dogs’ extent of movement into vulnerable landscapes as well as their level of dependency on supplementary resources. For example, Sepúlveda et al. (2014) noted that dog interactions with prey species in the temperate forests of Chile appeared to be driven by hunger while Ruiz-Izaguirre (2013) reported that ‘feral dogs’ independent of humans were found further away from households, had larger mean activity range and scavenged more readily on turtle nests. Unfortunately, the aforementioned studies were conducted through interviews and focal surveys, and crucial information regarding the dogs’ movement patterns were not examined. As such, it is difficult to contextualise the dogs’ potential impacts and the nature of these conflicts succintly.

# Applying the Movement Ecology framework

Movement allows an animal to search for important resources such as shelter, food and mates, and to avoid risk factors such as predators or any other form of danger (e.g., forest fires, human presence). The pattern of movement in an individual animal, that is used to describe a finite area, is termed as a home range. One widely cited definition of an animal’s home range is by Burt (1943): ‘that area traversed by the individual in its normal activities of food gathering, mating and caring for you. Occasional sallies outside the area, perhaps exploratory in nature, should not be considered as in part of the home range.’ However, the definition presented by Burt demonstrates several problems. Firstly, an ‘occasional sally’ can only be defined when the home range of an animal has already been well-established, and secondly, Burt’s definition remains one-dimensional: it only describes where an animal traverses and does not recognise the importance of variations in the intensity or patterns of space use (Kie et al. 2010). Therefore, the definition of an animal’s home range should be more than just a simple estimation of the area traversed, it should also include the quantification of the animals’ patterns of space use within said estimated area.

Traditionally, movement ecologists would monitor individual animals with the use of VHF (Very High Frequency) radiotelemetry and estimate their home range by plotting the movements of said individual over a period of time onto a map. However, data gathered from wild individuals in this manner were often sparse and inconsistent which made home range estimation difficult and inaccurate, which ultimately slowed the progress of animal movement studies. Nevertheless, the use of VHF still continues in the modern day as it is cheaply available and the lightweight tags allowed for a diverse range of animals (e.g., Asian hornets, bats, porpoises; Kennedy et al. (2018), Smith et al. (2011), Read and Westgate (1997)) could be studied. However, there are several drawbacks to using VHF radiotelemetry in the study of animal movement. Firstly, the animal may not necessarily visit all areas within its home range during the study period, and the quality (e.g., volume and accuracy) of the data collected from the observational period is dependent on the researcher’s ability (e.g., catching up with fast-moving animals) and availability (e.g., labour-intensive). In addition, the presence of the researcher during radio-telemetry can result in unnatural movement behaviours that can mis-represent the natural tendencies of the studied animal. In short, the information collected via traditional radio-telemetry is often lower in volume, lesser in detail and of poorer accuracy.

The many advances in GPS technologies have provided researchers the opportunity to use GPS loggers to monitor animal movements in wildlife telemetry studies. This has resulted in the collection of the studied animal’s spatial information where datasets are not only numerous and precise, but also highly correlated between space and time. Having access to the temporal information of spatial movement provides a window of opportunity to examine the patterns (i.e., frequency and extent) of space use in the studied animal. However, to do so, researchers would need modify or replace traditional home range estimators that were developed initially for the smaller datasets obtained from VHF radio-telemetry. Thus, researchers are now not only challenged with managing large volumes of information (> 10,000 location per animal), they are also tasked with selecting the most appropriate and functional home-range estimator for the analysis of home range sizes or movement patterns with the increased volume of GPS re-locations.

Through the rapid miniaturisation of electronic sensors, the field of wildlife radio-telemetry is approaching another growth spurt as GPS technologies are coupled with the use of sensors that can contiuously measure aspects of an animal’s state (e.g., heart rate, acceleration) and the external environment (e.g., temperature, depth). For example, researchers have incorporated animal-borne transmitters with light and temperature sensors (Wilson, Shepard, and Liebsch 2008), digital and video cameras (Loyd et al. 2013), and more recently, tri-axial accelerometers (Lush et al. 2016; Williams et al. 2017). These additions to wildlife telemetry, termed as ‘bio-loggers’ (Wilmers et al. 2015), are paramount to understanding the ecology of an animal by giving researchers the opportunity to not only describe behavioural contexts that were previously unobservable (e.g., fossorial or flying animals), they also provide researchers an opportunity to answer new questions about the physiological performance, energetics, movement patterns, and sociality of wild animals, as well as collect data on the environments in which they live.

One method of circumventing the limitations of directly observing animals in the wild comes with the use of tri-axial accelerometers (Williams et al. 2017). Tri-axial accelerometers allow researchers to characterise an animal’s movement patterns and behaviours by recognising the gravitational (static) and inertial (dynamic) acceleration caused by movement. As the three axes in an accelerometer are aligned orthogonally (to one another), researchers are able to quantify and realistically represent the three-dimensional movement or posture of an animal from acceleration forces measured simultaneously across the three seperate axes (X, Y and Z; heave, surge and sway, respectively). These acceleration sensors offers fine-scale interpretation on the variation and extent of animal movement patterns and behaviours, and could also be used to quantify energy expenditure (e.g., Overall Dynamic Body Acceleration, ODBA; see below) in space and time when used with GPS re-locations (Hammond et al. 2016; Resheff et al. 2016). This form of bio-logging, even though in its infancy stages with terrestrial animals (see Lush et al. (2016)), have already been explored with wild animals such as pumas (*Puma* [*concolor\*;@wangMovementRestingAttack2015*](mailto:concolor*;@wangMovementRestingAttack2015)*), Eurasian badgers (*Meles [meles\*;@mccluneTriaxialAccelerometersQuantify2014](mailto:meles*;@mccluneTriaxialAccelerometersQuantify2014)), as well as domestic species such as dairy cows (Vázquez Diosdado et al. 2015) and sheep (Marais et al. 2014).

Having access to bio-logging technologies has inevitably brought the study of animal movement and ecology into the realm of ‘Big Data’ science (Kays et al. 2015) where the size of collected movement data grows exponentially from longer sampling durations (i.e., increased battery life and storage capacity) and wider combination of biologging data types (i.e, GPS, acceleration, video recordings). Despite the easy availability of such technologies, the processing and meaningful application of these datasetscan be time-consuming and difficult. For example, accelerometers can be used to identify movement patterns and behavioural states through changes in the animal’s activity but most studies are limited to simple threshold-based detection of active/inactive states (Hammond et al. 2016) or classification into slightly richer behavioural states (Battaile et al. 2015; Vázquez Diosdado et al. 2015). This is particulary true for species that are near to impossible to follow and observe (Araii et al. 2000; Carroll et al. 2014; Yasuda and Arai 2009), thus making it difficult to draw true behaviours from such analysis.

Rather than using arbitrary values and thresholds to identify behavioural states, it is possible for one to combine and associate the collected acceleration values to observations of the studied actual animal behaviour to draw more robust conclusions on the animal’s true behaviour. Through this notion of analysis, researchers can address detailed behavioural questions on elusive, far-ranging species that do not occur in high densities (e.g., rare species) and/or are difficult to monitor continously (e.g., challenging terrain or landscape). However, the collection of behavioural and accelerometer data can be extremely time-consuming and the volume of the both collected datasets (accelerometer and behavioural observations) can be too large to process by hand. As such, researchers are relying on the use of Machine Learning Algorithms (MLAs) to address this challenge (Bidder et al. 2014; Resheff et al. 2016; Sakamoto et al. 2009).

Generally, there are two main approaches to building MLA models to predict movement behaviour or patterns from accelerometery outputs. The first approach termed as the ‘unsupervised’ classification method relies on the selected MLA model’s intrinsic ability to group and characterise similar-looking accelerometery outputs either through visual inspection of the data, or by using statistical methods such as *k* means clustering or *k* nearest neighbour algorithm (Bidder et al. 2014; Sakamoto et al. 2009). The unsupervised approach to MLA model building is often easier and can be readily applied to new or pre-existing datasets without the need to ground-truth the information. However, unsupervised MLA models are unable identify and predict specific behaviours of interest, and explain the differences between predicted behaviour states without additional ground-truthing. For example, Sakamoto et al. (2009) reported that his use of an unsupervised MLA model could not discriminate between time spent on land (e.g., resting) and dive ascent (e.g., motion, flight) in the in the European shag (*Phalacrocorax aristotels*). In this case, the posture of the animal played a subtle yet critical role in determining movement, but the unsupervised approach was unable to pick up the differences in the corresponding accelerometry outputs.

As for the second approach, the ‘supervised’ method of constructing predictive MLA models involves ‘training’ the MLA model on segments of accelerator outputs that have been classified with behaviour labels after direct observation of the animal tagged with an accelerometer (Resheff et al. 2016). These ground-truth models can then be used to classify unobserved behaviours from new accelerometer outputs into the pre-determined behaviour labels used in training the model. With sufficient training on computationally powerful models (e.g., random forest), differences in the accelerometery outputs of similar-looking behaviour or movement patterns can be identified (Resheff et al. 2016). Hence, the supervised learning approach would be the most ideal for the purpose of examining the movement patterns of free-roaming dogs. This is primarily due to the access to domestic dogs, which can be used as ground-truth models to train and validate the collected accelerometery outputs. Furthermore, this access to ground-truth models allows the identification of coarse or fine-scale behaviours of interest (e.g., foraging, resting) to the research project.

Despite its wide application on to many species, and capacity to predict a diverse range of behavioural states and patterns, there are several drawbacks to using the supervised approach to MLA model construction. Pre-determined behaviour labels, even if observed and prepared perfectly, may not be adequately representative of the behavioral pattern of the studied animal throughout the period of the research. In the case of non-captive individuals, tedious amounts of fieldwork may still be required to obtain sufficient enough observations, and the presence of the observer may have an impact on the natural behaviour of the observed animal. More importantly, the need for observations limits the scope of such research projects to observable species and to research labs with the necessary resources (in money, manpower, and knowledge) to carry out all the steps listed above.

# Thesis layout

In chapter 1, I focus on optimising the predictive MLA models used in the research project and the determination of the accelerometer thresholds necesary for moderating the frequency of GPS re-location collection in the wildlife tracking collar. The chapter mostly discusses the procedures involved in the model construction phase (e.g., training data collection, data labelling and transformation, model building and validation), and how it will be used to identify the accelerometer threshold used in the wildlife tracking collar. As with most field-based research work, optimising field equipment and procedures not only improves the accuracy and sampling duration of field data collection, it also allows for the collection of more biologically relevant information from the studied animals.

Chapter 2 explores the use of the constructed MLA model to predict the behavioural states and patterns of the collared free-roaming dogs from each study site. In addition, the chapter also examines the circadian rhythm of these animals with the use of the MLA model predictions, and the external factors that have influences on the peaks and troughs of the dogs’ circadian pattern. As very little is known about the circadian pattern of these animals, to have an understanding of the dogs’ circadian pattern not only informs us of their ecology, it also allows us to examine their potential impact on native wildlife.

For chapter 3, I will be examining the movement patterns of these free-roaming animals by estimating the home range sizes and shapes from GPS information collected from the free-roaming dogs of Singapore. To draw different biological interpretation in the spatial distribution of these animals, this chapter will use the spatial and temporal information present in GPS re-locations to explore intensity of space use (e.g., utilisation distribution), directionaility (e.g., step selection analysis) and extent of movement (e.g., minimum convex polygons) in dogs. With the findings from the earlier chapter, I will be exploring how the dogs’ circadian rhythm as well as the various environmental factors (e.g., intrinsic site-specific differences) that may influence the movement patterns of these animals.

Chapter 4 attempts to identify and explore the habitat preferences of the free-roaming dog by is performed by mapping GPS re-locations and the home range shapes estimated from the earlier chapter onto a raster Geographic Information systems (GIS) layer of the various study sites. In addition, this chapter will attempt to construct an ‘activity landscape’ to identify the spatial distribution of movement behaviours that are deemed impactful to wildlife. An activity landscape differentiates itself from the basic habitat selection analysis by specifically examining where impactful behaviour occurs. This is done by identifying GPS locations that are predicted to be impactful (i.e., running, foraging, eating) and then mapping the frequency and extent of these occurrences. Information such as this provides a more in-depthful and meaningful examination into the relative impact of the free-roaming dog on native wildlife.

In the final chapter, I will be exploring the energetic expenditure of the these free-roaming dogs through the use of a commonly used proxy, the Overall Body Dynamic Acceleration (OBDA; Wilson et al. (2006)). The ODBA method proposes that the most (and in many cases the major) variable factor in modulating energy expenditure in many vertebrates is movement, hence the measurement of bodily acceleration (through tri-axial accelerometer) should correlate with energetic expenditure. For this research project, a sequence of acceleration outputs were collected alongside each GPS re-location, and I could determine the OBDA value of each GPS re-location and derive the energetic cost of the dogs’ movement path through the landscape. Subsequently, by mapping the dogs’ energetic expenditure (through GPS re-locations), I can get an insight on how the environment and landscape influences the dogs’ spatial use by examining the energetic expenditure of the dogs’ different movement paths.

Collectively, the research project aims to use the aforementioned five chapters to examine the movement ecology of the free-roaming dog in Singapore by addressing the where, when, why, and how of movement. Using the framework as a guide, the chapters will be able to examine the relative impact and the potential role of the free-roaming dog in natural areas. Understanding how dogs interact within their inhabited natural landscape is an important tool to managing wildlife conservation efforts, as well as dog management programs in Singapore. Dissemination of these chapters through publication in peer-reviewed journals will also be useful to natural resource managers, wildlife conservationist, animal welfare groups, and other interested stakeholders to help guide control and management plans to help reduce dog-wildlife conflicts and transform indiscriminant dog removal and control into more ecologically justifiable dog management.

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