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CHAPTER 23

MONITORING THE LONG-DISTANCE MOVEMENT OF WILDLIFE IN ASIA USING SATELLITE TELEMETRY

By

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ABSTRACT

Satellite telemetry is an invaluable tool for monitoring the long-distance movement of wildlife in Asia. Recently, reduction in transmitter weight and other technological innovations have enabled a growing number of taxa in the terrestrial and marine realms to be tracked. We surveyed the literature and identified 30 satellite-tracking studies for 28 species in Asia; including 17 bird, 4 terrestrial mammal, 4 marine turtle, 2 whale, and one fish species. A majority of these species (19/28) are classified as vulnerable or endangered. Most studies (80%) observed international, transboundary movement of animals, and half of these transboundary studies demonstrate movement between at least 4 countries. Contributions of satellite telemetry to avian conservation in Asia are three-fold: identifying important migratory stop-over sites; mapping specific migratory route; and studying behavior. Studies of terrestrial mammals, marine vertebrates, and flying foxes in Asia have also been instrumental in elucidating the specific routes and timing of migration, connectivity of populations, home range size, patterns of habitat use, and foraging behavior. Long-distance movement data are essential to developing effective conservation plans for these vagile species, and are becoming increasingly relevant to human and wildlife health in predicting the spread of emerging zoonotic and epizootic diseases.

Key Words: Disease ecology, fruit bats, migratory birds, satellite telemetry.

INTRODUCTION

Vagile animal species present unique challenges to conservation biologists. These challenges include movement across political boundaries with incongruent wildlife protection laws, an extremely large management area (including archipelagos and sensitive border regions), and exposure of animals to a wide array of threats. In Asia, biodiversity is threatened by pressure from the highest human population densities in the world (Sanderson *et al.* 2002), rampant habitat destruction and degradation (Achard *et al.* 2002), networks of wildlife trade (Yiming & Dianmo 1998), pollution, and global climate change. Conservation of highly-mobile taxa in Asia is also stymied by a lack of knowledge regarding the specific routes and timing of migration, connectivity of populations across the landscape, patterns of habitat use, and foraging behavior.

We define long-distance movement (LDM) as the movement of individual animals across hundreds to thousands of kilometers which may be caused by seasonal migration, juvenile dispersal, returning to natal grounds for breeding, and/or extended foraging. We distinguish LDM from more narrowly defined terms such as long-distance migration and long-distance dispersal, which respectively refer to seasonal movement to and from breeding grounds (Webster *et al.* 2002) and rare events outside of the mean dispersal distance for an organism (Trakhtenbrot *et al.* 2005). Patterns of LDM for a large number of taxa, especially migratory birds, have been recognized for nearly a hundred years (Berthold & Terrill 1991). However, only recently with technological advances have we been able to accurately track these movements in their entirety and gain a more complete understanding of LDM in both the terrestrial and marine realms.

Approaches to measuring the LDM of wildlife include direct marking, population genetics, isotope signatures, and telemetry. Direct marking, or banding, has been widely used to track migrants, especially for birds and bats (Berthold & Terrill 1991; Fleming & Eby 2003). Movement can also be measured indirectly, including a growing body of literature that uses population genetics. DNA-based methods have great utility in unraveling the historical connectivity between populations; and novel approaches are able to identify first-generation migrants using multi-locus genotypes (Paetkau *et al.* 2004). Similarly, stable isotopes found in tissues of migrant individuals are used to infer patterns of movement indirectly, although this method suffers from a lack of geographic resolution and questionable accuracy (Kelly & Finch 1998; Rocque *et al.* 2006). Although useful, the above methods are unable to reveal the *specific paths* of animal movement. Radio telemetry has been invaluable in tracking the movement of individuals for many species in Asia, but it is limited by a short range (dozens of kilometers) and the need to constantly monitor signals on the ground. Satellite telemetry overcomes many of these obstacles and allows for animals to be tracked remotely, in near real-time, anywhere on the planet. In this review, we will summarize the past 15 years of research using satellite telemetry to monitor the LDM of wildlife in Asia and discuss the relevance of these studies to both conservation and the emergence of infectious diseases.

SATELLITE TELEMETRY METHODOLOGY

Transmitters

Platform Transmitter Terminals (PTTs) are the devices, or tags, that allow users to track individual animals. At user-defined intervals, PTTs transmit messages to low-flying satellites. PTTs are powered by batteries alone, or are rechargeable with a solar panel. To extend battery life and collect data for long-range studies, PTTs are often programmed to transmit data for only a limited period each week (e.g. 8 hours every 4-5 days). Frequency of transmission must be selected carefully depending on the questions being addressed. Live animal capture for PTT deployment can sometimes be logistically challenging, involving helicopters and cannon nets (Higuchi *et al.* 2004), mist nets in the rainforest canopy (K.J.O., unpublished data), snares in remote Himalaya (McCarthy *et al.* 2005), and chemical immobilization (Venkataraman *et al.* 2005). PTTs are attached via harnesses, collars, adhesives, or other hardware. Trials should be conducted to ensure that methods of attachment have a minimal effect on the animal's movement, behavior, and health. For example, half (18/37) of the Eastern Curlews tracked from Australia aborted their migration to Asia; this may be part of the natural behavior, or could also have been due to the increased energetic load of attached transmitters (Driscoll & Ueta 2002). As a rule-of-thumb, the transmitter and collar weight should not exceed 4 % of the animal's body mass

(Bander & Cochran 1991). Recent miniaturization of PTTs (<20g) has enabled a number of medium-sized birds and even large bats to be tracked. Financial costs of PTTs can be prohibitive and are often the reason for small sample sizes. On average it will cost $3000-4000 to track one animal per year (Kenward 2001).

Additional sensors can be used in conjunction with standard satellite tracking PTTs. Integrated sensors are used to corroborate location findings (e.g. ambient light sensors (Shaffer *et al.* 2005)), to collect environmental data (e.g. sea-surface temperature (Shaffer *et al.* 2005)), or to record behavioral information (e.g. dive depth and duration for sea turtles (Yasuda & Arai 2005)). Archival pop-up satellite tags, which release from an animal at a set time and float to the surface to transmit data, have also been used on pelagic fish and whales species (Block *et al.* 1998; Kahn 2005)). Most recently, the integration of Global Positioning Systems (GPS) data recorders with satellite PTTs has significantly improved the accuracy and spatial resolution of animal tracking studies (within tens of meters), and will certainly become more widely-used as these sensors become smaller and lighter (Yasuda & Arai 2005).

Satellites and data collection

Since its inception in the late 1970s, the satellite tracking system has been run almost exclusively by Service Argos, Inc. -- a global data telemetry and geo-positioning service company (Kenward 2001). Argos equipment is flown on board near polar-orbiting satellites in collaboration with the National Oceanic and Atmospheric Administration (NOAA) and the French space agency (CNES). Location is calculated by the Doppler shift in the transmitted frequency as satellites approach, then move away from each PTT (Seegar *et al.* 1996). Data are processed at centers in the US and France and geographic coordinates are made available to researchers over the internet in as little as 2 hours. Argos categorizes each data point into one of seven location classes: Z, B, A, 0, 1, 2, and 3, in ascending order of accuracy. The range of accuracy for classes 0, 1, 2, and 3 are: >1000m, 350-1000m, 150-350m, and <150 m, respectively. There are no estimates of location accuracy for classes A or B; and Z refers to invalid locations. Software programs (e.g. STAT) are freely available for the analysis of Argos data and facilitate the integration with environmental data layers and development of web-based content (Coyne & Godley 2005).

LITERATURE REVIEW

We searched all the literature between 1991-2006 using ISI Web of Knowledge and Zoological Record for keywords “satellite telemetry” and “satellite tracking” and identified all publications in which animals were partially- or fully-tracked through Asia. Additional publications were found using literature cited or from our personal databases. We identified 30 satellite telemetry studies (for 28 species) from Asia for which original data were presented (Table 1). These included 17 bird, 4 mammal, 4 marine turtle, 2 whale, and one marine fish species. Most studies (80%) observed international, transboundary movement of animals; in some cases the number of political boundaries crossed was very large, e.g. 11 countries (Higuchi *et al.* 2005) and 8 countries (Driscoll & Ueta 2002). We included endangered status for each species based on the IUCN 2006 Red List (http://www.redlist.org/), and found that 19/28 (67%) of species satellite-tracked in Asia are classified as critically endangered, endangered, or vulnerable. The remaining species are of lower conservation concern or have not yet been categorized under IUCN criteria. Sample size for studies was generally low; over half of the studies had a sample size of less than five. In Table 1 we summarize the results of these important studies. We discuss the conservation significance of this research in Asia as it applies to birds, marine vertebrates, terrestrial mammals, and volant mammals in the following sections.

TABLE 1: IMPORTANT SATELLITE TELEMETRY STUDIES IN ASIA

Species	Scientific name	IUCN [a] 2006	N=	Days tracked	Study Year(s)	Max [b] Dist. (km)	Mean [c] Dist. (km)	Home range (km^2)	Countries [d]	Type of study	References
Bar-headed Goose	*Anser indicus*	NE	2	88-137	1999-2000	780		24-50	China, India	Migration; Home range	(Javed et al. 2000)
Demoiselle Crane	*Anthropoides virgo*	NE	4	98-138	1995	3,400*	3,050*		Pakistan, Afghanistan, India, Mongolia, China, Kazakhstan	Migration	(Kanai et al. 2000)
Houbara Bustard	*Chlamydotis macqueenii*	NE	4	150-1,277	2000-03	4,294*	3,935*	76-247	China, Kazakhstan, Uzbekistan, Turkmenistan	Migration; Home range	(Judas et al. 2006)
Oriental White Stork	*Ciconia boyciana*	EN	13	113-435	1998-2000	3,208*	2,759*		China, Russia	Migration	(Shimazaki et al. 2004b)
Whistling Swan	*Cygnus columbianus*	LC	1	46	1990	3,000*			Japan, Russia	Migration	(Higuchi et al. 1991)
Whooper Swan	*Cygnus cygnus*	LC	8	91-168	1994-95	3,985*	2,935*		Japan, Russia	Migration	(Kanai et al. 1997)
Wandering Albatross	*Diomedea exulans*	VU	13	66-389	2001-02	267,000	183,800 (1 yr)		Indian, Atlantic, Pacific Oceans	Migration; Behavior	(Weimerskirch et al. 2006)
Common Crane	*Grus grus*	LC	2	66	1993	4,208*	4,161*		India, Pakistan, Afghan. Uzbekistan, Kazakhstan, Russia	Migration	(Higuchi et al. 1994)
Red-crowned Crane	*Grus japonensis*	EN	14	25-88	1993-94	2,287*	1,177*		Russia, China, N. Korea, S. Korea	Migration	(Higuchi et al. 1998)
Siberian Crane	*Grus leucogeranus*	CR	13	2-166	1995-96	5,586	4,121		Russia, China	Migration	(Kanai et al. 2002b)
Siberian Crane	*Grus leucogeranus*	CR	1	164	1996	3,600*			Iran, Kazakhstan, Russia	Migration	(Kanai et al. 2002a)
Hooded Crane	*Grus monacha*	VU	2	123-162	1992	3,800*	3,484*		Japan, N. Korea, S. Korea, China, Russia	Migration	(Higuchi et al. 1992)
White-naped Crane	*Grus vipio*	VU	11	109-186	1991-93	2,897*	2,558*		Japan, N. Korea, S. Korea, China, Mongolia, Russia	Migration	(Higuchi et al. 2004)

Species	Scientific name	IUCN [a] 2006	N=	Days tracked	Study Year(s)	Max [b] Dist. (km)	Mean [c] Dist. (km)	Home range (km^2)	Countries [d]	Type of study	References
White-naped Crane	*Grus vipio*	VU	19	120-167	1991-93	2,728*	2,277*		Japan, N. Korea, S. Korea, China	Migration	(Higuchi et al. 1996)
Steller's Sea Eagle	*Haliaeetus pelagicus*	VU	28	47-759	1997-99	1,839*		274-1,181	Japan, Russia, China	Migration; Home range	(McGrady et al. 2003)
Eastern Curlew	*Numenius madagascariensis*	NE	37	10-338	1997-99	8,000+*			Australia, PNG, Indonesia, Taiwan, Philippines China, Korea, Japan	Migration	(Driscoll & Ueta 2002)
Dalmatian Pelican	*Pelecanus crispus*	VU	3	---	2002				Kazakhstan, Uzbekistan, Afghanistan	Migration	(Morimoto et al. 2005)
Honey-buzzards	*Pernis apivorus*	NE	3	243-390	2003-04	22,623	16,924	32	Japan, China, Vietnam, Laos, Cambodia, Thailand, Malaysia, Indonesia, Philippines, N. Korea; S. Korea	Migration	(Higuchi et al. 2005)
Black-faced Spoonbill	*Platalea minor*	EN	18	1-244	1998-99	2,000+*			China, Taiwan, N. Korea, S. Korea	Migration	(Ueta et al. 2002b)
Asian Elephant	*Elephas maximus*	EN	1	91	2003			289	India	Home range; Habitat;	(Venkataraman et al. 2005)
Asian Elephant	*Elephas maximus*	EN	2	186-323	1995-96			343-6,804	Malaysia	Migration; Home range	(Stuwe et al. 1998)
Mongolian Gazelle	*Procapra gutturosa*	NE	4	119-360	2002-03	1,111	790		Mongolia	Migration; Habitat	(Ito et al. 2006)
Large Flying Fox	*Pteropus vampyrus*	NE	4	7-112	2003-05	810	530		Malaysia, Indonesia, Thailand	Migration; Home range	Epstein et al, unpublished; (Daszak et al. 2006)
Snow Leopard	*Uncia uncia*	EN	1	79	1996-97			1,590-4,530	Mongolia	Home range; Behavior	(McCarthy et al. 2005)

Species	Scientific name	IUCN [a] 2006	N=	Days tracked	Study Year(s)	Max [b] Dist. (km)	Mean [c] Dist. (km)	Home range (km^2)	Countries [d]	Type of study	References
Loggerhead Turtle	*Caretta caretta*	EN	26	30-458	1997-2001	9,000+			Pacific Ocean	Migration; Behavior	(Polovina et al. 2004)
Green Turtle	*Chelonia mydas*	EN	3	37-103	2001	1,855	1,268		China, Taiwan, Japan	Migration	(Song et al. 2002)
Green Turtle	*Chelonia mydas*	EN	8	7-57	1994-97	1,909	980		China, Taiwan, Japan, Philippines	Migration	(Cheng 2000)
Hawksbill Turtle	*Eretmochelys imbricata*	CR	2	12	2004			1,567-1,845;vs.03-.009	Thailand	Home range; PTT vs. GPS	(Yasuda & Arai 2005)
Olive Ridley Turtle	*Lepidochelys olivacea*	EN	10	30-458	1997-2001	7,282			Pacific Ocean	Migration; Behavior	(Polovina et al. 2004)
Blue Whale	*Balaenoptera musculus*	EN	1	60	2005	685**			Indonesia	Migration; Behavior	(Kahn 2005)
Sperm Whale	*Physeter macrocephalus*	VU	1	42	2005	1,110**			Indonesia	Migration; Behavior	(Kahn 2005)
Whale Shark	*Rhincodon typus*	VU	6	7-128	1997	8,025	2,326		Philippines, Malaysia, Brunei, Vietnam	Migration	(Eckert et al. 2002a)

[a] IUCN Red List 2006 Threatened Species Database, CR=Critically Endangered, EN=Endangered, VU=Vulnerable, LC=Least Concern, NE=Not Evaluated
[b] Maximum cumulative distance tracked for an individual; "*" = one-way distance of seasonal migration; "**" = linear distance between start and end points from archival satellite pop-up tags
[c] Mean cumulative distance = total distance recorded for all animals/no. of animals tagged.
[d] Political boundaries crossed for all satellite-tagged individuals per study

APPLICATION OF SATELLITE TELEMETRY TO CONSERVATION IN ASIA

Birds

The majority of satellite telemetry studies from Asia are avian, and these have recently been reviewed (Higuchi & Pierre 2005). Here we will discuss some of the key papers highlighted in that review, and include the work of several additional studies published in the past year. Contributions of satellite telemetry to bird conservation in Asia are three-fold: 1) identifying important migratory stop-over sites; 2) mapping specific migratory routes; and 3) elucidating behavior.

Identifying important migratory stop-over sites

Satellite telemetry has enabled us to identify important stop-over, wintering, and breeding sites for migratory bird species. This information can be used to recommend conservation strategies for single threatened species or be collated for multiple species to identify critical habitats across the landscape and delineate boundaries for networks of protected areas (Haig *et al.* 1998). For example, the Korean Demilitarized Zone (DMZ) was identified as a stop-over, wintering, and breeding site of key importance for three endangered species (Red-crowned crane, White-naped crane, and Black-faced spoonbill) (Higuchi *et al.* 1996; Higuchi *et al.* 1998; Ueta *et al.* 2002a). For White-naped cranes, time spent in the DMZ amounted to 31-87% of the migration period (Higuchi *et al.* 2004). This underscores the need to keep this area undeveloped in the face of possible reunification and growing economic pressure from North Korea. Involvement of the DMZ itself also highlights the importance that military lands and sensitive political borders can have in conservation, especially by way of establishing *de facto* protected areas.

Previously-unknown resting sites for critically endangered Siberian cranes have also been identified using satellite telemetry (Kanai *et al.* 2002a; Kanai *et al.* 2002b). Protected area boundaries were overlaid with these stop-over sites and two critical areas in China were identified where most resting locations occurred. These sites are located outside of reserve boundaries. Wetlands are becoming increasingly rare in China due to heavy development, and the protection of these remaining, unprotected sites is critical if long-distance movement (LDM) in this species is to be sustained (Kanai *et al.* 2002b).

Satellite telemetry data have recently been used for more rigorous methods of hypothesis testing (Higuchi & Pierre 2005). Wetland sites for oriental white storks were analyzed using a network model (Shimazaki *et al.* 2004a; Shimazaki *et al.* 2004b). This method was used to identify sites as the most important links in the migratory chain between Russia and China based on distance, connectivity to other sites, and period of time birds spent at each site; and to test the effects of the loss of important sites along this chain (Shimazaki *et al.* 2004a). Remote sensing has also been used in conjunction with satellite telemetry to characterize the habitat at important migratory stop-over sites for several threatened species (Minton *et al.* 2003; Morimoto *et al.* 2005).

Specific Migratory Routes

Satellite telemetry data has allowed entire avian migratory routes to be traced. In many cases, birds moved through multiple countries and across thousands of kilometers (Table 1). The long-distance extent of these migrations are exemplified by honey-buzzards which flew 10,000+ kilometers each way along their autumn and spring migrations from Japan to wintering sites in Malaysia and the Philippines (Figure 1) (Higuchi *et al.* 2005). In this study, one female returned back to Japan via a longer, unexpected route down the Korean peninsula (Higuchi *et al.* 2005). This behavior may have been to reduce the migratory distance over the ocean, a phenomenon also seen in migratory birds in other parts of the world (Papi *et al.* 1997). Other Asian studies have confirmed that migration paths are not always selected to minimize migration distance, but may be correlated with environmental factors such as habitat quality *en route* (Fujita *et al.* 2004), avoidance of high-elevation mountain ranges (Judas *et al.* 2006), and availability of prey (McGrady *et al.* 2003).

Several multi-lateral conservation agreements to protect migratory birds have been developed (Bowman 1999). These include three action plans in the East Asian-Australasian flyway, for Anatidae (ducks, geese, and swans), cranes, and shorebirds (www.wetlands.org); and a Central Asian Flyways Action Plan that was recently released by the secretariat for the Convention on Migratory Species (www.cms.int). These agreements lay out plans to collect data on migratory species and coordinate conservation efforts among range states throughout Asia. Current and future satellite telemetry studies will only strengthen these conservation agreements and international efforts.

Migratory Behavior

Different demographic groups in a species may display different migratory behaviors. Ueta and Higuchi (2002) analyzed LDM data of adult vs. immature birds for Steller's Sea Eagles, Black-faced Spoonbills, and White-naped Cranes. They found that both total migration period and number of resting days were significantly longer for immature birds. Management plans for these bird species should factor in the different migratory behaviors for juveniles and adults.

Satellite tracking data can also be used to infer threats to key stopover sites by detecting changes in behavior. Siberian cranes were found to have resting periods significantly longer in Chinese than in Russian territory (Kanai *et al.* 2002a). The authors hypothesized that this was because Chinese wetlands were heavily developed, making resting sites few and far between, whereas in Russia, the wetlands were more plentiful so resting periods could be shorter. Understanding the timing and the exact route of LDM may also be used to reduce mortality from anthropogenic threats. For example, one study examined the foraging behavior and foraging movements of pelagic albatrosses in an effort to reduce the interaction and bycatch by longline fishing fleets (Weimerskirch *et al.* 2006).

Marine vertebrates

A lack of information on the migration, population connectivity, and basic biology of marine organisms is a major impediment to their conservation. Satellite telemetry in the marine environment has been challenged by the limitation of transmitting signals from under water, but studies using new technologies have began to shed light on LDM of marine organisms. Recent innovations include salt-water switches to turn transmitters on when exposed at the surface (Cheng 2000), archival pop-up tags (Block *et al.* 1998), and integration of PTTs with light- and sea surface temperature geolocating devices (Shaffer *et al.* 2005). In Asia, LDM monitoring for marine species has included: green (Cheng 2000; Song *et al.* 2002), hawksbill (Yasuda & Arai 2005), loggerhead, and olive ridley turtles (Polovina *et al.* 2004); blue and sperm whales (Kahn 2005); and whale sharks (Eckert *et al.* 2002b).

Several studies have recorded movement through the Exclusive Economic Zones (EEZs) of several countries within Asia. This includes the post-nesting migration of green sea turtles that travel through EEZs of China, Japan, and the Philippines (Cheng 2000; Song *et al.* 2002), and whale sharks tracked through coastal waters of Malaysia, Brunei, Philippines, and Vietnam (Eckert *et al.* 2002b). Tagging of two whale species in Indonesia confirmed that the Savu Sea is an important migratory corridor for cetaceans and support on-going efforts to establish a large marine protected area in this region (Kahn 2005). Studies have also have shown that individuals of some species (e.g. loggerhead turtles) are capable of migrating across the entire Pacific basin to the coastal waters of North America (www.toppcensus.org). Similarly, pelagic seabirds such as wandering albatrosses can cover hundreds of thousands of kilometers during their first year at sea in the southern Indian and Pacific Oceans (Nicholls *et al.* 2000; Weimerskirch *et al.* 2006). These long-range, transboundary movements through coastal waters or across entire ocean basins emphasize the need for international management of these species.

Behavioral information has also been collected in the marine environment using integrated sensors, for example the vertical use of habitat by charting dive depth, time-at-depth, and daily maximum dives for sea turtles (Polovina *et al.* 2004). PTT/GPS receptors have also been used to collect accurate, fine-scale movement and home range data (Yasuda & Arai 2005). These behavioral studies combined with movement data are important to reduce incidental bycatch from fishing fleets.

Satellite telemetry has shown that movement between marine populations can be extensive, but these and other studies should be corroborated with population genetic data to gain a more complete understanding of population connectivity. Movement of individuals does not necessarily imply genetic exchange. For example, marine turtles are known to have a high level of nesting site fidelity, despite transoceanic voyages (Bowen *et al.* 2004). Polvina *et al.* (2004) tracked 35 turtles captured and released from longline fishing boats in the waters off Hawaii. They genotyped individuals to identify populations of origin and found that all of the loggerheads (n=26) were found to have come from nesting beaches in Japan, and three of nine olive Ridley's came from coastal beaches in the Western Pacific.

Terrestrial Mammals

Great migrations of terrestrial mammals are becoming a threatened ecological process throughout the world (Berger 2004). Only a handful of published studies have characterized the movement of mammals in Asia using satellite telemetry, although this includes some exciting work relevant to conservation. The paucity of studies may reflect a technical limitation of receiving signals under dense forest cover especially near the equator. In the Himalayas and Tibetan plateau, seasonal migrations of Mongolian gazelle were found to correlate with habitat quality (Ito *et al.* 2006). Railroads were found to be a significant barrier to movement in a separate analysis of Mongolian gazelle migration; neither of two satellite-tracked females would cross the railroad despite spending significant time along its length (Ito *et al.* 2005). The patterns of movement, home range size, and habitat use for solitary snow leopards have been described (McCarthy *et al.* 2005). Not surprisingly, in comparing results from both satellite- (N=1) and radio-tracked (N=4) animals, satellite telemetry was found to have greater utility in determining the home range size of snow leopards in this remote part of the world (McCarthy *et al.* 2005).

Satellite telemetry has also been tested in mitigating human-wildlife conflict with Asian elephants (Venkataraman *et al.* 2005). Characterization of the spatial and temporal use of habitat can be a cost-effective way to minimize unwanted interactions in areas of multiple use, such as at the interface of human settlements and national parks. The post-translocation movements of forest elephants in Malaysian national parks has also been monitored with satellite telemetry (Stuwe *et al.* 1998).

In most cases, the LDM of mammals in Asia is an order of magnitude less than what has been measured for avian movement (Table 1). This may be because many terrestrial mammals will not travel across areas of high human disturbance and non-continuous habitat. Throughout much of Asia, habitats are highly fragmented from anthropogenic disturbance; and unlike birds, it may be impossible for mammals to travel between distant patches. One exception is the movement of large flying foxes, the only volant mammal that has been satellite-tracked in Asia.

Volant Mammals

In contrast to other terrestrial mammals, many bat species require conservation strategies more similar to those applied to migratory bird species. In the past several years PTTs have become small enough (~20g) to be deployed on large bats. The largest bats in the world, flying foxes (Genus: *Pteropus*), are of suitable size for satellite telemetry. The first bats ever satellite-collared were two grey-headed flying foxes *(P. poliocephalus)* in Australia which were followed flying ~1000 km each in a period of 10 months (Tidemann & Nelson 2004).

Flying foxes are ecologically and economically important species, pollinating and/or dispersing seeds for over 289 plant species in the Old-World tropics (Fujita & Tuttle 1991). Most species of *Pteropus* are globally threatened due to habitat loss and hunting (Mickelburg *et al.* 1992). Four large flying foxes, *P. vampyrus,* were captured in Peninsular Malaysia and tracked as part of a 4-year study on the emergence and ecology of Nipah virus (Daszak *et al.* 2006). The PTT failed on one collared bat, but successful tracking of three other bats revealed previously unknown patterns of movement.

One *P. vampyrus* was tracked flying across the Strait of Malacca between Peninsular Malaysia and Sumatra, a finding which suggests that stretches of ocean (~50km) are not a significant barrier to dispersal for this species (Figure 2). This observation is supported by a lack of genetic differentiation between *P. vampyrus* populations around the Sunda shelf (K.J.O., unpublished data). Home range analysis suggests that bats spent extended periods foraging in Sumatra, Peninsular Malaysia, and Thailand (Epstein et al, unpublished). The three collared bats were followed for periods of 12, 14, and 16 weeks and flew 360, 810, and 420 km, respectively. *P. vampyrus* were found to move between Malaysia, Indonesia, and Thailand which supports the recommendation that they should be included under Appendix 1 of the Convention on Migratory Species and that wildlife legislation and management plans should be coordinated across these international borders (Hudson 2004).

IMPLICATIONS FOR DISEASE ECOLOGY

In addition to the above applications to conservation, monitoring the movement of wildlife in Asia has important implications for human and wildlife health. Emerging infectious diseases have received significant attention in the past few years. Satellite telemetry has great potential to predict the future spread of zoonotic and epizootic diseases, those transmitted between wildlife and humans or between animal populations. Below we discuss the application of this technology to better understand the transmission dynamics and ecology of Nipah virus and avian influenza.

Nipah virus

Nipah virus (NiV), a novel paramyxovirus, is among a growing number of zoonotic diseases that affect the nervous system (for review see, Olival & Daszak 2005). NiV was first identified during a swine and human outbreak in peninsular Malaysia in 1998-1999, in which 105 of 265 infected people died (40%) (Chua *et al.* 2000). Subsequently, there have been five human outbreaks of NiV in Bangladesh between 2001-2005 with 102 documented cases and 76 (75%) deaths (Epstein *et al.* 2006). Serological surveys across Southeast Asia and South Asia have confirmed that flying foxes are the most important natural reservoir hosts for NiV (Chua *et al.* 2002; Harcourt *et al.* 2005; Reynes *et al.* 2005; Wacharapluesadee *et al.* 2005). In Malaysia, NiV was transmitted from flying foxes to pigs most likely from saliva-contaminated fruit or urine; and then pigs amplified the virus and infected humans via respiratory secretions (Mackenzie & Field

2004). In Bangladesh, there appears to be direct transmission from bats to humans, and also evidence for human-to-human transmission of the virus (Hsu *et al.* 2004).

For the past four years, a multi-disciplinary team of researchers have been investigating the natural history and ecology of NiV and its main reservoir host, *P. vampyrus*, in order to better understand the process of zoonotic disease transmission and predict future outbreaks of the disease (www.henipavirus.org). Ecological investigations include field surveys to identify the distribution of bat roosts, population sizes estimates, studies of foraging ecology and habitat use, serological surveys of wild populations, and satellite telemetry (Daszak *et al.* 2006). Satellite telemetry is being used to trace regular and seasonal movement patterns of flying foxes in Southeast Asia, and to identify risk areas to predict future NiV outbreaks in the region (Figure 2).

Avian flu

Recent concerns about a potential pandemic of avian influenza virus have led to an increase in disease surveillance of migratory wild bird species (Munster *et al.* 2005). During 2004-2005, epizootics of avian influenza virus (H5N1 strain) devastated the poultry industries in Asia, and caused significant mortality in some wild bird populations (Liu *et al.* 2005). Additionally, between December 2003 and April 2006 the virus has infected 203 people and caused 113 deaths (WER 2006). Wildfowl and shorebirds are believed to be the natural reservoir of influenza A viruses; over 26 avian families and 105 species have been found to carry the virus (Olsen *et al.* 2006).

Satellite telemetry offers one of the best methods to understand the LDM of these natural reservoir hosts in order to predict the future spread of avian influenza within Asia and between continents. This information will be vital in the event of an increase in virulence or transmissibility of this virus. Several important host species have recently been satellite-tracked including Bar-headed geese (Javed *et al.* 2000), Northern pintails (Miller *et al.* 2005), White-fronted geese (Fox *et al.* 2003), and Whooper swans (Kanai *et al.* 1997). Research is currently underway to increase the number of host species tracked in Asia including ducks, rooks, egrets, and hawks (H.H., unpublished). These avian studies in Asia and North America are also of great utility to predict the spread of West Nile Virus, another important emerging zoonotic and epizootic disease.

CONCLUSIONS

For the past fifteen years, satellite telemetry has been used to monitor the long-distance movement of animals in Asia. This includes twenty-eight species, many threatened and endangered, in the terrestrial and marine environment. Recent miniaturization of satellite transmitters has allowed entire migratory routes of medium-sized birds and large fruit bats to be traced. A majority of studies reviewed demonstrated movement of animals between two or more countries. Conservation efforts for these highly-vagile taxa have been limited by a lack of knowledge regarding the specific routes and timing of migration, location of stop-over sites, habitat use, foraging behavior, and population connectivity for each species. Satellite telemetry studies have contributed greatly to our understanding of all these processes, and are being used to strengthen international efforts to protect these transboundary animals. Furthermore, in the face of a growing threat to human and wildlife health from emerging zoonotic diseases, natural reservoir host species have been tracked to understand the ecology of emerging viruses and predict their future spread. It is certain that the application of satellite telemetry to biodiversity conservation and disease ecology will become more widespread as the cost and weight of transmitters continue to go down.

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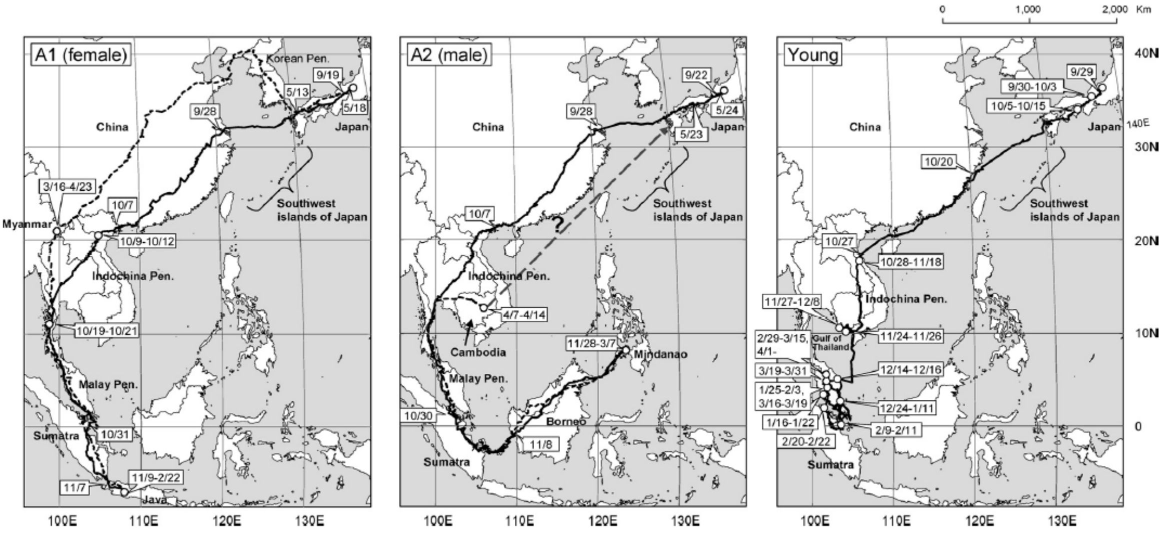

Figure 1. Migration routes of 3 Honey-buzzards satellite-tracked in autumn 2003 and spring 2004. Solid lines represent autumn migration routes, dotted lines represent spring migration routes, and open circles represent breeding, stopover, and wintering sites. Because of lost radio contact, the route of the male was uncertain between 14 April and 23 May, as indicated by a broken straight line with a question mark. *Reproduced with author permission from (Higuchi et al. 2005), copyright transfer permission is pending from the publisher.*

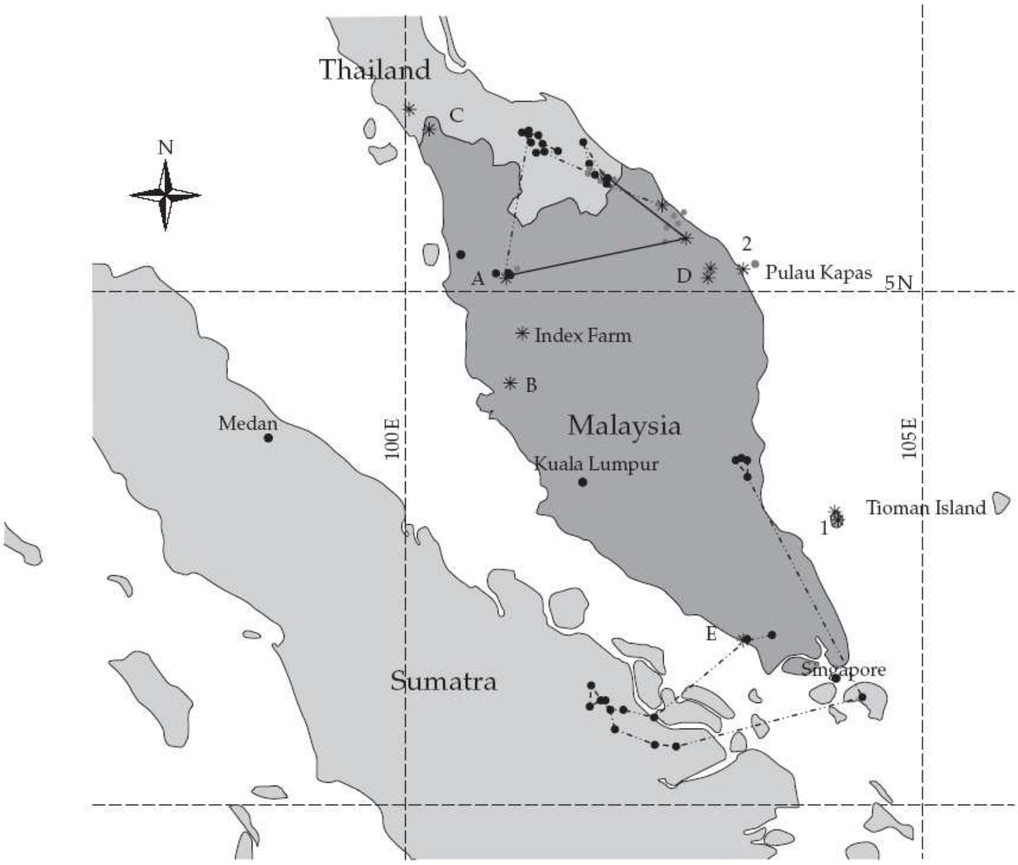

Figure 2. The tracks represent flight paths of 3 satellite-collared fruit bats, *P. vampyrus*. The time between points is 10 days. Colony locations with NiV seropositive bats are identified by an asterisk. *Reproduced with author permission from (Daszak et al. 2006), copyright transfer permission is pending from the publisher.*

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